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# Maximising Penetration of Distributed Generation in Existing Urban Distribution Network (UDN)

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# Maximising Penetration of Distributed Generation in Existing Urban Distribution Network (UDN)

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**Doctor of Philosophy**

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# Abstract

Electrical power generation is currently moving towards greater penetration of distribution generation (DG), using multiple small generators instead of fewer and larger units. This can potentially create improvements in efficiency, by allowing use of waste heat (cogeneration). However, it also generates new problems related to control and co-ordination of large numbers of DGs, usually connected across the urban distributed network (UDN). In particular, concerns about security of supply and reliability together with the integration of new energy resources, are presenting a number of new challenges to system operators. One of the major changes that are being observed is the connection of significant levels of generation to the UDN. To accommodate this new type of generation the existing UDN should be utilised and developed in an optimal manner. It is well known that present arrangements for planning, dispatching and protection of central power generators are not directly applicable to the new technology.

This thesis presents a mathematical method that facilitates the large scale integration of CHP generation, as the most common type of DG, connected onto the UDN. A new methodology is developed to determine the optimal allocation and, size of CHP generation capacity with respect to the technical, environmental and economic constraints of the UDN. The method estimates the adverse impact of any particular constraints with respect to the size and location of DG/CHP plants connected into the UDN. Also, the method provides the basis for quantifying the contribution that DG/CHP units makes to the security of energy supply i.e to what extent the particular DG/CHP can reduce the operational performance demand for the UDN facilities and substitute for the network assets. The method is implemented and tested on a 34 busbars network that represents a section of an UDN. The impact of CHP generation on losses

in the UDN is also analysed and incorporated into the optimal capacity allocation methodology.

The installation of CHP generation is leading to a major change in the way UDNs are designed and operated. UDNs are now used as a media to connect geographically distributed energy generation to the electrical power system, thereby converting what were originally energy supply networks to be used both for distribution and harvesting of energy.

A mathematical model in the form of a Multiple Regression Analysis is presented in order to determine the maximum capacity of CHP generation that may be connected in a given area, while taking account of connection costs as well as technical, environmental, economic and operational setting constraints. Results obtained from various analyses related to the network performance and management are used as data for multiple regression analysis. These analyses include: load flow, fault analysis, environmental and economic analysis. The increased applications of CHP generation presents a substantial challenge to the existing connection policies used to connect CHP plant into UDNs. The section of a typical Irish UDN is used as a case study, and with reference to the available network parameters, the cost and benefits of CHP generations are determined under a number of planning and operational strategies. It is shown that a substantial increase in the net benefits of CHP generation is gained if the appropriate connection method is applied from the start and equally that significant CHP generation connection costs are sustained if ad hoc methods are employed.

Connection of CHP generation can profoundly alter the operation of a UDN. Where CHP generation capacity is comparable to or larger than local demand there are likely to be observable impacts on network power flows and voltage regulation. In fact, two

major problems to be considered are the voltage levels and operation of protection during faults and disturbances. New connection of CHP generation must be evaluated to identify and quantify any adverse impact on the security and quality of local electricity supplies. There are a number of well-established methods to deal with adverse impacts caused by CHP generation connection into a UDN. While a range of options exist to mitigate adverse impacts, under current commercial arrangements the developer will largely bear the financial responsibility for their implementation. The economic implication can make potential schemes less attractive and in some instances have been an impediment to the development of CHP generation in urban areas. Development of a CHP generation system connection algorithm corresponding to the Least Cost Technically Acceptable (LCTA) method is absolutely vital in order to maximise the penetration of CHP generation into existing UDN with respect to different UDN/CHP system operational settings/constraints and minimal economic implication. In this thesis, results from a number of mitigation methods analysis are compared and used to create the connection process algorithm. This algorithm equally can be applied in the connection process of other distribution generation technologies into existing UDNs.

# Declaration

I certify that this report which I now submit for examination for the conformation exam of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This report was prepared according to the regulations for post graduate study by research of the Dublin Institute of Technology and has not been submitted in whole or part for an award in any other Institute or University.

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Candidate

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## List of Abbreviations

| | |
|---|---|
| AVC | Automatic Voltage |
| CHP | Combined Heat and Power |
| CHPI | Combined Heat & Power Interface Protection |
| CPI | Consumer Price Index |
| CSI | Customer Supply Interruption |
| CSTL | Customer Supply Time Lost |
| CT | Current Transformer |
| DG | Distributed Generation |
| CER | Commission for Energy Regulation |
| DLAF | Distributed Adjusted Factor |
| EPA | Environmental Protection Agencies |
| ESB | Electricity Supply Board |
| EPSS | Electricity Power Supply System |
| FIXTC | Fix Tap Changer |
| GHG | Greenhouse Gas |
| HV | High Voltage |
| IC | Internal Combustion |
| IRR | Internal Return of Return |
| IEA | International Energy Agency |
| LI | Loss Index |
| LV | Low Voltage |
| LCTA | Least Cost Technically Acceptable |
| MEC | Maximum Export Capacity |
| MIC | Maximum Import Capacity |
| MSE | Mean Sum of Errors |
| MSR | Mean Sum of Residuals |

| | |
|---|---|
| MV | Medium Voltage |
| NPV | Net Present Value |
| OLTC | On Line Tap Changer |
| PCC | Point of Common Coupling |
| PLR | Power Loss Reduction |
| PS | Power System |
| PV | Photo Voltaic |
| SCADA | Supervisory Control data Acquisition |
| SME | Small and Medium Size Enterprise |
| SOE | State Owned Enterprise |
| SPH | Separate Power & Heat |
| SSE | Sum of squares due to Error |
| SSR | Sum of Squares to due Regression |
| SST | Total Sum of Squares of Dependent Variable |
| UDN | Urban Distribution Network |
| UDNO | Urban Distribution Network Operator |
| UDNP | Urban Distribution Network Planner |
| ULTC | Under Load Tap Changer |
| VPP | Virtual Power Plant |
| VT | Voltage Transformer |
| STG | Separate Thermal Generation |
| SEG | Separate Electrical Generation |
| T & D | Transmission and Distribution |
| TVD | Total Voltage Deviation |
| TVPDI | Total Voltage Profile Deviation Index |

## List of Symbols

| | |
|---|---|
| $S_I$ | Net injected VA by the DG unit into the network |
| $P_{DG}$ | Real power generated by the DG plant |
| $Q_{DG}$ | Reactive power generated by the DG plant |
| $P_{Load}$ | Real power consumed by the load |
| $Q_{Load}$ | Reactive power consumed by the load |
| $R_L$ | Resistance of the line |
| $X_L$ | Reactance of the line |
| $P_{DGi}$ | Injection active powers of DG to the network busses |
| $Q_{DGi}$ | Injection reactive powers of DG to the network busses |
| $P_{Di}$ | Active power loads demand |
| $Q_{Di}$ | Reactive power loads demand |
| $P_i$ | Active power of the buses |
| $Q_i$ | Reactive power of the buses |
| $V_i^{min}$ | Lower bound of voltage $V_i$ of bus i around the rated value |
| $V_i^{max}$ | Upper bound of voltage $V_i$ of bus i around the rated value |
| $S_t$ | Apparent power and |
| $S_t^{max}$ | Thermal limit. |

| | |
|---|---|
| $I^{CAP}$ | Fault capacity of each set of switchgear at bus i. |
| y | Dependent variable |
| $\beta_0$ | Intercept ( value when all the independent variables are 0) |
| $\beta_j$ , | Corresponding m regression coefficients |
| $V_{mini}$ | National voltage standard minimum limit |
| $V_i$ | Voltage at busbar i |
| $V_{maxi}$ | National voltage standard maximum limit |
| $I_{Fault}^{Min}$ | Minimum fault current level |
| $I_{Fault}^{Rated}$ | Rated fault current level |
| $I_{Fault}^{Max}$ | Maximum fault current level |
| E | System driving voltage |
| Z | Impedance of the network from the fault point back to and including source or sources of a fault current. |
| $Z_Q$ | Impedance of upstream network |
| $Z_T$ | The impedance of transformer |
| $Z_L$ | Line impedance |
| $Z_L$ | Line impedance |
| $Z_F$ | Fault point impedance |

| | |
|---|---|
| $c_{max}$ | Voltage factor for calculating the maximum fault current (e.g. for MV ≈1.1) |
| $E_n$ | Line Voltage |
| $U_n$ | Phase voltage |
| $I_{\substack{Fault \\ CHP}}$ | Fault current contribution from the CHP plant |
| r | Line resistance per metre |
| L | Length of line |
| $P_L$ | Active power transport through line |
| $Q_L$ | Reactive power transmitted through line |
| $V_p$ | Phase voltage |
| $E_{thermal}$ - $CO_2$ | Emission generated by separate heat production |
| $E_{electricity}$ - $CO_2$ | Emission generated by separate electricity production |
| $E_{CHPemission}$ - $CO_2$ | Emission generate by CHP generation |
| $N_{CHP}$ | Total number of busbars with installed CHP plants, |
| $P_{CHPi}$ | Rated electrical power output of CHPs installed at each busbar |
| $C_{i1}$ | Installation costs ( normally €/MW) of CHPs unit installed at each busbar i. |
| $C_{i2}$ | Equipment costs (normally €/MW) of CHPs unit installed at each busbar i. |

| | |
|---|---|
| $E_i$ | Energy savings of each customers supplied from busbar *i* |
| $P_{losses}$ | UDN/Grid losses due to size and location of CHP plants |
| $I_{SC,i}^{with\ DG/CHP}$ | Calculated short circuit current at the bus i |
| $I_{SC,i}^{Rated}$ | Rated value short circuit current at the bus i |
| $S_{SC,i}^{with\ DG/CHP}$ | Calculated short circuit VA at bus i |
| $S_{SC,i}^{Rated}$ | Rated value short circuit VA at bus i |
| Vmin | Minimum voltage limits determined by UDNP/UDNO for every busbar in the network |
| Vmax | Maximum voltage limits determined by UDNP/UDNO for every busbar in the network. |
| $V_{Level}^{DG/CHP}$ | Voltage level after DG/CHP system is connected |
| $P_{Gi}$ | The output of active power of i$^{th}$ generator including grid supply |
| $Q_{Gi}$ , | The output of reactive power of i$^{th}$ generator including grid supply |
| $P_{Lk}$ | The active power of k$^{th}$ load connected to the network |
| $Q_{Lk}$ | The reactive power of k$^{th}$ load connected to the network respectively |
| $\bar{V}$ | Voltage rated value determined by the UDNP/UDNO |
| $N_{br}$ | Number of branches |
| $R_l$, | The l-th branch resistance |
| $I_l$ | The l-th branch current. |

| | |
|---|---|
| $\Delta P$<br>$\Delta Q$<br>$\Delta n$ | Vectors of the variations of CHP plant P and Q operating levels and the OLTC position of transformers in the network |
| $K_{iP}$,<br>$K_{iQ}$,<br>$K_{in}$ | Vector sensitivity coefficient of the voltage variations at the network busses |
| $H_{P_{loss}P}$,<br>$H_{P_{loss}Q}$,<br>$H_{P_{loss}n}$, | Vectors of sensitivity coefficient of active UDN losses. |
| $P_{cp}$ | The power at connection point between the UDN and the site network |
| $P_l$ | The power consumed by the load connected at the site network |
| $P_j$ | The power output from CHP plant(s) connected at the site network |
| $I_{UDN}^{max}$ | The maximum current contributed by the network |
| $I_i^{Rated}$ | The maximum rated current of any network component |
| $(m_{GHG})_{CHP}$ | Mass of green-house gas emitted by CHP system |
| $(m_{GHG}^{W})$ | Mass of green-house gas emitted from electricity generation |
| $(m_{GHG}^{Wlosses})$ | Mass of green-house gas emitted by generation of the electricity that is lost during transmission & distribution |

|  |  |
|---|---|
| $(m_{GHG}^{Q})$ | Mass of green-house gas emitted from thermal energy generation |
| $V_{CHPi}$ | Actual voltage after CHP system is connected |
| $R_i$ | Resistance of branch i |
| $X_i$ | Reactance of branch i |
| $\lvert V_i \rvert$ | Voltage magnitude at bus i |
| $E_{loss}$ | Energy losses in the network |
| $P_{loss}$ | Power loss of the network before connecting CHP system |
| $P_{loss}^{CHP}$ | Power loss of the network after CHP system connection |

# Chapter 1

## 1.1 Electrical Power System

The main purpose of an electric power system is to satisfy the customer demands in a reliable manner as economically as possible. At present the electrical power system market includes deregulated and competitive electric power actors where they have a range of alternatives with respect to their use of electricity and their payment for electricity services. These actors are able to participate in time-based markets and meet price-fixing that can vary widely depending on supply and demand. Power systems are undeniably considered as one of the most important pieces of infrastructures of a country. Their importance arises from a multitude of reasons that include: technical, social and economic. Technical, as the commodity involved requires continuous balancing and cannot be stored in an efficient way. Social, because electrical power has become an essential commodity of the life of every person in the greatest part of our planet. Economical, as every industry relates not only its operational but also its financial viability in most cases with the availability and the price of the electrical power. The reasons mentioned above have made the power system a subject of great interest for the electrical engineering sector [17]. A traditional power system's primary mission is to produce power at central generating stations and deliver that power to electrical power consumers at their place of consumption and in ready-to-use form. The electrical power system must convey power to the customers, which means it must be spread across the territory of the utility in rough proportion to customer locations and demand. This is a primary requirement of the electrical power system, and one so elementary that is often overlooked – the electrical power system must cover ground– reaching every customer with an electrical path of sufficient capacity to satisfy every customer's demand for electric power. The electric power must be high quality too. This means power must be reliable and that voltage must be stable and within standards.

Electricity demand is growing rapidly worldwide, from 9.4% in 1973 to 17.2% in 2008 in the share of energy consumption [5]. Global Electricity demand is projected to grow at an annual rate of 3.3% in the period 2006 to 2015, slowing down to 2% per year on average in 2015 – 2030 [6]. This upward trend toward a higher percentage of energy consumed for electrical power will continue for the foreseeable future reflecting the growth of modern industrial society. This trend has increased the importance of electricity networks and how they are operated and planned. It has focused the attention of policymakers and politicians on how this asset is being managed. The evolution of the electricity industry over the last 100 years has mainly been a technical one. Traditionally, electricity systems have been run by vertically integrated utilities with the focus on the engineering aspects rather than economic issues. This usually led to a high quality of supply for the consumer but perhaps at the expense of cost effectiveness.

Power generating stations, transmission and distribution systems are the main components of an electrical power system. These components are connected through transmission lines, which also connect one power system (grid, area) to another. A distribution system connects all the loads and generation capacity in a particular areas to the transmission system. For economical and technological reasons, individual power systems are organized in the form of electrically connected areas. From the energy utilization point of view electricity is still being regarded as a highly effective means of energy carrier. At present the demand of electricity has greatly increased and in order to support this demand a modern electrical power system becomes a complex network of transmission lines interconnecting the power generating stations to the major load points in the overall power system. The aim of electrical systems is to continuously meet the demand from all customers. In order to achieve this goal, power plants produce electrical power in distant sites and deliver it to customers through the transmission and distribution systems on a second by second basis. The complex interaction for the delivery of electrical power follows a set of physical laws in order to move electricity from one point to another. As depicted by Fig 1.1, the main concept of the power delivery system consists of hierarchical voltage levels.

Electrical delivery systems consist of several key power delivery pieces of equipment; and they can be classified as:

- Transmission system: Function as the interconnected grid between major power generating plants and the main load centres; by operating at the highest voltage level these intricate lines provide a strong bond between generators so they can be synchronised with the system.
- Sub-transmission system: Fulfils the purpose of taking power from transmission substations and delivering it to the distribution substations; usually at this stage large industrial customers are supplied.
- Distribution substations: Function as the centres that link the transmission grid with the distribution primary feeder system. This key task is achieved through transformers that convert the incoming power from sub-transmission voltage levels to the lower primary voltage for distribution. In addition, voltage regulation by means of OLTCs can also be applied at this level.
- Primary system: Operates at the feeder distribution voltage. It consists of all power lines, laterals included, between the distribution substations and service transformers. Small industrial clients can be connected at this juncture.
- Secondary system and service level: Is fed by the service transformers and directs the power at utilisation voltage to residential and commercial customers.

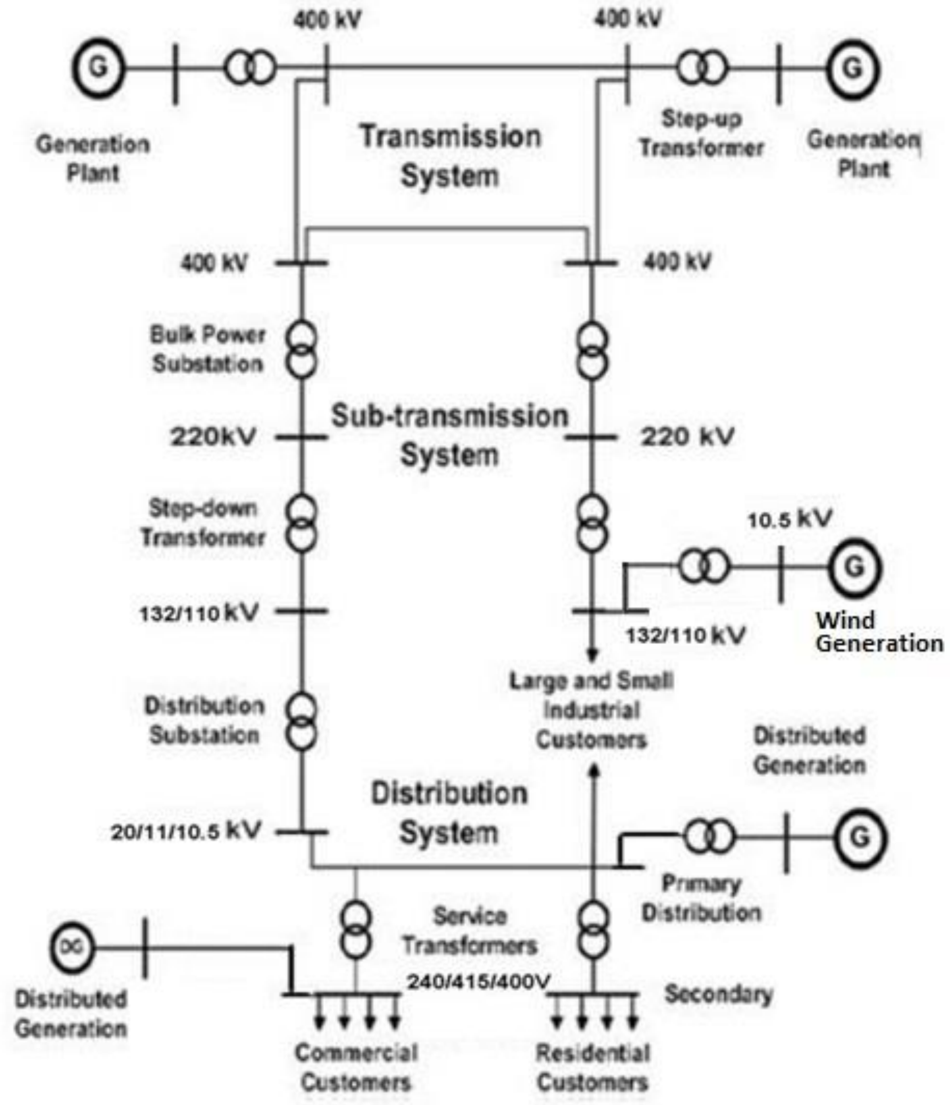


**Fig. 1.1 Overview of the Electrical Transmission and Distribution Infrastructure (adapted from [36])**

A number of recent drivers have altered the situation described above. For example, EU Directive 2009/72/EC was aimed at the introduction of common rules for the generation, transmission, distribution and supply of electricity. Depending on its location, technology, penetration and robustness on the system, the integration new electrical power generation may bring about various challenges for electrical power system operators. It is the responsibility of the system operator to plan and develop the electric power system, schedule and dispatch generation, operate the electricity market and ensure system security. System operators are now faced with the challenge of maintaining the high quality of supply that consumers expect while faced with volatile fuel prices, dwindling and increasingly insecure energy resources and the integration of new forms of energy. These issues when dealt with in a liberalized market situation are not merely technical but also economic and environmental. As such, due consideration must be given to costs at every stage of planning and operating the system. The electric power system is an energy transport network and with the predicted large growth in electricity demand, it is likely to become an even more important energy transport system.

## 1.2 Generation, Transmission &Distribution

The power system consist of generation plants, transmission systems, distribution systems as illustrated in Fig.1.2 and these are the most important elements of power system planning [7].

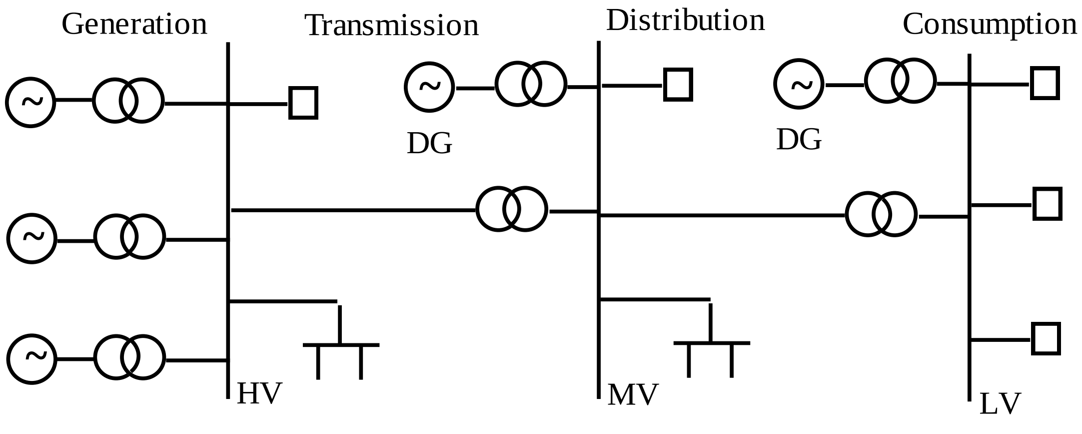


**Fig. 1.2 Electrical Power System (Overview, Single-Line Diagram) (adapted from [11])**

Generation system units have as the primary task to supply the power system with electric power and are placed in geographically dispersed locations where the system units normally contain more than one generation unit. Generation units operate based on different energy sources, e.g thermal (oil, coal, natural gas, etc), nuclear, renewables (hydro, wind, solar, tidal) etc. There are several conversion processes in conventional electric power plants, which often end up with turbines transforming mechanical energy to electrical energy. From the generation units, energy is delivered to the transmission system via step-up transformers. Generation units differ widely in capacity and controllability but can, so far, be considered as deterministic as most of them are able to generate at predefined power levels. Generation units are normally classified as base, intermediate or peak-load units. Base load units have a high load factor, in the range of 80%. They are normally designed to operate at a constant load level during normal operations. Peak load units are characterized by short start time and fast ramping rate and are used to serve the load for some hours of the day during peak demand periods. The load factors of these are usually ranging from 5% to 20%. Intermediate load units are used to follow the daily or seasonal load fluctuations, and the output of these plants is adjusted up or down to balance the variations of the demand during the day. The load factor of these ranges from 20% to 80%.

Transmission system units have as their primary task to connect generation units to consumption points and create large power pools for increased reliability. High voltage AC transmission offers high transmission capacity and low transmission losses. The transmission system consists of several separate parts following networks servicing the same control area that operate at different voltage levels, usually at high (110kV) or very high voltages (400kV), and are interconnected almost only by substations. However, some large generation and load units are connected to the transmission system. The transmission network also serves to integrate adjacent power systems. The transmission network include various equipment to maintain voltage levels and phases, e.g. transformers (step-up/-down, voltage-regulators, phase shifters), lines/cables, series capacitors, shunt and series reactors, etc. A large number of circuit breakers and disconnectors are also included for equipment protection and the possibility to disconnect power units or areas with malfunction. Beside the possibilities in controlling the voltage and phases, the frequency and power balance is maintained by ordering specific generation units capable of managing the task.

Distribution system units are similar in structure to the transmission system but cover a much smaller geographical area and have the main task to supply energy to consumers at standard voltage levels by single phase and/or three-phase AC connections. The distribution networks receive electrical energy from the transmission system at power delivery points and the network system voltage is stepped down in stages by several substations. Operated passively with limited control activity, Fig 1.3 the voltage control is provided by on-load auto tap transformer down to the 10.5kV (20kV) primary substations which must then accommodate all voltages drops in the network below.

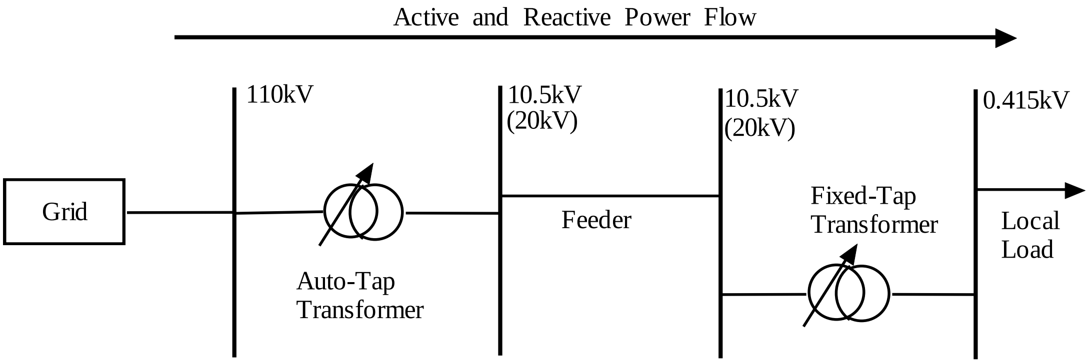


**Fig 1.3 Traditional Distribution Network (adapted from [101])**

While most distribution system are set up as ring circuits, they are normally operated as a radial system in order to keep fault levels low and facilitate simplified protection schemes.

Conventionally, distribution networks are built up as radial systems including equipment such as; distribution transformers, feeder sections, switches, fuses, reclosers and automatic load transfers.

As already mentioned the power system includes production, distribution and consumption units where process actors are responsible for interacting with each other to operate and support the load demand. Unresolved system planning problems or constraints will eventually become system operation problems and constraints and will therefore affect customer reliability of power supply. Reliability of supply is defined as the ability to supply adequate electric service on a nearly continuous basis with few interruptions over an extented period of time [8,9]. With this in mind any level of power supply reliability less than 99.9 % of time is unacceptable in any developed country. Because of this task, electric power system planning and management is extremely complex. The task of running the power system remains as complex as ever and is constantly facing new challenges including high penetration of Distributed Generation (DG).

## 1.3 DG/CHP System in Urban Area in Energy Supply System

In the last two decades we have seen a trend towards the development and deployment of distributed generation (DG) due to government policy changes and increased availability of small capacity generation technologies. Electrical power generation from DG is playing an increasing role in the supply of electricity in liberalized electricity markets. The popularity of DG is on the rise due to a number of reasons: increasing difficulty faced in installing new transmission and distribution infrastructure, recent technological advances in the area of DG technologies and most importantly deregulation of the power system. The nature of DG connected to the UDN is smaller plant usually up to 1MW in the form of CHP generation with limited central control, connected at a low or medium voltage level. Currently, CHP generation is attractive to both UDN operators and electricity users, as it provides meaningful advantages to both.

CHP plant serving Small and Medium Size Enterprises (SMEs) and in some cases domestic consumers, form the back bone of on-site energy generation capacity in UDNs, replacing existing on-site thermal energy plant and substituting to a large extent, the commercial electricity power supply.

Additional benefits of a CHP generation include: reduction of greenhouse gas emission, increase in SMEs business reliability, improved electrical power quality, increase energy efficiency, resulting in significant financial and environmental benefits. By definition CHP generation is a small-scale power generation technology that provides electrical power and thermal energy supply at or close to a consumer sites [1]. Normally, the CHP is connected to an UDN at a point of common coupling (PCC) that is not directly connected to the bulk power transmission system. The general structure of UDNs are in most cases characterized by the radial layout of the network that consists of many LV feeders, which can include one or more branches. They are traditionally designed with the assumption that power will flow in one direction from the HV/MV (110kV/10.5kV) via 10.5 kV distribution system (cables or overhead lines) and supply customer via MV/LV (10.5kV/0.4kV). A radial UDN feeder will feed loads from a single point of supply (HV/MV substations) which greatly simplifies the task of protecting the network. Some UDN customers have very high load demand (e.g SMEs and large commercial/residential buildings) for whom CHP generation appeals as a means of lower energy costs. Normally, this is not a problem if the energy generated by the CHP plant is used on site as opposed to being exported to the network. The consumers are connected directly to the feeder or one of its branches usually using only one phase (domestic) or three phase (SMEs). The feeders are supplied from MV/LV substations that typically include a transformer with the rating range of a few hundred kVA up to 1.6 MVA. In most cases transformers are equipped with an off – load tap changer. UDNs consist typically of underground cables having larger cross sections than rural overhead line distribution networks. The introduction of DGs into the distribution system can significantly impact the operating state and dynamics of both the transmission and distribution systems. Connection of CHP plants in an UDN fundamentally alters the operation of the network power flow, voltage regulation and fault current level especially where CHP generation capacity is comparable to local power demand and specifically where export of energy occurs. While at low/modest levels of CHP generation penetration in an UDN may not have significant impacts on the high voltage transmission system, the impacts at the lower voltage distribution level could be much bigger especially with respect to fault current levels, the magnitude and direction of real and reactive power flow, the system voltage (both steady-state and transient) and the system stability under various small and large signal transient conditions. The impacts and interactions can be both positive and negative depending on the UDN operating characteristics and the CHP plant operating mode, placement and size. Proper placement plays a very important role since power flows at the interface substations and throughout the networks depend on geographic distribution of all generation sources with respect to demand irrespective of the voltage at the connection point. For CHP generation to have a positive impact, it must at least be suitably integrated and coordinated with the UDN operating practices and feeder design [2,16]. In order to realise the positive effects and enhance the UDN capacity limits while contributing to system security and quality of supply, local optimization would be required accompanied by taking advantage of any inherent regulation capability of dispersed generation. In short, the addition of CHP generation will usually cause changes in voltage magnitudes and power flows in the UDN. These changes will affect the network losses. There are obvious implications for the current rating of lines resulting from modified power flows, and voltage changes could see voltages rise to undesirable levels. In addition, power injected by CHP plant may result in a voltage that is within limits at the CHP generation site but could be out of limits further downstream [2, 16]. The addition of extra power generation to the network also impacts on the network fault current levels, possibly causing fault currents to increase beyond the fault breaking capacity of circuit breakers. The essence is that adding DGs to a passive UDN makes it an active distribution network, similar to a mini transmission system and extra thought must be given to its operation and control. More specifically, in voltage profile and regulation analysis, available transmission capacity analysis, as well as cost analysis, the connection point, type, size and location of CHP plant, the voltage regulator settings and independence characteristics of the line must all be considered for various load and load density levels. Any new connection of a CHP generation must be assessed to identify and quantify any potential negative impact on the security and quality of local electrical power supplies. While a range of options exist to alleviate negative impacts, under current commercial arrangements, the DGs developer will largely bear the financial responsibility for their connection. The economic consequences can make potential schemes less attractive and in some instances have been impediments to the development of CHP generation schemes. The connection method is designed by the network operator to efficiently connect the CHP plant into the network in accordance with the network planning criteria. The connection charge is based on the LCTA principle [2]. The network operator will study the impact of the CHP generator scheme on load flow, voltage profile and fault current levels and the appropriate network reinforcement cost will be determined based on these studies. This thesis develops a methodology using multiple linear regression analysis techniques for systematic and rational placement of a CHP generation plant in the UDN where operational conditions must be within given limits.

## 1.4 Motivation

Since the industrial revolution began in the 19th century people have increasingly been migrating from rural to urban areas, seeking a higher quality of lifestyle that provides them with easy access to services and commodities. According to the United Nations, by the year 2030 nearly two thirds of the global population will be located in cities [3]. In addition, the challenges of reducing the emission of greenhouse gases while still “managing to keep the lights on" are issues that must be addressed at urban centres in both developed and developing countries [4]. These unavoidable circumstances will cause city planners and key infrastructure stakeholders to face a great task in providing good quality services, while meeting environmental targets, to an ever increasing number of consumers.

The motivation for this interest include:

- Increase of security and reliability of UDN energy supply: use of DGs can increase the self-sufficiency of the electrical provision, expand the energy source portfolio and improve UDN support in terms of local/global regulations and ancillary services supply. Taking into account the islanding opportunity, DG can minimise/avoid power outages for customers and deliver profitable contributions for the restoration process.
- Advantages in UDN planning and operation: high penetration of appropriately integrated DGs reduces congestion in upstream systems leading to the postponement of transmission system development. Connection of DG plants is available also from an authority point of view due to the fact that it is generally easier to find sites for DG plants than for large central power plants. Moreover,

DG units can be brought online in a short period of time compared with large central power plants.

- Present energy market competitiveness supported by development of small-scale, efficient, relative cheaper generators enable DG plants to be more attractive for both the new-entry small stakeholders in the electricity market and big companies promoting competition (because investment decisions are made based on shorter term profits).
- More efficient use of primary energy resources (i.e. natural gas and oil) and reduction in greenhouse gas emissions is not generally techno-economically realistic for large fossil fuel-based power plants located outside urban area and it is difficult to utilize the waste heat generated from the energy conversion process. Small-scale efficient and environmentally friendly CHP plants can be exactly sized to match the needs of several domestic or commercial/industrial SME customers, allowing the use locally of the waste heat produced as a by-product of electricity generation. This provides high economical benefits and harmful pollutant emission reduction. In addition, the generation of energy locally reduces its transmission leading to power losses reduction.

Together with the potential benefits provided by installation of DG in UDN discussed here, there are several technical issues related to problems which must be investigated. In fact, whereas a small number of generators do not present a problem, the future vision of electrical power systems presents a scenario based on high penetration of DG in UDN, which inevitably introduces a number of technical problems. The major technical issues related to the presence of DGs in the UDN include:

- UDN planning and operational issues with high penetration of the DG normally connected at low voltage level can cause serious problems for UDNO. Starting from the present situation, both the network and network architecture call for a revision. In order to facilitate high penetration of DGs in UDN, the network protection system needs to be redesigned in order to manage the increase in voltage and fault current level, while at the same time being able to deal with bidirectional power flow.
- Power reserve and balancing are other important issues related to high penetration of DGs in a UDN. At present DGs installed in UDN are fully controlled by the owner of DG plant. Therefore, they are anticipated by UDNOs as quite unpredictable, intermittent and not dispatchable. A high penetration of DGs can cause serious problems if UDNOs are not able to access reserve power from the upstream grid. In addition, transmission network operators (TNOs) have the problem of forecasting the reserve to avoid sudden UDN instability.
- Infrastructure and provisions of gas supply in urban area can cause a serious problem for gas fuelled CHP technologies experiencing the record growth trend in integration in UDN. Therefore, security of supply concerns may arise due to gas demand/offer discrepancies. These may also be linked to possible unscheduled imported gas shortages or constraints in the gas transmission/distribution system.

Connecting DGs to the UDN produces a range of impacts that must be limited to protect the security and quality of electricity supply. Mitigation techniques currently employed may add significantly to the cost of development and discourage investment into DG technology development. The inappropriate siting of new CHP plants, or poorly phased development can lead to the sterilisation of an entire UDN and lower the opportunity for connecting CHP plants without UDN upgrades. Government targets for

DG/CHP generation installation will require more holistic development of the existing UDN infrastructure.

## 1.5 Irish Urban Distribution Network

Electricity Supply Board (ESB) was established under state law and operates as a State Owned Enterprise (SOE). The Electricity Supply Board Act was passed in 1927 to set up the ESB, a corporate body to control and develop Ireland’s electricity network [10]. The ESB is majority owned by the Irish Government with the Minister for Finance and the Minister for Communication, Energy and Natural resources holding 85% and 10% respectively of ESB’s issued share capital. The remaining 5% of the issued share capital is hold by the Employee Share Ownership Trust. ESB is the licensed owner of the electricity transmission and distribution system in the state. The Irish electricity sector is dominated by ESB and its 75 subsidiaries which comprise a vertically integrated electricity business. As shown in Table 1.1, ESB is active at all levels of the electricity sector in Ireland, namely: power generation, electricity transmission and distribution and the wholesale and retail supply of electricity. ESB is also active in the provision of engineering consultancy services; for the most part it provides these services to businesses engaged in the construction and refurbishment of the system in Ireland. Since 2000, EU member states have gradually opened up their electricity markets to competition [10,12,13]. Full market opening took place 2005. The electricity market is also fully open for green and CHP generation suppliers. Even with this, it is likely that ESB will maintain a highly dominant position in the electricity market with ownership of over 60% of the generating capacity [14,16].

Urban distribution networks (UDN) make up the last link in the chain of supplying energy to the residential, commercial and industrial consumers. The UDN density and complexity are generally larger than for transmission systems which feed them via HV/MV substations.

**Table. 1.1 Segment of Electricity Sector In Republic of Ireland**

| Segment | Republic of Ireland | | |
|---|---|---|---|
| | Owner | Operator | Regulator |
| Generation | ESB and Others | ESB and Others | CER |
| Transmission System | ESB | EirGrid | CER |
| Distribution System (Urban/Rural) | ESB Network | ESB Network Ltd. | CER |
| Suppliers (SEM) (ESB and Others) | N/A | Various | CER |

UDNs also have particular characteristics which differentiate them from transmission networks. The core differences lie in the number of specific types of devices, multiphase possibilities and widely varying types of loads. Moreover, most of these consumers are connected to only one of the three phases and as a consequences; the system is usually unbalanced. In Ireland the UDN consist of; the MV and LV electricity networks used to deliver electricity from the transformer stations to connection points such as SMEs, houses, offices, shops, and street lights, and is owned by ESB Networks. ESB Networks is also the distribution system operator and is responsible for building, maintaining and operating the entire distribution level network infrastructure. This includes all overhead electricity lines, poles and underground cables. ESB Networks has responsibility to all electricity customers, irrespective of their supplier, for:

- Connection to the network
- Reading meters and passing these readings to the different supply companies
- Restoring supply in cases of interruptions and emergencies

The operation of the entire distribution network in Ireland is conducted by ESB Networks Limited, a separate wholly-owned subsidiary of ESB. ESB Network Limited, as the licensed UDN operator is in control for planning, development, construction, operation, maintenance and connection to the UDN. ESB Networks Limited is also responsible for the installation, maintenance and reading of electric meters. ESB Network Limited as network operator earns revenue principally through chargers for these UDN functions. These charges are regulated by Commission for Energy Regulation (CER).

In Ireland and other countries, voltage rise and fault current level tends to be the dominant constraint and quite often the critical factor when offering capacity on the network. This is due to the existing network in Ireland, which outside Dublin is typically a weak network with a low Short Circuit Level or fault level. In addition, Irish UDNs are in most cases characterised by the high load density, strong environmental constraints and radial layout with many LV feeders, which can include one or more branches as shown in Fig 1.4. UDN feeders consist typically of underground cables having large cross sectional area with a length normally less than 10 km. Urban HV/MV networks supply a number of MV/LV substations that typically include a transformer with range of a few hundred kVA up to 2 MVA. In most cases the transformers are equipped with an off-load tap changer. Moreover, being a new kind of energy source, DG have various advantages and would be of great help to the security and reliability of a UDN energy supply if they are sized and sited properly.

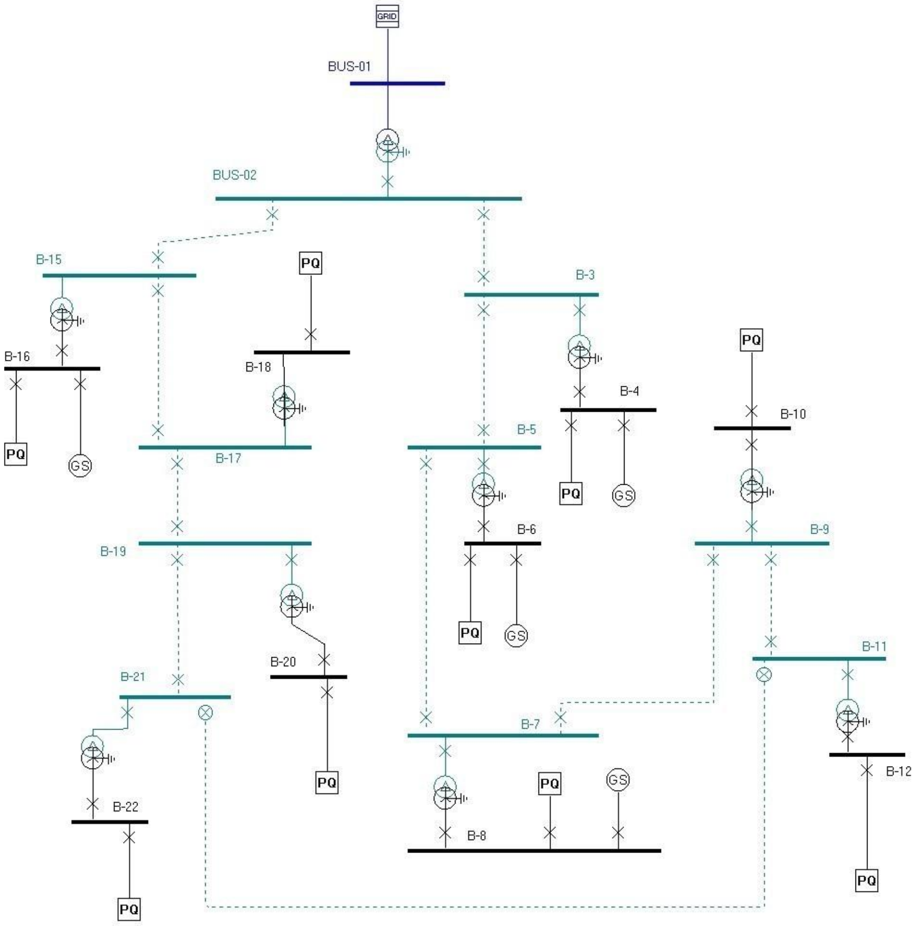


**Fig.1.4 Typical Urban Distribution Network Layout with DG (see Appendix 6 for equipment specification)**

Therefore, it is believed that widespread application of DGs would be part of the of urban network's planning development in the future. When considering the method of connection for the generator, ESB Networks as the system operator will often consider more than one option of the connection. To determine the most appropriate connection method ESB Networks apply the LCTA principle [2,16]. LCTA evaluates a connection option in light of the technical standard against which the system is planned and operated and then, assuming those standards are met, consider the capital cost of the equipment required to facilitate the connection of the generator. The economic implication of the DG connection into the UDN can make a potential scheme less attractive and in some instances have been an impediment to the development of DG schemes.

## 1.6 Objectives

The capacity of CHP generation connected to the UDN will increase significantly as a result of EU government targets and initiatives. CHP generation can have a significant impact on the technical, economic and environmental setting for customers and electricity suppliers . The connection of CHP plants at UDN creates a number of well documented impacts with voltage rise and fault current level being the dominant effects. A range of options have traditionally been used to mitigate adverse impacts but these generally revolve around network upgrade, the cost of which may be considerable. Where CHP plant capacity is comparable to or larger than local demand there are likely to be observable impacts on the network technical concerns that include: equipment ratings, short circuit level, voltage rise, losses, power quality and protection. New connection of CHP plant must be evaluated to identify and quantify and adverse impact on the security and quality of local electricity supplies. The first objective of this thesis is to identify and quantify any adverse impact on the security and quality of a UDN performance that can be produced by connection of CHP plant. The second objective is to develop a mathematical model that will allowed the determination of optimal size of a CHP plant that can be connected at any busbars in the UDN. In order to demonstrate that analysis of a 34 busbar UDN is created that represents a real UDN located in the South of Ireland.

## 1.7 Contributions

The thesis mainly contribute to knowledge not by introducing sophisticated mathematical models and theories, but by proposing method that is based on both practice and theory that provide support for solving issue of today and tomorrow's UDNs. UDNs that are planned operated and maintained in a liberalised market, which brings the environmental an economic aspects into the focus alongside the technical and more specifically to provide solution for an effective strategy to facilitate maximum penetration of DG/CHP system into the existing UDN.

This work brings together statistical theory through classical operational analysis of distribution system in order to meet the future requirements for an effective management of a UDN with high penetration of DG/CHP capacity.

The studies in this thesis introduce an algorithm that allows UDNP/UDNO and potential DG/CHP system developer to estimate what is the maximum of the DG/CHP system capacity that can be connected at any particular point in the UDN corresponding to LCTA principle. It also presents an algorithm that allows UDNP/UDNO and DG/CHP system developer to estimate impact of any size of DG/CHP system on the UDN operation and at a same time estimate the connection cost that correspond to LCTA principle.

The prospect of independent ownership for small size DG/CHP systems in urban area as encouraged by the current deregulation of energy supply sector broadens the appeal further. The fact that energy supply restructuring process is moving the energy sector away from the traditionally operated energy supply system and cost-based regulation toward increased exposure to market forces. These changes introduce a set of significant uncertainties regarding the operation of the UDN and the DG/CHP systems connected to the network. In response to the new and potentially conflicting economic and technical constraints of a growing number of independent DG/CHP systems, the new balance between market forces and UDNO control will be found to coordinate the UDN and DG/CHP systems connection/operation.

For the UDN to operate reliably and efficiently, it must accommodate both the engineering needs to maintain adequate network services and the economic push for the independent and decentralised decision making. To facilitate that, this thesis introduces a general steady-state modelling and optimisation framework that allows optimum connection of DG/CHP systems according to the LCTA principle. It also present an algorithm that allows UDNP/UDNO and DG/CHP system developers to estimate the impact of any size of DG/CHP system on the UDN operation and at a same time estimate the connection cost that correspond to LCTA principle.

In this respect, the main contribution of this thesis that can be utilised by the UDNP/UDNO, DG/CHP system developers and to some degree power system regulator can be summarised as follows :

- Development of a model for describing a steady-state operation of UDN with high penetration of DG/CHP system
- Using this model an approach for optimising operation of UDN through connection of DG/CHP systems is formulated.
- A mathematical model ( Multiple Regression Analysis) is formulated allowing UDNP/UDNO and DG/CHP system developer to determine the maximum size and optimum place for DG/CHP system connection in UDN.
- Development of an algorithmthat facilitate connection of CHP system into existing UDN according to the LCTA principle.
- Several basic examples are presented in order to demonstrate the use of the optimisation models.

The models proposed in this thesis differ from other published material in the following way:

- The objective of this work is to provide a general method of assessment which take into account capacity and location of DG/CHP plants to be connected into a UDN.
- In comparison with other published material regarding connection of DGs into the distribution network [97,117,144,180,199], where only specific constraints are analysed, this thesis provides a systematic approach that utilises analytical/mathematical tools to assess a broad range of technical, economic and environmental impacts on urban energy supply introduced by DG/CHP system integration .
- The proposed models facilitate the analysis that enables the investigation of the integration of an arbitrary amount of DG capacity into a UDN.
- Any DG/CHP system technology can be considered.
- The general formulation ensures high flexibility in terms of modelling detail and accuracy.
- The simplicity of the proposed model enables the UDNP/UDNO and DG/CHP developer to analyse the technical, economic and environmental impact of any size of DG/CHP plant connected to an arbitrary point in the UDN.

## 1.8 Publications

List of Publication

[1] J. Loughnane, S. Boljevic, “The Impact of Combined Heat & Power plant on Electrical and Thermal Energy Supply for an Industrial Plant”, UPEC (Sept. 2005), University College Cork, Cork, Republic of Ireland.

[2] S. Boljevic, N. Barry, “ The Impact of Combined Heat & Power Plant Using Normally Flared-off Gases in Petrochemical Plant”, UPEC (Sept. 2006), Northumbria University, Newcastle, UK.

[3] S. Boljevic, N. Barry, “ The Impact of Combined Heat & Power on Thermal Energy Supply for an Small and Medium Size Enterprise”, UPEC (Sept. 2007),University of Brighton, Brighton, UK.

[4] S. Boljevic, M. Conlon, N. Barry, “ The Impact of High Penetration of CHP Generation on Urban Distribution Networks”, UPEC (Sept. 2008),University of Padova, Padova , Italy.

[5] S. Boljevic, M. Conlon, “ The Contribution to Distribution Network Short-Circuit Current Level from the Connection of Distributed Generation”, UPEC (Sept. 2008),University of Padova, Padova , Italy.

[6] S. Boljevic, M. Conlon, “ Fault Current Level Issues for Urban Distribution Network with High penetration of Distributed Generation”, 6th International Conference on the European Energy Market, 27-29 May 2009, Katholieke Universitet Leuven, Leuven Belgium.

[7] L. Buckley, S. Boljevic, “ The Impact of CHP Plant on Thermal and Electrical Energy Supply for Large Dairy Process Facility”, UPEC (Sept. 2009),University of Glasgow, Glasgow , UK.

[8] S. Boljevic, L. Buckley, " The Impact of CHP Plant on Thermal and Electrical Energy Supply for Large Dairy Process Facility", XIX International Symposium Research Education Technology (Sept 2009), Bremen, Germany.

[9] S. Boljevic, M. Conlon, " Voltage Stability Analysis of an Urban Distribution Network (UDN) with High Penetration of Combined Heat & Power (CHP) Generation", UPEC (Sept. 2010), Cardiff University, Cardiff , UK.

[10] D. Caples, S. Boljevic, M Conlon, " Impact of Distributed Generation on Voltage Profile in 38kV Distributed System", EEM11, May 2011, Zagreb, Croatia.

[11] B. McHugh, S. Boljevic, M. Conlon, " Feasibility Studies on Technical and Economic Impact of Combined Heat and Power (CHP) Generation on Energy Supply for Commercial Small & Medium Size Enterprise (SME), UPEC 2011, South Westphalia University, Soest, Germany.

[12] S. Boljevic, M. Conlon, " Optimal Sizing of Combined Heat and Power (CHP), Generation in Urban Distribution Network (UDN), UPEC 2011, South Westphalia University, Soest, Germany.

[13] S. Boljevic, M. Conlon, "An Optimal Sizing Method for Combined Heat and Power (CHP) Plants Normally Installed by Small and Medium Size Enterprise (SME) in Urban Distribution Network (UDN)" ,EEM12 2012, Florence School of regulation, Florence, Italy.

[14] T. Neally, S. Boljevic, M. Conlon, " Impact of Combined Heat and Power Generation on an Industrial Site Distribution Network, UPEC 2012, Brunel University, London, UK.

[15] S. Boljevic, "Planning Algorithm for Optimal Combined Heat and Power Generation Plant Connection in Urban Distribution Network (UDN)", EEM14 2014, Krakow, Poland.

[16] S. Boljevic, “Planning Algorithm for Optimal CHP Generation Plant Connection in Urban Distribution Network (UDN) according LCTA Principle”, UPEC 2014, Cluj-Napoca, Romania.

[17] S. Boljevic, “Combined Heat & Power Plant Connection Into Urban Distribution Network According to Least Cost Technically Acceptable Principle”, UPEC 2015, Staffordshire University Stoke on Trent, UK.

## 1.9 Thesis Outline

This thesis explores engineering, economic and policy questions associated with integration of small scale CHP generation units into UDN. To accommodate and maximise the expanded use of CHP generation in the existing UDN in the near term, the thesis analyses issues related to maximum penetration of CHP generation for the UDN such as selecting the optimal locations and size of CHP plants to be connected within the UDN performance defined by engineering criteria. The outline of this thesis is summarised in the followings:

- Chapter 1 is an introduction to this thesis which gives the background and explains the key reasons that motivated this research work. This chapter states the objectives and the main contribution achieved.
- Chapter 2 reviews the relevant literature relating to the issues and modelling approaches in the field of integrated analysis of energy infrastructures with distributed generation. Additionally, previous work that has dealt with DG/CHP generation integration and distribution network analysis is outlined. Therefore, the gap in the literature is identified and serves to gain perspective on the research work of maximum integration of CHP generation into UDN addressed in this thesis.
- Chapter 3 analyses the integration issues of CHP generation into the existing UDN. The issues such as voltage profile, fault current level and losses associated with location and mode of operation of CHP plants is analysed. Following this analysis UDN control requirements in the presence of the CHP generation are outlined. In addition, environmental and economic impacts of CHP generation in existing UDN is presented. These analysis are explained using the test UDN network.
- Chapter 4 expands the framework outlined in Chapter 3 by developing the optimisation model taking into account primarily technical constraints caused by

connection of CHP plants and that include: fault current level, voltage rise level, network losses and customers energy demand. A mathematical optimisation model is developed using the multiple regression analysis. In addition to technical constraints, environmental and economic constraints are incorporated into the mathematical optimisation model. Finally the model is applied to a test network.

- Chapter 5 presents the description and analysis of possible changes in operational settings of the UDN and CHP system proposed by the UDNP/UDNO in order to maximise the benefits of the CHP system connection for both utility and CHP developer. In addition to that and in the light of these changes, the techno-economical and environmental impacts of CHP generation are discussed and analysed.
- Chapter 6 presents a detail description and analysis of the CHP system connection on the UDN operational technical constraints and consequences of that impacts on CHP system connection method corresponding to the LCTA principle.
- Chapter 7 presents conclusions and implication for the work presented in this thesis. It also suggest the future work that has to be continued based on work presented in this PhD thesis

# Chapter 2 Literature Review

## 2.1 Evolution of Energy Services Networks

Energy generation technologies have a vital role in social and economic development at all scales, from household, community to regional, national, and international level. Among its welfare effects, energy is closely linked to environmental pollution, economic development, and quality of living.

Urban energy service networks, which normally refer to both natural gas and electrical infrastructures, have been traditionally designed and operated separately from one another [32]. However, current conditions that exist could arguably cause this condition to change. This is because natural gas has become a common fuel of choice to reduce the carbon footprint of populations [20]. Thus, the task of integrating the energy system for either planning or operational purposes creates new challenges for participants, which in turn makes them seek knowledge of the growing opportunities in the industry. Some critical issues participants need to deal with in order to satisfy the needs of future energy service networks are:

- Rearranging monopolistic frameworks towards a liberalised market approach that provides easy access to new participants [21].
- Developing reliable forecasts in local networks with distributed technologies [22].
- Grasping strategies to implement intelligent management systems [9].
- Obeying the policies set by authorities to reduce greenhouse gas emission [23].

In addition to these challenges, promising progress is occurring in the area of DG and conversion technologies. This is because these new technologies are no longer obliged to operate based on economies of scale, which means that by connecting them at low voltage levels they can provide power at a site close to the consumers [24]. Proper application of DG technologies at significant capacity has the potential to enhance “where, how and when” customers obtain their energy. Also, this group of technologies could possibly have positive effects on topics regarding the environment, energy efficiency use, and security of supply. Although there are multiple types of distributed energy resources (DERs), this thesis will mainly focus on CHP generation as the most common type of DG installed at UDN. The fact that natural gas is seen as the fuel of choice for most of the many countries committed to the environment. This fact has caused the prominent deployment of gas appliances for the majority of consumers [25]. CHP generation units that normally run on natural gas are able to produce both electricity and heat at very high overall efficiency. If sized, located and operated properly, CHP plants offer the possibility to enhance the performance of the urban network infrastructures. These circumstances have contributed to reach a consensus that utilities need to focus on the integrated resource planning and optimisation of the operation of their assets in order to enhanced network performance [26]. In the case where CHP units are used to generate both electrical and thermal energy for urban areas, these will be effects from the UDNOs perspectives of the electrical power flow. Consequently, other assets related to techno-economical variables would be affected in a similar way. As pointed out in [36] the following trends can be assumed for the future of energy service networks:

- New CHPs technologies should be introduced so that UDNOs can take advantage of their techno-economical and environmental characteristics.
- Control mechanism in each infrastructure should be flexible in reacting to diverse generation and load patterns which enable the enhancement of energy delivery.
- An objective mediator entity with optimal decision making capacity/power is required to coordinate the interactions between UDNOs and the grid connected DG/CHP technologies.

- In order to enhance energy delivery, urban natural gas networks and electrical UDNs should be assessed by viewing both infrastructures as a whole integrated system.

From the above it can be concluded that the interrelationships between the energy services have to be identified and quantified so that every participant can have access to relevant data that will allow them to act accordingly. If the infrastructures are synthesised, it will be possible to address issues such as reducing the overall energy delivery operating costs of UDNs based on the penetration level of DG technologies. Accordingly, power flow tools which incorporate multiple energy carriers are required to perform this kind of study. Fig 2.1 illustrates the layout of components which are considered essential for the model that can be used to obtain an insightful assessment of the energy supply in the urban area of study. Using the power flow tools available, it is possible to determine the in-depth techno-economical performance of individual natural gas and electric power systems. The theoretical framework analysing the impacts of distribution generation technologies might have on the electric DNs began in the early 1980's [27,28]. At that time, the deployment of these technologies was not imminent and this fact delayed further research on this subject. However, due to the recent technical progress and implementation of DG for non-industrial users, a set of significant uncertainties in operation of power delivery systems were introduced. Henceforth, the scientific community has begun to address DGs by using different approaches and perspectives based on the facts of how the siting of a number of small scale DG units installed in a DN impact on the environmental, economical, technical and control of the distribution system.

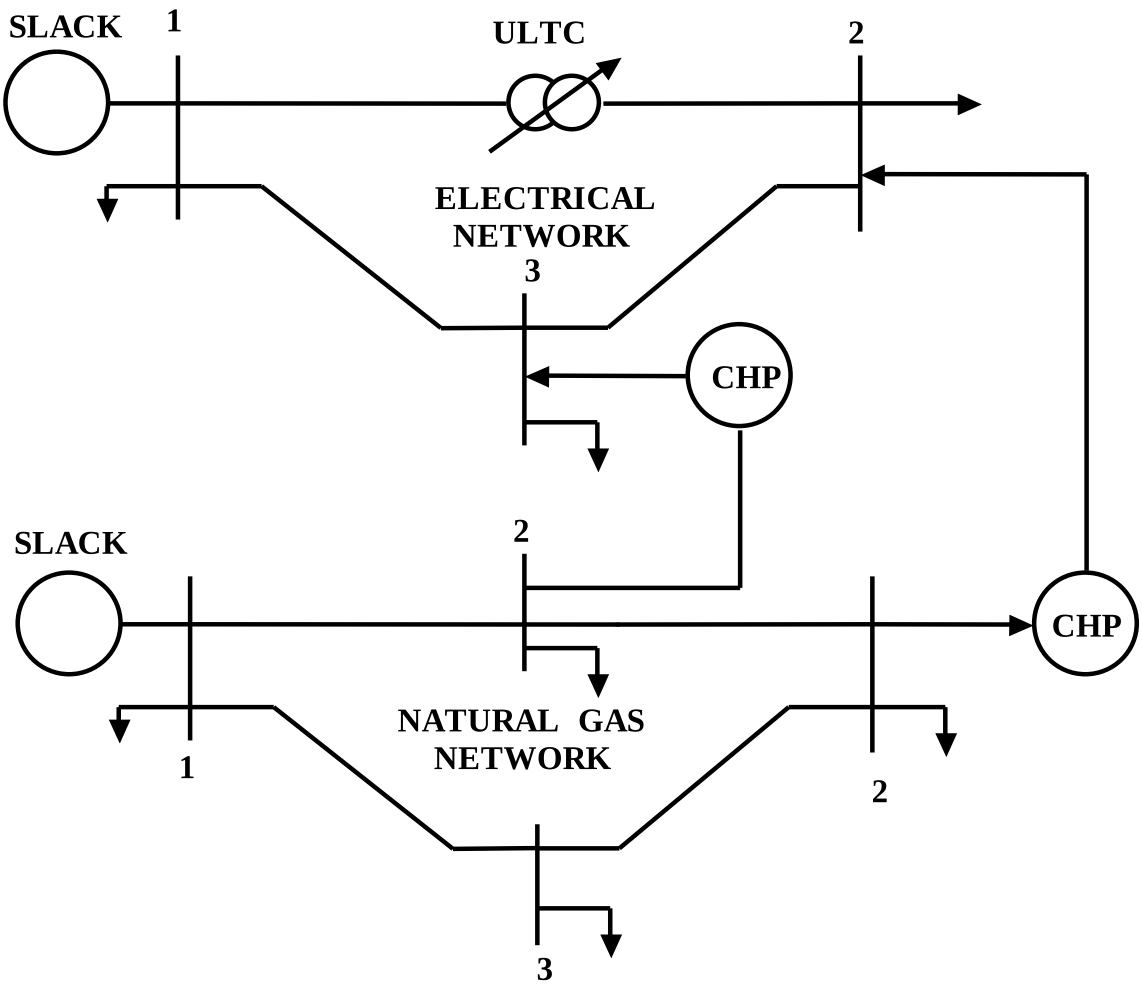


**Fig 2.1 Typical Distributed Generation Deployment in Urban Distribution Network (adapted from [36])**

Equally important is how power system architectures develop as a result of the above impacts and competitive market forces. Although the decentralization of electric powered generation surrounds many research fields, efforts to date have mainly focused on modelling and addressing DGs in relation to planning and operational issues [29,30]. However, the management of DGs installed in distribution networks generates the following concerns that were classified in [31]:

- Distribution generation: Consists of devices that vary in their technology and allow local energy production [24,32-35].

- Demand response: Focus on energy saving plans through the deliberate control of load or generation participation during times of system need [37-40].

From the early 1990’s a number of countries have promoted multiple restructuring and policy incentives that intensify deregulation of their different energy sectors [41]. This approach, has been viewed as a means to achieve improved economic and environmental performance compared to the past centralised and usually monopolistic energy sector [42,43]. At present, efficient network development has presented some difficulties with private owners of the energy generation infrastructure when it comes to dealing with DGs installation in UDN. This is because UDNOs are concerned with the uncertainty of the timing, location and size that many small-scale generators will bring to their infrastructure. Due to this uncertainty, UDNOs have the priority of underlining a competitive operation and location of assets which require real-time tools that maintain techno-economical efficiency; thus giving UDNOs and DGs owners a good rate of return on their investments [44,45]. Equally, UDNO must have information regarding the optimal operation of DGs connected to their assets to assure good network performance [46,47]. Nevertheless, within the different energy contexts in DN, the propagation of DG application is a reality and will not easily be discarded as a power generation alternative [48,49]. Therefore, UDNOs need to make the most out of this situation. To achieve this goal the industry and academic research community has to answer the question of how can the application of new power generation technologies help drive better UDN performance [50]. As outlined in [36] some of the contributions DG technologies normally installed in UDN can provide to the energy supply can be summarised as follows:

- DG is an attractive option for promoting energy efficiency which could be applied either from a technical, economical or environmental perspective [50,51].

- Local energy sourcing encourages participants to take advantage of price elasticity based on electrical demand [37,52,53].
- DG technologies can enhance network performance with adequate monitoring through supervisory control and data acquisition (SCADA) equipment [54,55].
- Greenhouse gas emission problems can be directly addressed by using DG technologies [56, 72, 56]
- The increased presence and preference for a specific DG technology might impact the development of local fuel supply infrastructures [44].
- DG availability can reduce, to a certain extent, both dependency and vulnerability of the electrical distribution system from the effect of congestion in power lines. The adoption of DG alternatives can defer investment in substations, network reinforcement, and large generation plant installation. There are options which generally take a longer time to provide a return on their capital investment. [52,57]
- Network power supply quality conditions can benefit from the connection of local resources to the network [58,59, 71].
- The evolution of DG technologies is creating the necessity established for their interconnection to the distribution network [60].

All these issues arise since traditionally UDNs have not normally been focused on operational effectiveness [26]. As suggested in a number of publications, increased penetration of DGs in UDN will shift towards a more intelligent network that will change the way that UDNOs consider at DGs and help them to improve the strategic and operational processes [54, 61, 62]. In conclusion, this means that the electric UDNs that we have today will require innovative approaches to meet the challenges that DGs create [63,64].

## 2.2. Power System Evolution

Until the early 1990's the Electricity Power Supply System (EPSS) was typically integrated with a franchise monopoly to be the sole supplier of electricity nationally. There were a few exceptions where electrical power generation facilities were provided by state municipal governments or large industrial facilities. In the traditional power system, the load demand in the UDN is supplied exclusively by power delivered through the substation shown in Fig 2.2 In such systems frequency does not fluctuate significantly and most of the control effort in the network is only focused on maintaining the desired local voltage profile. Therefore, the primary concern of the traditional power system is to build and operate generating capacity that is required to meet the energy and power demand of UDN customers under certain power quality. In the case of the traditional UDN, it had vertically integrated structure and was regulated and operated without the price-based incentives of a competitive market to guide customers in maximising energy efficiency [97].

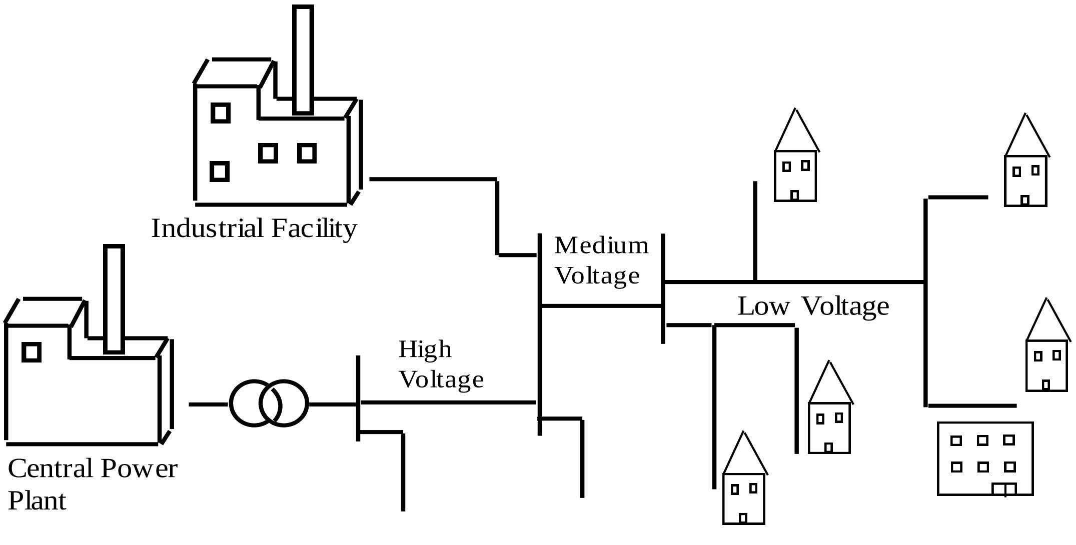


**Fig 2.2 Traditional Urban Distribution Network (adapted from [15])**

During the last two decades most developed countries have gone through reasonably comprehensive privatisation, restructuring and deregulation programs in their energy sectors that were previously regulated monopolies. These processes are introducing market forces to power generation in particular. As a consequence there has been dramatic changes in how the power system should be organised, regulated and operated [65]. As a result, there is a growing list of trials in restructuring and reform to study. While these reforms have not always proceeded without argument or led precisely to the results predicted/desired, the general trend of public policy has continued to support liberalisation and to move forward with additional reforms in the electrical energy generation sector. The apparent problem with the existing electrical power systems is that the transmission and distribution systems are still natural monopolies. The logical solution that is to separate the potentially competitive power generation and supply side might then operate on competitive markets terms, and the natural monopoly would be regulated in a way that will allow DG to participate with real competition. The regulated prices would be set at a level that allows the owner of DGs to finance operation and investment while providing incentives for power generation efficiency. If the electric power generation market is to be sufficiently competitive, the restructuring process will introduce market forces to the power system in general, and to the generation sector in particular. In the early stages of the restructuring process a few small-scale distributed generators in the form of CHP plant may be installed in the UDN providing electrical and thermal energy supply mainly for small and medium size enterprises (SME). Further into the restructuring process it is likely that multiple DG technologies, mainly in the form of the CHP will be sited in the UDN as shown in Fig 2.3 which shows customers and different types of energy sources distributed throughout the network. In this situation, the power system must assume a significant role for DG which will raise the following questions: type of DG technology, size of energy output of DG, location of installation, operational patterns and installation cost. Some questions focuses on the behaviour of DG generations within a UDN and other questions refer to the performance of the UDN itself. The UDN restructuring process raises engineering concerns of maintaining network performance standards (losses, fault current level and voltage level in particular) as a growing number of active power generating devices with diverse characteristics are sited within the UDN. The fundamental changes to the UDN operational behaviour caused by DGs connection may demand that the issue of local (geographical) stability be revisited. New generation and control technologies will continually improve efficiency, but at any given point in time there is a maximum possible operational efficiency of the UDN.

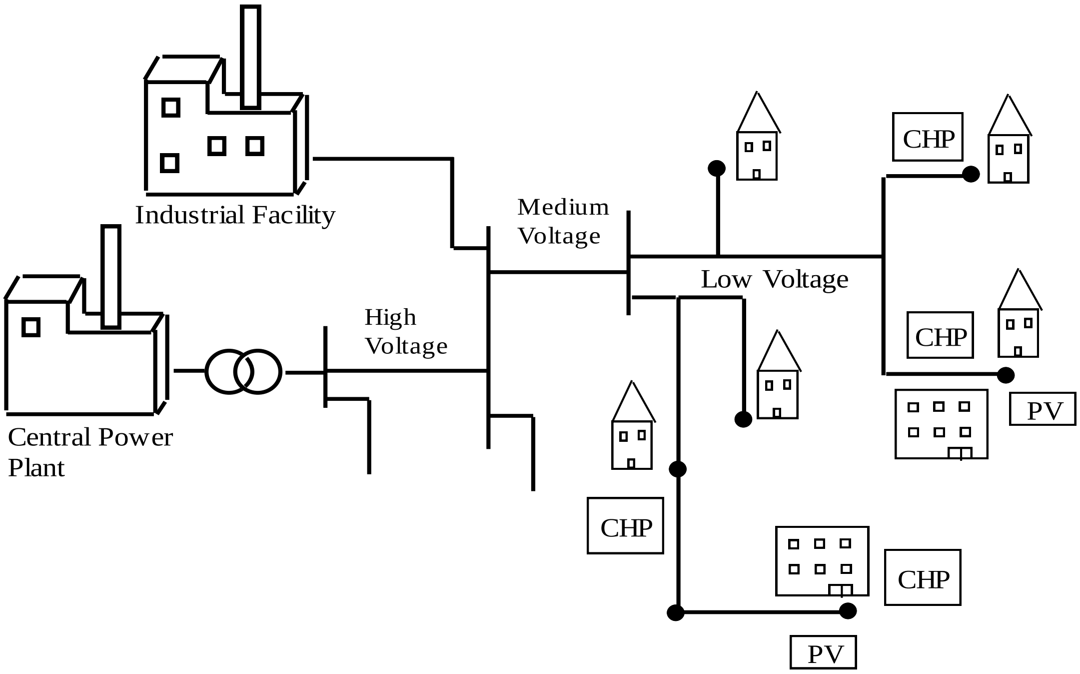


**Fig 2.3 The Future Structure of UDN With Multiple Distributed Generation (adapted from [15])**

The UDN architecture is not unique but it is characterised by high load density, strong environmental constraints and radial layout that consists of many LV feeders, which can include a number of branches. In addition, most of power consumers supplied by the UDN are connected to only one phase out of three phases which make UDN systems unbalanced most of the time. Once the performance of DGs, operating in a competitive market, within a single UDN is understood, the examination of the performance of UDN with maximum penetration of DG can start [66].

### 2.2.1. More Decentralised assets for Electrical Power Systems

Decentralised electrical power generation is not a completely new concept. In fact, historically, the first electrical power plants were built up close to the customers requiring energy supply [68]. As a consequence of technological evolution in power generation, increases in electricity demand and the improvement of AC systems allowed the transmission of electricity over long distances, which led to an increase in the size of the generation power plants. This allowed utility companies to capture low cost energy with economies of scale, while diversifying risk. All this resulted in increasing convenience and lower per unit costs. To satisfy this massive electricity demand, systems consisting of large transmission and distribution system and large power generation plants, were constructed [33]. Liberalisation and deregulation of the power generation industry led to the introduction of competition in the segment of power generation. In transmission and distribution networks the natural monopoly element has been maintained subject to network regulation [67]. The fact that electricity exhibits a combination of attributes that make it distinct from other products: non-storability in economic terms, real time variations in demand, low demand firmness, random real time failures of power generation and transmission and the need to meet the physical constraints of the network operation [67]. One of the consequences of liberalisation is the new way in which the now separated networks interact with each other. Although thus classical model of the power system suffered several problems of reliability and efficiency only from the late 1980’s, when economic and social scenarios changed; the on-site small-size generation started to receive increased interest and serious analysis of the potential benefits. Factors driving this change include:

- The deregulation of the electricity market,
- Fuel efficiency is generally higher because localised DGs operating in the form of CHP generation allows the use of heat/cooling as well as generating electricity,
- The attractive possibility to achieve enhanced power supply quality,
- It reduces network losses and reduces transmission and distribution costs,
- Decentralised electrical power system requires less backup capacity than centralised power generating system because, unlike a system of a few large power plants, a system of many small DGs does not suffer the major impact of the outage of a single generator,
- Most importantly, decentralised electrical power systems offers the opportunity to cut greenhouse gas emission along with the other environmental benefits of a reduced dependence on fossil fuels and nuclear power.

This tendency is encouraged by the world policies on the promotion of renewable energy resources and CHP generation, market competitiveness as well as at the maximisation of efficiency. Such a condition is being emphasised with the implementation of connection methods which are not generally adequate to cover the investments that UDN require to allow the integration of distributed energy resources. Due to these reasons the rate of DGs connections to UDNs is rapidly increasing [89]. In a number of countries the maximum limit of allowing connections of DGs in UDNs that can be managed with the traditional passive networks approach has been reached. The prospect of radical change in the structure of power delivery in UDN become more visible day by day due to the availability of small and reasonably low-cost power generations. Therefore, important investments and research are needed in order to provide the UDN infrastructure – already involved in the deregulation process to successfully manage the challenges due to present and future scenarios.

### 2.2.2. Meeting the Challenges of Decentralised Power Generation

EU and other developed countries are beginning a transition from centralised and largely fossil-fuel and nuclear-based power systems delivering electricity to passive consumers, toward a more decentralised power system relaying to a large extent on small-scale (sometimes intermittent) generation from renewable energy sources (RES) and CHP units, allowing greater active participation of consumers by becoming producers themselves and/or by smarter demand response management of their own energy use. The theoretical framework analysing the impacts DG might have on the electrical distribution network began in the early 1980s [27,69]. However, the deployment of these technologies was not imminent and this fact delayed further research on this subject. However, due to the recent technical improvement and implementation of DGs for non-industrial users, this field is once again a focal point for researchers. The scientific community has begun re-addressing DGs by using different approaches and perspectives. Although the decentralisation of electric power generation surrounds many research fields, at present efforts mainly focus on modelling and addressing DGs by using different approaches and perspectives [29, 30]. However, for power system engineers that study the management of DGs, these concerns were classified by [31] into:

- Technical concerns associated with distributed generation compatibility relate to the ability of distributed generation equipment to function effectively as part of the electrical power system as it exists today. DGs must meet engineering requirements with respect to voltage, frequency, power quality, be able to rapidly isolate faulty equipment from the rest of the system and must have a reasonable ability to withstand abnormal system operating conditions (fault ride through). Depending on the operational settings there may be additional network operator requirements with respect to control over the output level and the ability to actively contribute to voltage management. Network operator requirements for individual DG plants can usually be effectively dealt with in connection rules.

- Security concerns can be regarded as an extension to technical concerns from the component to the local or system-wide level. They arise at both the transmission and distribution levels.

At distribution level electricity supply security concerns are local and mostly relate to the ability of distributed generators to:

- ➢ Contribution to voltage control in the vicinity of, and down stream from, the generator, while complying with islanding policy requirements.
- ➢ Contribution to managing distribution network flows in the vicinity of the generator.
- ➢ Avoid excessive fault current levels while still contributing to fault identification and clearance.
- ➢ Minimise impact on power quality.
- ➢ Behave in a manner that can be adequately predicted by mathematical models for use in power system simulation studies, and that can be adequately forecasted for system security assessment.

At transmission level concerns can be system-wide and are mostly related to the ability of distributed generators to:

- ➢ Ride-through disturbances emanating from the power system and thus avoid contributing to a cascading outage.
- ➢ Contribute to voltage and frequency control and to stabilising system operation following a disturbance.
- ➢ Output reduction in order to avoid overloaded or insecure power system operation.

- The commercial concerns associated with compatibility of DG can be split into financial and legal aspects:
- Financial support and investment in appropriate DG (type, location, timing) while avoiding inefficient subsidy.
- Development and implementation of commercial rules at both transmission and distribution levels that can accommodate DG with respect to traditional power systems and that encourage investment in complementary technologies such as responsive generation and responsive demand.
- Development and implementation of commercial regimes that correctly specify and allocate risk associated with distributed generation technology and encourage and facilitate efficient (physical and/or financial) risk management by either distributed generation owners themselves or by other appropriate parties.

Since the early 1990's most of the EU and other developing countries have promoted multiple restructuring and policy incentives that increase deregulation and decentralisation of different energy sectors [41]. This approach with a focus on free competition, has been seen as a means to achieve a greater economic performance than in the past centralised and usually monopolistic environment [42]. At present, efficient network development has found some setbacks with private owners of the infrastructure when it comes to dealing with DG installation. This is because DNOs are concerned with the uncertainities that timing and location of many small-scale generators will bring to their infrastructure. Due to this uncertainty, network operators have the priority of underlying a competitive operation and location of assets which require real-time tools that maintain techno-economical efficiency; thus giving utilities a good rate of return on their investments [45]. Likewise, utilities require information on of DGs connected to their assets to assure a good network performance [47].

Regardless, within a different energy context, the propagation of distributed generation is a reality and will not easily be discarded as a power generation alternative [49]. Therefore, power system operators need to make the most out of this circumstance. This gives rise to the question: “how can the integration of new generation technology help drive the better use of the distribution grid and assets. [50]

The increased presence of DG technology and the contribution that DG technologies provide has the potential to transform the present DN into a smarter grid [54].

### 2.2.3. Benefits and Issues of Distributed Generation

The electrical power systems and particularly UDN of developed countries are changing to reach three main energy – related challenges, namely environmental sustainability, security of supply, and competitiveness. The International Energy Agency IEA [76] lists a number of factors that contribute to this evolution, such as developments in distribution generation technologies, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity, the electricity market liberalisation and concern about climate change. In the liberalised market environment, the DG offers a number of benefits to the market participants. As a rule, customers attach different weights to certain features of energy supply, and DGs technologies can help energy suppliers to supply the type of energy service they prefer. One of the most interesting features is the flexibility of DG that could allow market participants to respond to changing market conditions, i.e. due to their small sizes and the short construction lead times compared to most types of larger power plants. These fundamental improvements must be pursued considering the continuously increasing electricity demand. In this context governments, researchers and network companies look at DGs as one of the most suitable solutions. The motivation for this interest include [77]:

- Increase security of electricity supply, use of DG technologies can increase the autonomy of the electrical provision, diversify the energy source portfolio and assess system support in terms of local /global regulations and ancillary services supply. Considering the islanding opportunity, DG can reduce /avoid power outages of customers and deliver profitable contributions for the restoration process.
- Advantages in transmission and distributions network operation and planning: high penetration of suitably integrated DGs reduce congestions in upstream systems leading to the postponement of transmission/distribution system development. The built up of DG plants is favourite also from an authority point of view. In fact, it is generally easier to find sites for a DG unit that can be brought online much more quickly.
- Energy market competitiveness: development of small-scale, efficient, relatively cheaper generators enable DG plants to be more attractive for both the new-entry small players of the electricity market and big companies fostering the competition (because investment decisions are driven by shorter term profits).
- More efficient use of primary energy resource: it is generally not techno-economically feasible, for large fossil fuel-based power plants to the utilise the waste heat stemming from the energy conversion process. Small-scale efficient and environmentally friendly CHP plants can be exactly dimensioned to match the needs of several customers, allowing the use locally of the waste heat produced as a consequence of electricity generation. This possibility could increase the efficiency, capturing high economic benefits. To generate energy locally and avoid its

transportation leads to loss reduction. CHP generation system's cost effectiveness, flexibility and the speed which it can be deployed/construct relative to conventional power generation plants offer power system operator a way to hedge against unknown future energy demand and price. It can help constrained, overloaded UDNs, increase their flexibility and allow adaptation to unforeseen peaks in local UDN electricity demand requirements. One of the often overlooked benefit of the CHP generation is its ability to improve the economic and performance of renewable energy resources such as wind and solar powered generation mainly due to its intermittency of power supply. CHP generation systems can ramp up quickly to help UDNO to balance supply and demand. It is proven, cost-effective solution and readily available low risk strategy for reducing global pollution and increasing economic efficiency.

- Distributed generation could serve as a bypass for transmission and distribution costs or as a substitute for investment in transmission and distribution capacity. Of course, this is possible only to the extent that alternative primary fuels are locally sufficiently available. Otherwise increased use of distributed generation could result in congestion in other networks, such as the gas transport network. One site production could result in cost savings in transmission and distribution about 30% of electrical energy costs [76]. The smaller the customers size, the larger the share of transmission and distribution costs in the electricity bill (above 40% for households). As such, it is seen as one of the biggest potential drivers for the distributed generation development. In some cases, it can even be used as an alternative to connecting a customer to the grid in a stand-alone application. Furthermore, locating the generation close to the loads could also contribute to reduce grid losses.

Beside the potential benefits outline above, also there are several issues related to operational problems that need to be investigated. The question of power quality and distributed generation is not straightforward. On one hand distributed generation contributes to the improvement of power quality. In the areas of the network where voltage support is difficult, distributed generation offers significant benefits for the voltage profile and power factor correction. On the other hand, large-scale introduction of decentralised power generating units may lead to instability of the voltage profile. The bi-directional power flows and the complex reactive power management can be problematic and lead to voltage profile fluctuation. Additionally, short-circuits and overloads are supplied by multiple sources. The major issues related to the presence of DG in a distribution network are listed as follows: [77]

- Distribution network planning and operation issues: DGs are preferably installed into the distribution network and starting from the protection systems and networks architecture call for revision. Specifically, protection systems need to be redesigned in order to manage more critical voltage and fault current values.

- Power reserve and balancing: The connection of a large number of DG sources can cause serious problems in distributed networks especially in high density UDN if network operators are not able to access reserve power from the upstream transmission system. In addition Transmission Network Operation (TNOs) will have the problem of accurately forecasting the reserve in the least cost way.
- Power quality: many DGs are interfaced with the network by a power electronic interface, which can generate harmonics.
- Infrastructure and provision given the recorded growth trend of natural gas fuelled CHP technology integrated in distribution networks, security of supply may be of

rising concerns due to gas demand/offer unbalances [76]. These may be also linked to possible unscheduled imported gas shortages or constraints in the gas transmission/distribution systems.

Although DGs are becoming an important paradigm for electricity generation, it will never be able to replace the centralised power production. In fact centralised generation remains necessary to maintain the stable operation of the network in terms of voltage and frequency control.

#### 2.2.3.1 Distributed Generation for Customer Application

In the new restructured electricity market DG has a wide range of applications. DNOs can benefit from using DG in their planning process [50]. DG owners and customers can use DG to reduce their cost of energy. Some of the benefits depend on project-specific characteristics, including technology, fuel source, emission controls, operating patterns, customers load shape and load-shedding capability and characteristics of the network where the generation is connected. Policies to advance penetration of DGs should take into account how to achieve desired benefits outline in [70] and include:

- Lower Cost of Electricity

  The transmission and distribution cost of electricity represent approximately 30% of the total price in average [76], e.g. SMEs with on site generation (DG/CHP plants) might find that the cost of installing and operating onsite generation lower than cost of buying electricity and gas (used to generate thermal energy) from the network. The difference between the two costs represents the value of the benefit to the SMEs. This value is case sensitive and depends on electricity price, load profile, DG unit capital, and operational and maintenance cost[78,80]. The benefits of this application are regarded to be the main driver for most customers considering DG installation [78].

- Consumer Electricity Price Protection

  DG can minimise the risk associated with electricity price instability when price spikes appear due to congestion, generation shortage and market power [80]. The owner of DG located in an urban area can remove uncertainty from the energy cost by having a long term fuel contract for a fixed price. Moreover, the SMEs will have the flexibility of switching between DG and utility generation if real-time pricing is used. The size of this benefit depends on price instability and SMEs risk preferences [78].

- Enhanced Demand Response

  Without DG, most energy users including SMEs do not have the means to react to changes in electricity price fluctuations. Onsite generation appeals to energy consumers with its appealing flexibility. Premises with installed DG units in their facilities will certainly consider generating their own electricity instead of buying from the system when electricity prices are higher than that for their own generation. This situation will appear as a demand response and elasticity in electricity markets, ultimately reducing electricity prices and price volatility for the benefit of all consumers. [79] The value of this benefit will increase as onsite generation penetration levels increase up to a certain level beyond which the value starts decreasing. Although this benefit is very difficult to quantify, it can be estimated on a case by case basis using market analysis tools [78].

- Improved Reliability and Power Quality

  For electrical power users concerned with both reliability and quality of the power supply, DG is an attractive solution. The reliability in this context can be expressed as the expected duration of an outage over a period of time, while power quality is expressed by the frequency of occurrence and duration of voltage sags. The value of this application depends on the frequency, duration and timing of interruptions and voltage sags. It differs from one class of customers to another and even within the same class [80]. The value of higher reliability and power quality is the main and sometimes the only driver to install onsite DG in places such as hospitals, high-rise buildings and process industries with sensitive loads. The value of this application is characterised by the avoided costs incurred in the case of interruption and malfunction due to poor power quality. [78]

- Combined Heat and Power Generation

  In CHP generation, heat is generated as a by product when fuel is being burned to produce electricity. It has been reported that for the average power plant, two thirds of the energy content of the input fuel is converted to heat [81]. Unlike electricity, heat cannot be transmitted efficiently to customers over long distances. A CHP-DG unit generates electricity and uses the generated heat energy locally. Common DG-CHP projects have been reported to have an overall average efficiency of 75-85%, and in some systems, the value exceeded the 80% level [81]. CHP generation application has a substantial value for the premises in urban areas with heating or cooling requirements matching electrical energy demand as it reduces the overall fuel needed to meet electricity and heat requirements. The financial value of a CHP-DG operation is perceived directly by the CHP generation developer and as a direct overall energy savings requirements. Another value is greenhouse gas emission reduction which is more difficult to quantify [78].

### 2.2.3.2 Distributed Generation for UDN Application

In a liberalised energy market, the UDNOs are considered as the actors who should ensure that whatever power is produced by whatever party is delivered to that party's customer. For UDNOs, this means that it is up to them to facilitate an industry with a considerably different structure and considerably different requirements than in the past. The main driver to install DGs into UDNs are outlined in [70] and these include:

- Deferred or avoided UDN Upgrading

  DG is becoming a viable choice in power delivery in UDN planning [32,83]. UDNOs can avoid expensive UDN expansion and other network reinforcements by installing DG in selected locations. DG has the potential to relieve power distribution congestion in UDN and reduce power losses in both UDN and to some degree in transmission systems. Since transmission and distribution assets utilisation represent a considerable share of the total price of electricity, DG can save up to 30% of the electricity cost on average by simply deferring (avoiding) upgrade of transmission and distribution (UDN) system [77]. Besides, extenting the UDN is economically not practical. Utilities could gain substantial savings by using locally generated power [83]. The cost of UDN capacity expansion projects would otherwise be reflected in the price of electricity paid by consumers.

- Reduced Power System Losses

  Unlike central power plants, DG is located near consumers; therefore, the resistance in the current path is much lower than that between central plants and electricity consumers. Moreover, DG will reduce the loading of transmission lines and relieve heavily loaded lines leading to more reduction in power loss. It was demonstrated that loss reduction depends on DG penetration, technology, dispersion, location and reactive power control [84]. The value of this benefit can be substantial in some cases of UDN where network losses are approximately 6-8% [217,218]. Although loss reduction calculations can be done using power flow calculations, a lot of data is required and the results are valid only for certain loading profiles [80]. Nevertheless, it should be mentioned that in the rare situation with certain loading levels, especially with light loads, the DG might result in increasing the energy losses compared to situations for which DG is not used.

- Voltage Support to UDN

  DG can be used to support the UDN voltage profile specified by the UDNO in accordance with EN50160 through the injection of reactive power. This in turn improves power quality for nearby customers and reduces losses in UDN. Losses are reduced when reactive power is locally provided consequently, as this minimises the reactive component of the current flowing in the network. The benefit of this application is not substantial because there could be other cheaper means for the adequate operational voltage profile support that are used in UDN such as switched capacitors. Besides, the voltage profile support in UDN is normally characterised by being a localised problem [78].

- Provision of Ancillary services

  Different types of ancillary service that DG unit can provide, including: voltage control, regulation, load following, spinning reserve, supplemental reserve, backup supply, network stability, continuous transfer, and peak shaving is described in [85]. Nevertheless, it should be mentioned that such services are rarely required by UDNOs at present. The value of those services varies depending on the services provided and the condition of the connection contract between the DG and UDN. Spinning reserve, supplemental reserve, and network stability are of equal interest to the DNOs/TSOs . On the other hand, backup supply, peak shaving, load following and continuous transfer provide the DG owner with direct financial value, avoiding the costs and inconvenience of interruptions in this case.

#### 2.2.3.3 DG Indirect Application- Other Benefits

- Improving Network Security

  Using DG to supply critical loads will reduce network dependence in large central plants and the transmission system, which could be forced out of the system or become inoperative due to faults. This use in turn will reduce the impact of critical system component failures. Although this benefit is spread to the whole of society and could be substantial, it is very difficult to quantify [78]. Furthermore, diversifying the fuel source is advantageous to system security.

- Reducing Emissions

  Emission like NOx ,CO, $CO_2$ gases are byproducts of electricity generation. Renewable DG technologies do not produce emissions when converting renewable energy to electricity. Other technologies such as CHP plants might have lower levels of emissions than those produced by displaced central plant generation. This benefit affects the whole society but is difficult to evaluate. However, clean DG technologies owner's receive incentives for reducing the health risks associated with emissions [78].

## 2.3. Distributed Generation Technology

DG technologies can provide energy solutions to a variety of customers in urban areas that are more cost-effective, more environmentally friendly and in most cases provide higher power quality than conventional energy supply. The wide variety of DG technologies based on size of the output and on various primary energy sources are available at present in energy market. Each type of distributed generation has, however its own technical and commercial characteristics. For example some of DGs technologies that are currently employed in urban area in some cases are environmentally friendly but are not cost effective; others offer high efficiency with low fuel cost, but emit significant greenhouse gases emission. In addition some DGs are suitable for application but lack of durability for continuous output. From the customers point of view DGs are currently being used by some customers to provide some or all of their energy needs. Some customers use DG to reduce energy demand charges imposed by their utility companies while others use it to provide premium power or reduce environmental emissions. DG can also be used by UDNO to enhance performance of the network discussed in 2.2.3.2. With so many factors to consider, it is often difficult for the planner to decide which type of DG technology is best suited for the specific task [98]. Below, a list of the typical DG technologies employed in urban area is given in [24,98].

- Combined heat and power plants
- Photovoltaic cells
- Fuel cells
- Wind turbines

- Combined heat and power plants

  CHP is a specific form of DG, which refers to strategic placement of electric power generating units at or near customer facilities to supply on-site thermal and electrical energy needs. It is not a technology but an approach to applying technologies. While the conventional method of producing electricity and thermal energy separately has a typical combined efficiency of 40% that is very low in comparison to efficiency CHP systems operation described in 2.2.3.1. It has a potential for a wide range of applications and the higher efficiencies result in lower emissions than separate heat and power generation systems. Beside advantage outline in 2.2.3.1 additional advantages of CHP generation installed in urban areas include the following:[90]

- CHP plants can be strategically located at the point of energy use. Such on-site generation avoids the network losses associated with electricity purchases via the network from different power stations.
- CHP is versatile and can be coupled with existing and planned technologies for many different applications in commercial and residential sectors in urban areas.

Beside the advantages mentioned above there are several barriers that impede cost-effective CHP applications including a lack of common and interconnection to gas and electricity UDN, discriminatory utility standard connection rates and emission regulations that do not recognise the improved efficiency and pollution benefits of CHP systems.

CHP systems consist of a number of individual components: prime mover, generator, heat recovery electrical/thermal interconnection configured and integrated as a whole. The type of equipment that drives the overall system (prime mover) typically identifies the CHP systems. There are three types of prime movers that are currently employed in CHP systems installed in urban area.

- Internal Combustion Engines
- Micro turbines
- Gas turbines

- Internal Combustion Engines

Reciprocating internal combustion engines (ICEs) are widespread and well-known technology and in principle works like a car engine. ICEs convert heat from combustion of a fuel into rotary motion which, in turn, drives a generator. ICEs are one of the most common prime mover technologies used for DG (CHP) connected to an UDNs shown in Fig 2.4 They represent a proven technology with low capital cost; with size range, from a few kW to a few MW; good efficiency and good operational reliability. These characteristics, combined with the engines’ ability to start up quick during a power outage and not requiring much space for installation, make them the main choice for CHP generation. The key barriers to ICE usage are: high maintenance and fuel cost, which is the highest among the DG technologies; high NOx emissions, which are also highest among the DG technologies and a high noise level [89, 90]. There are two basic types of reciprocating engines: spark ignition (SI) and compression ignition (CI). SI engines for power generation use natural gas as the preferred fuel, although they can be set up to run on propane, gasoline or landfill gas. CI engines (diesel engines) operate on diesel fuel or heavy oil, or they can be set up to run is a dual-fuel configuration that burns primarily natural gas with a small amount of diesel pilot fuel. The diesel engine has historically been the reciprocating engine for both small and large power generation applications. At present diesel engines are increasingly restricted to emergency standby or limited duty cycle services because of greenhouse gas emission concerns. Consequently, the natural gas fuelled SI engine is now the engine of choice for the high duty cycle marked (over 5000 hr/year). Current generation natural gas engines offer low purchase and installation cost, fast start-up, proven reliability when properly maintained, excellent load following characteristics and significant heat recovery potential. Overall CHP system fuel efficiencies reaching up to 90% are routinely achieved with natural gas engines as prime mover. Reciprocating engine technology in general has improved dramatically over the past three decades, driven by economic and environmental pressures for power density improvements, increased fuel efficiency and reduced greenhouse gas emission.

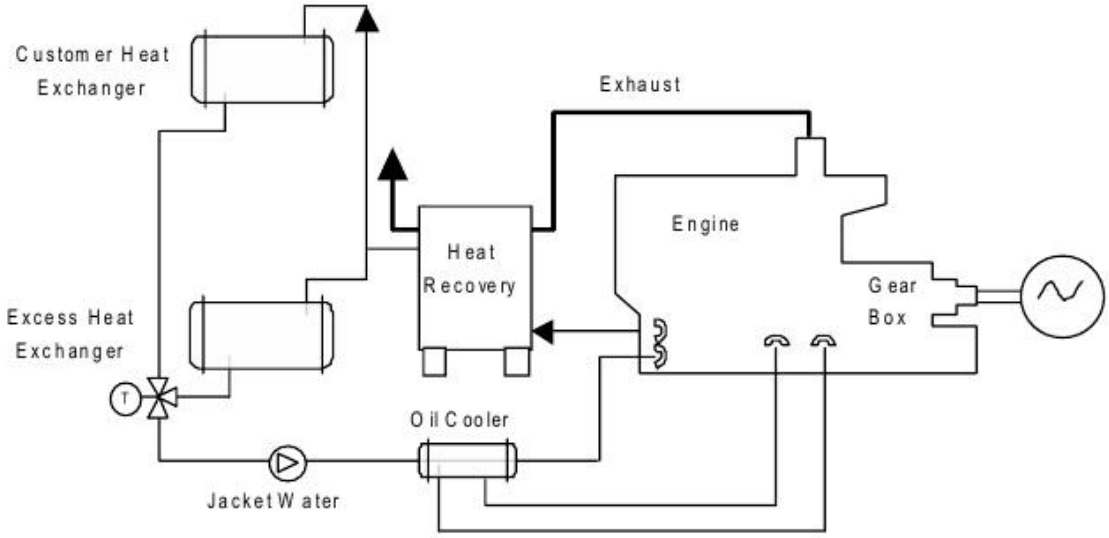


**Fig. 2.4 Reciprocating engine based CHP System [90]**

- Microturbines

Microturbines are small thermal devices that burn gaseous and liquid fuels to create high speed rotation that drive an electrical generator [90]. The technology used in microturbines is derived from aircraft auxiliary power systems. One striking technical features of microturbines is their extremely high rotational speed. The single shaft turbines rotates up to 60,000 rpm and electronic inverter converts the high frequency power into a 50Hz frequency supply. The size range for microturbines available is from 30 to 350 kW. The fact that microturbines run at high speed and can be used mainly in power generation or in CHP systems. Microturbines are suited for DG applications due to their flexibility in connection methods, ability to be stacked in parallel to serve larger loads, ability to provide stable and a reliable power and low emissions. The main disadvantages of microturbines as a prime mover of CHP systems at present are their short track record and high costs compared with IC engines. Most suitable customers located in urban area for microturbines applications include services such as: data processing, financial, telecommunications, restaurants, lodging, retail, office buildings and other commercial sectors.

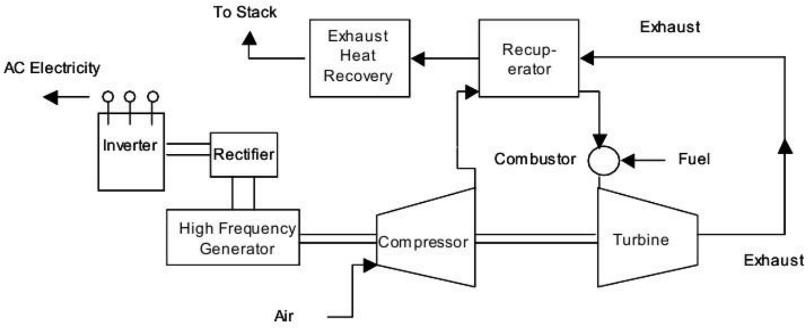


**Fig 2.5 Micro-turbines based CHP System (Single-Shaft Design)[90]**

- Gas Turbine

Gas turbine have been used for power generation for decades and range in size from simple cycle units starting at about 1MW to over a hundred MW [90]. Units from 1-15MW are generally used for industrial application as on site power generation and as mechanical drivers. It is one of the cleanest means of generating electricity and using natural gas as primary fuel emit substantially less $CO_2$ per kilowatt-hour (kWh) generated than any other fossil fuel technologies in general commercial use. Gas turbines are particularly useful when higher temperature steam is required than can be produced by a IC engine. Gas turbines produce high-quality exhaust heat that can be used in CHP configuration to reach (electricity and useful thermal energy) efficiency up to 85%. The installation and maintenance cost of gas turbines differ greatly depending upon the emission and noise control regulations in the region where they are sited. Gas turbines traditionally have been used by utilities for peak shaving capacity. But with changes in the power industry and advancement in the gas turbine technology, the gas turbine is now being used as a component of CHP systems installed in urban areas.

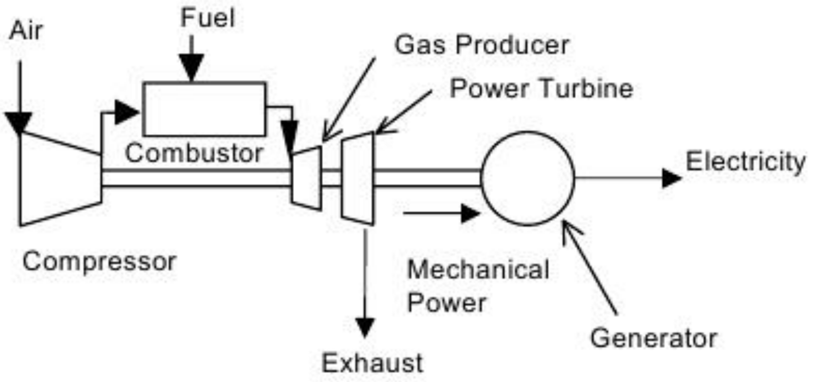


**Fig 2.6 Gas Turbine based CHP System [90]**

- Photovoltaic

Photovoltaic (PV) systems, commonly known as solar panels, are currently widely available for installation in urban area, are reliable and require minimal maintenance and operate and most importantly generate no greenhouse gas emission. Due to the fact that PV only works while sunlight is available and have large footprint, PV systems are not widely used in urban area at present.

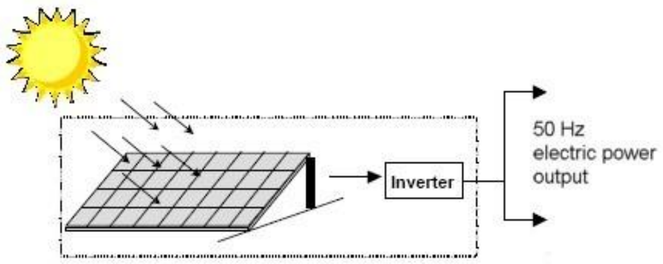


**Fig 2.7 Photovoltaic (PV) System [98]**

PV systems involve direct conversion of sunlight into electricity. PV systems have been used as the power source for applications like water pumping, remote building communications, satellite and space vehicle, as well as for megawatt-scale power plants. Though a PV device has a very low operating cost, it is capital intensive and it manifests a low efficiency which makes the PV system expensive. Without subsidies, PV power remains two to five times as expensive as centrally generated electrical power. However, where there is no network, PV power can be cheapest electricity source. PV system can also be competitive during peak demand periods. The PV implementation is encouraged by the almost unlimited availability of sunlight, long life cycle, high modularity and mobility, easy maintainability (since there are no moving parts), very low operation cost, environmentally friendly, availability for off-grid application and short time for design, installation and start-up. Mostly, individual PV modules range from 20W to 100kW. Several barriers for PV systems include significant area requirements due to the diffuse nature of the solar resource, higher installation cost than other DG technologies, and intermittent output with a low load factor [88, 91, 92].

- Wind Power

One way to generate electricity in a renewable way is to use wind turbines that convert the kinetic energy contained by the wind into electricity [100]. The wind is an infinite primary energy source and therefore wind power generation is taking a key role in generating electricity from renewable energy resources. By 2013, more than 117.3 GW wind power capacity in total in which 110.7 is onshore had been installed in Europe [140]. Germany, Spain and Denmark are the leading countries in wind power, and they account for around 78% of the total wind power capacity in Europe. Both off-shore and on-shore wind power implementations are increasing rapidly. Today, large wind power plants are competing with fossil-fuelled power plants in supplying economical clean power in many parts of the world [92]. In this sense, wind power is more like central generation than DG. The size of commercial wind turbines has increased significantly from 50kW in early 1980s to be up to 4.5MW at present [94]. This increase obviously creates an economy of scale for the wind power technology and the fact that wind turbines need large footprint make wind power generation unsuitable for installation in urban areas. The main challenges of the wind power technology are intermittency and network reliability [95]. Since wind power generation is based on natural forces, it cannot dispatch power on demand. Thus, as the share of wind energy increases, integration of wind turbines into the electric network will need more attention. Another barrier is transmission availability. As often the best locations for wind farms are in remote areas without close access to a suitable HV transmission line.

- Fuel Cell

Fuel cells are electro chemical devices that convert the chemical energy of a fuel directly to usable energy in form of electricity and heat without combustion. Fuel cell has the potential for clear, quiet and very efficient power generation-benefits that have driven significant investment in their development in the past two decades. This is quite different from most electric generating devices (e.g. combustion engines and gas turbines) which first convert the chemical energy of a fuel to thermal energy, then to mechanical energy, and finally, to electricity [90]. A fuel cells consists of a positive electrode (anode) and a negative electrode (cathode). Electrochemical reactions create ion flows, that generate electricity. Fuel cells produce electricity with high efficiencies, up to 40 to 60% , with negligible harmful emissions. One fuel cell only produces a small amount of electricity and large amounts can be obtained from a stack of fuel cells. Fuel cells are modular and produce low noise pollution, because they have no moving parts. These characteristics make fuel cells suitable as DG in urban areas. In the future, the electrical network can be combined with the gas and hydrogen infrastructure. This new structure may further increase implementation of fuel cells as DG. As with most new technologies, fuel cells face a number of formidable market-entry issues resulting from product immaturity, system complexities and unproven product durability and reliability. These translate into high capital cost, lack of support infrastructure and technical risk for early adopters [88, 98]. While the future of fuel cells holds many unknown, the many advantages of fuel cells suggest that they have potential to significantly change how electricity is produced.

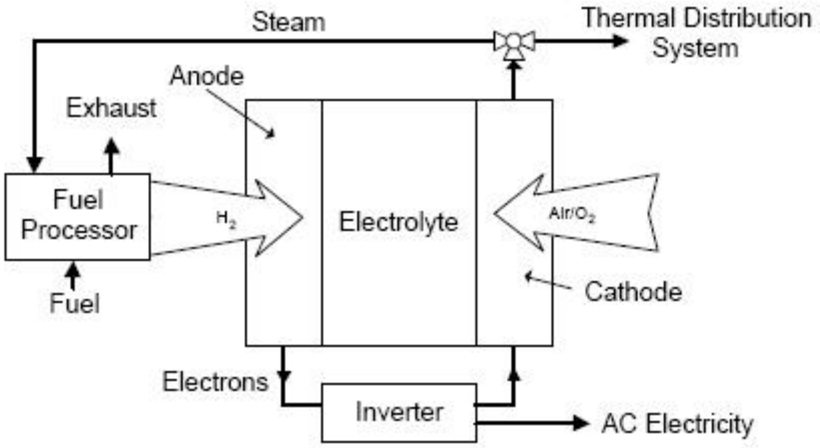


**Fig 2.8 Fuel Cell [98]**

2.4 General Planning and Operational Issue in UDN

The planning process employed by UDNO is a decision-making process that evaluates many different options for meeting future electricity demands and selects the optimal mix of resources that minimise the cost of energy supply while meeting reliability needs and other objectives [99,50]. With traditional UDN planning, the UDNO takes into consideration objectives that include: demand to be met, reliability to be achieved and applicable government policies and regulations. The planner then selects patterns that will meet these objectives with minimum financial requirements. In order to take the traditional planning approach several steps further, the following should be taken into planning process:

- Goal-setting is an essential step in an effective planning process. Goals should be directly related to the UDNO vision of UDN, should be achievable based on what the UDNO can realistically control and should be designed to be appropriate to as many stakeholders as possible.

- Evaluate all options from both the supply and demand sides in a fair and consistent manner. All options should be evaluated against a common and comprehensive evaluation standard, one that considers every aspect pertinent to any option and one that addresses all the goals. For UDN planning this means evaluating alternatives against criteria and attributes that represent the UDN's requirements, standards and constraints. For UDN planners this means matching customer needs with marketing standards and guidelines.
- Minimise costs to all players (not just costs to the utility)
- Create a flexible plan that allows for uncertainty and permits adjustment in response to changed circumstances.

The traditional goals of UDN planning are reliable service, economic efficiency, environmental protection and fairness. Reliable services are essential for the balancing of customers and in some cases investor interests (i.e., balancing the quality of services against cost). In addition, it is also necessary to balance the interests of the various customers connected to the UDN as part of urban energy utility as well as the interest of present and future energy generation/consumers facilities. Because of the distinct electrical characteristics of UDN operational reliability, the type, size and location of a DG unit and the diversification of energy used make it an urgent need to address how to make sure the proper utilisation of the UDN structure and how to efficiently coordinate various types of generation/consumption of electric power. To ensure secure UDN operation in an engineering sense this means monitoring sufficient perceived cost effective reliability criteria such as: technical, economic and environmental efficiency.

A number of recent studies suggest that UDN planning efforts should try to cultivate a shared long-term vision to focus efforts, increase collaboration and sustain momentum towards specific goals, thereby leading to long-term energy savings. Additionally, planning can help to identify mechanisms through which energy efficient technologies and practices should be adopted. These mechanisms include: policies, programs, funding sources and adjustments to existing practices.

### 2.4.1. DG-UDN Technical Issues

Connection of all power generation plants fundamentally alters the operation of the UDN. There will be observable impacts on the UDN power flows particularly where DG capacity is comparable to local demand and specifically where export occurs. There is a risk that new connections will impact adversely on the security and quality of local electricity supplies and accordingly they must be evaluated carefully by UDNO. [50,101]. Distributed generation sited and sized correctly has much potential to improve UDN performance. Because UDNs designs and operating practices are traditionally based on radial power flow, strong load density in some cases up to 30MW/km$^2$ . In most cases, the UDN is designed as a passive network to facilitate unidirectional flow of power from the transmission system via the HV/MV substation and via the MV distribution system down to the connected load at the extremities of the LV circuit via a MV/LV transformer. The load connected to UDN LV circuit is characterised by the number of particular types of devices, the multiphase possibilities and the widely varying types of loads most makes the network unbalance most of the time. When power is required to flow in the opposite direction, operational management difficulties of a technical nature arise. Therefore this fact creates a special technical challenge for connection of DG. In contrast to large central power plants, DG is normally installed at or near the load sites. Operating in parallel with existing system DG causes different conflict in UDN operation such as protection coordination and voltage profile control. One of the main consequences generated by connection of DG into UDN is conversion of UDN from passive to active UDN similar to an active HV transmission system. The penetration level of DG in the UDN is increasing and therefore it is relevant to consider and analyse the following technical issues including: voltage profile management, fault current, protection coordination and losses in the UDN.

#### 2.4.1.1. Traditional Voltage management of the UDN in the Presence of DG

In general, the performance of a UDN and the quality of services provided are measured in terms of freedom from interruptions and maintenance of satisfactory voltage levels at the customer’s premises that is within limits appropriate for the type of service [105] and in accordance with the national grid code corresponding to EN50160. Due to economic and logistical considerations, normally an UDNO cannot provide each customer with constant voltage matching exactly the name plate voltage on the customer’s apparatus. Therefore a common practice among network operators is to stay within preferred voltage levels normally set by the national standard. The selection of techniques for voltage control are available depends upon the particular UDN requirements. However, voltage regulation in UDN is normally provided by tap changer (TC) transformers that operate automatically under load. Fig 2.9 Voltage-regulation under load tap changers (ULTC) is designed to maintained automatically a predetermined level of voltage that would otherwise vary with the load. As the load increases, the ULTC boosts the voltage at the substation to compensate for the increase volt drop in the primary feeder. In a case where customers are located at a long distance from the substation or where voltage drop along the line is excessive, additional regulators or capacitors, located at selected points on the feeder, provide supplementary regulation.

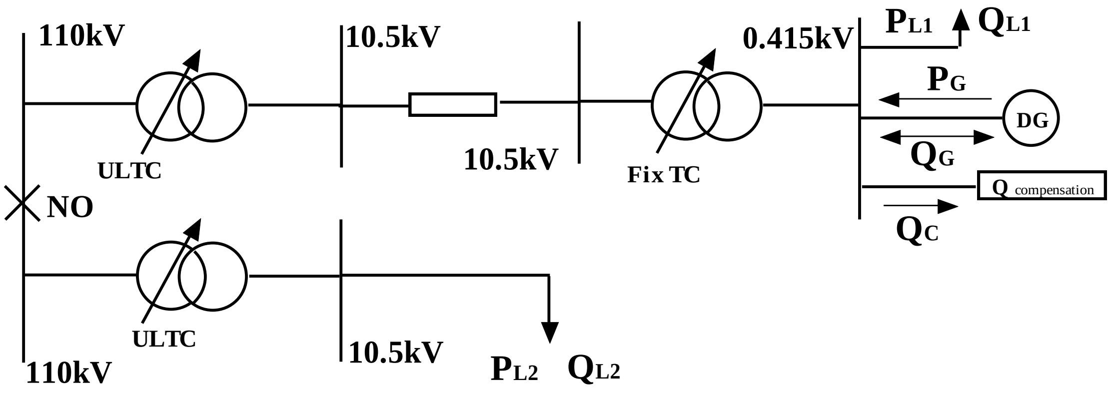


**Fig. 2.9 UDN module composed of two feeders (adapted el [102])**

The connection of a DG in a UDN has the effect of rising the voltage at the DG connection point and along the primary feeder that can lead to overvoltage for nearby customers. The need to limit this voltage rise, rather than exceeding thermal capacity of the feeder, often determines the limiting size of the DG that may be connected to a particular location of UDN. An initial estimation of voltage rise caused by the connection of a DG can be obtained by analysing the network shown in Fig 2.10

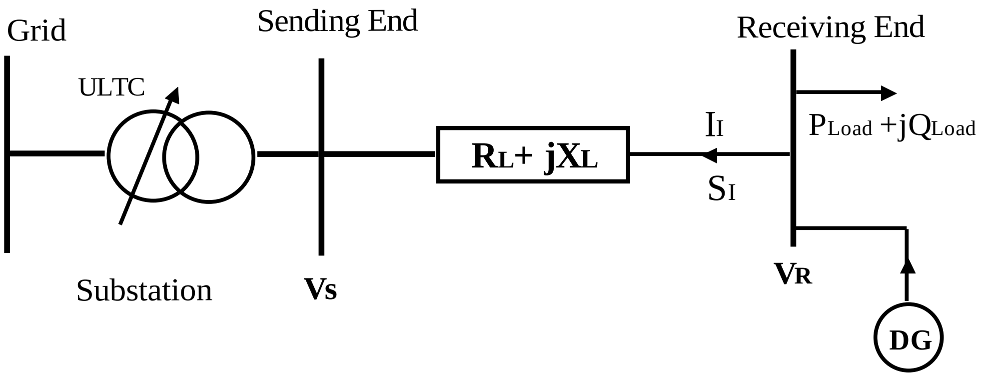


**Fig. 2.10 Connection of DG at end of feeder (adapted [104])**

From the Fig. 2.10 the net value of injected power to the network is be defined as:

$S_I = P_I + jQ_I = (P_{DG} + jQ_{DG}) - (P_{load} + jQ_{load})$ (2.1)

$S_I$ is the net injected VA by the DG unit into the network

$P_{DG}$ , $Q_{DG}$ are the real and reactive power generated by the DG plant

$P_{Load}$ , $Q_{Load}$ are the real and reactive power consumed by the load

$R_L$ , $X_L$ are the resistance and reactance of the line

Since $S_I = V_R I_I^*$ and $I_I = (P_I - jQ_I)/V_R^*$

$$V_R = V_S + I_I Z_L = V_S + (R_L + jX_L)\,(P_I - jQ_I)/V_R^* =$$

$$= V_S + (P_I R_L + Q_I X_L)/V_R^* + j\,(P_I X_L - Q_I R_L)/V_R^* \qquad (2.2)$$

In general the voltage δ between $V_S$ and $V_R$ is very small, $(P_I X_L - Q_I R_L)$ is also small and therefore can be omitted.

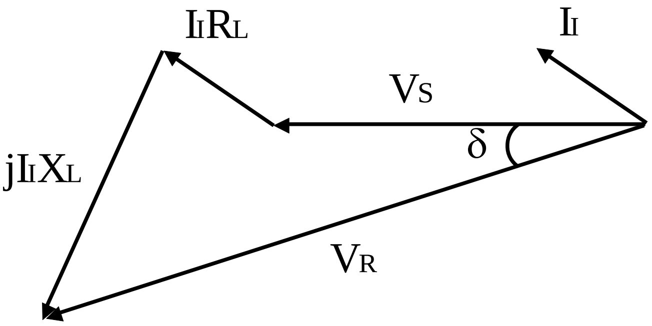


**Fig. 2.11 Phasor diagram of line voltage (adopted from [104 ])**

The value of the voltage rise ΔV approximately is :

$$\Delta V = (P_I R_L + Q_I X_L)/V_R^* =$$

$$= [(P_{DG} - P_{LoAD})R_L + (Q_{DG} - Q_{Load})X_L]/V_R^* \qquad (2.3)$$

The active power increases the voltage at the connection point, whereas the reactive power can further increase or reduce it depending on the DG operational mode. Synchronous generators (as normally used in CHP system connected into UDN) can generate or absorb reactive power, but induction generators only consume reactive power. These outcomes in combination with the system R/X ratio or UDN characteristics and load profiles, determine whether the voltage level at the connection point is increasing with increasing of power output from DG unit or not [104, 106].

The allowable voltage rise is dependent on the network strength and how the network is currently operated (e.g. how close the existing voltages get to allowable voltage maximum prescribed by the local/national standard). Voltage rise is often the main consideration for DG connection into traditionally weak UDN that are difficult to upgrade. Therefore, voltage rise often puts limits on the size of DG unit that can be connected in a particular location in UDN. This situation can occur long before power flow reverses or the thermal limits of the lines/cables being reached.

To mitigate the adverse impact of a DG on the voltage profile in the UDN, under current practice there are two means of controlling the UDN voltage profile within statutory limits. One approach is to limit DG output and another approach is using coordinated voltage control by adjusting tap changers and reactive compensators [103].

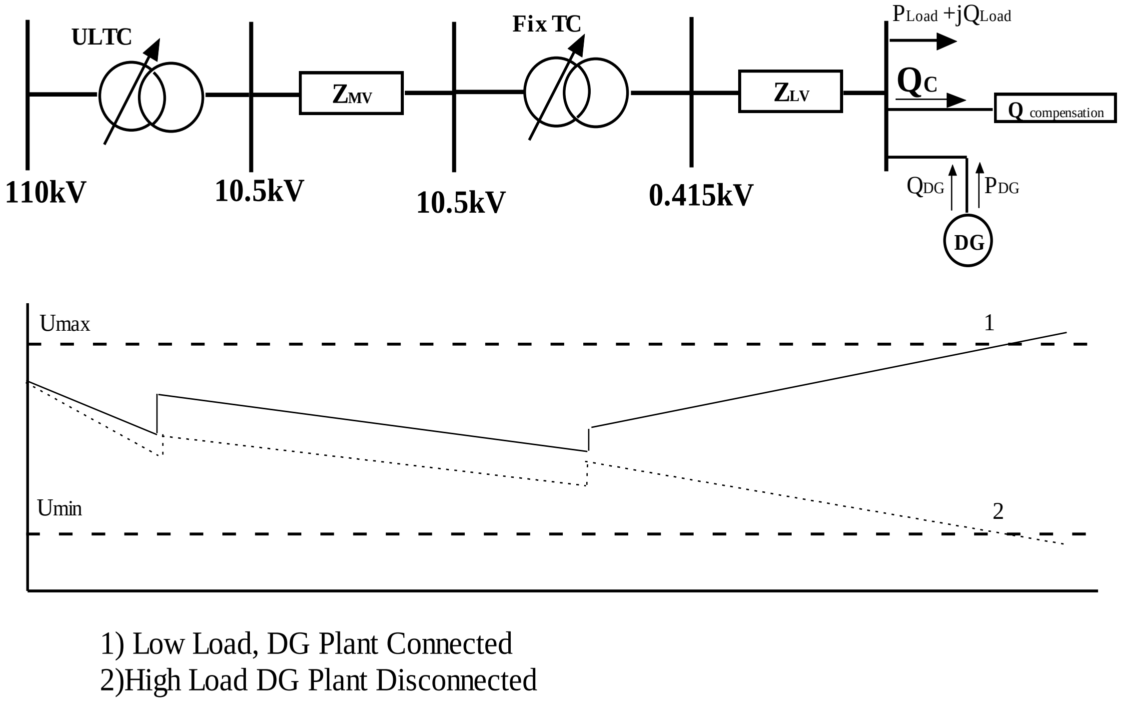


**Fig.2.12 a) DG plant Connection Layout; b) Voltage profile in the Network, [24,66]**

In addition to these methods, two less frequent methods employed to mitigate voltage profile violation in UDN are conductor upgrading and connection of DG at higher voltage. The first set of measures are considered to be effective in mitigating voltage rise but they are of an operational nature and have implications for the developer revenue or local quality of supply. The remaining measures are used to reduce voltage rise by reducing network impedance through greater conductor cross-sectional area or operation at higher voltage. While these tend to create fewer operational restrictions, the capital costs may be considerable [24, 101].

#### 2.4.1.2. Traditional Fault Management in UDN in the Presence of DG

High fault levels are often named as a major issue that makes the cost of DG connection into UDN unaffordable. For safety reasons fault levels must always be below the rating of equipment in the UDN. Connecting a DG into a UDN has the effect of increasing the fault levels close to the point of connection. The magnitude of the fault level that can be facilitated by an UDN is normally determined by the rating of the existing switchgear in the vicinity of the point of connection. This upper limit is usually referred to as the design fault level in the part of the network [2]. design fault levels in a UDN is very often a limiting factor in the connection of new DGs. Normally, UDNO would not permit the connection of new DG which would push the maximum fault levels beyond the network design fault levels. If that is the case the UDNO may require the DG developer to contribute to the cost of new equipment, mainly switchgear, to accommodate the increase in fault level caused by the connection of new DGs. When a fault occurs in the network a fault current will flow to the fault location and it consists of the currents namely from three sources: infeeds from the HV transmission system, infeeds from DGs and infeeds from rotating load such as motors. The UDNO calculates fault levels during network planning and also for operational situations based on the above mentioned sources. Fault level and fault current level calculations are indispensable part of the connection planning process for DG in UDN [ 107, 108 ].

In vertically operated power systems where the primary forms of UDN supply is via HV/MV transformers from the transmission network, the main changes to fault levels over time were mainly due to additional supply transformers.

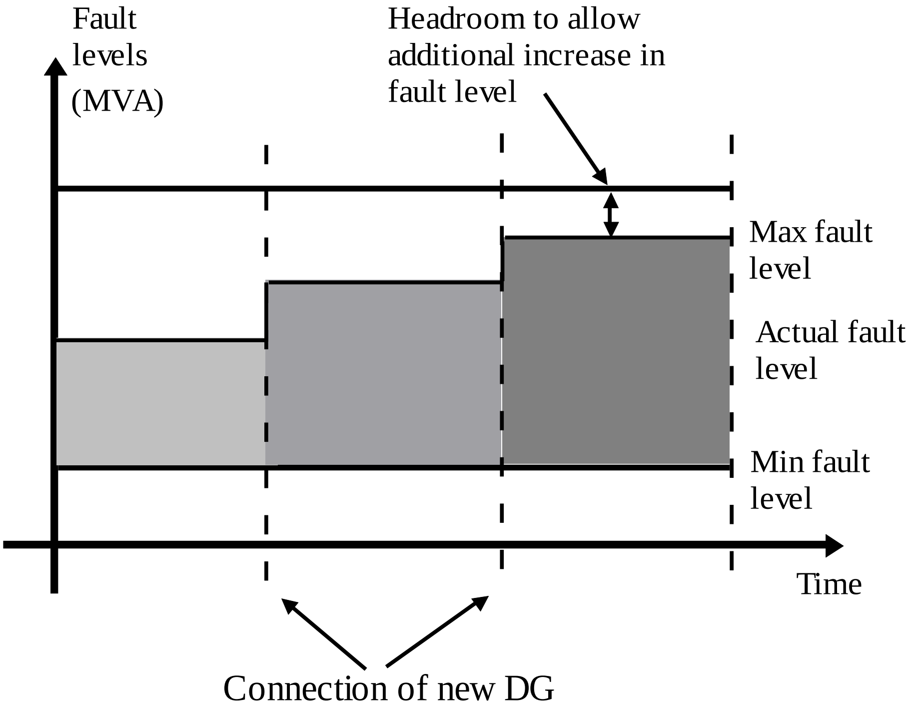


**Fig. 2.13 Fault Levels (adopted from [2])**

In today's UDN , the connection of DG provides an additional contribution to the fault level and the embedded nature of the DG makes the fault calculations more complex as they should take into account the consequences of operational switching combinations to a degree not required when all generations were via the HV transmission system. The fault level contribution from DG connected into UDN is determined by a number of factors including: [107, 109]

- The type of DG as different types of DG contribute differently to fault current.
- The distance of the DG from the faults as the increased cable impedance over reduce the fault current

- The configuration of the network between the fault location and the DG contributing to the fault level, as different path of the flow of the fault current will change the magnitude of the fault current due to cable impedances and other installed equipment such as power transformer.
- The method of connection of DG to the network. Directly connected $DG$ will contribute significantly to the fault than DG connected via a power electronics interface.

  The purpose of the fault calculations is to determine the effects caused by the connection of DGs to the network related to the planning, design and operation of the network. These effects include:

- The fault level headroom available across the UDN;
- The fault level contribution from all DG types;
- The current levels and growth trends of DG penetration
- Thermal effect of fault current on UDN components;
- Mechanical stress on UDN components.
- Coordination of protection devices.

The fact that fault level measurement technology is not commercially available to allow on-line fault level monitoring, fault level calculations must be reviewed regularly to account for changing configuration of the network and loads over time in order to ensure that adverse impacts of fault level are kept at an acceptable level. To achieve that there are a number of methods to manage the increase in fault levels currently employed in UDN and these fall into two groups: increasing the fault level design limit of the network components or reducing the fault level to below the design limit of the existing network components. There several methods that are currently used by UDNO to manage fault level described in [109, 110, 111] and these include:

- Uprating and replacement of existing network components,
- Increase impedance,
- Is limiter,
- Superconducting fault current limiter,
- Power Electronics,
- Solid state fault current limiter,
- Network splitting and reconfiguration,
- Sequential switching,
- Active fault level management.

At present in UDN the most frequent method to manage the increase in fault level is to upgrade and replace the existing network components but in the event where connection of DG causes the fault level to rise above the existing switchgear rating, it becomes necessary to find ways to reduce the fault level as a cheaper alternative to replacement of the switchgear, which in most cases is a costly solution.

### 2.4.2. Active and Reactive Losses

Due to the high cost of electrical energy, the subject of loss minimisation in power system and in particular in distribution systems has focused research activities in order to achieve maximum reduction of electrical energy losses. Beside economic/environmental consideration, the effect of electrical energy losses in the form of heat that increases the temperature of the system component that can result in premature component failure. Consequently, loss minimisation in the system has developed as a subject of intensive research. Electrical losses are always involved as electrical power is moved from generating stations to loads demand points due to the resistance of each element in the transmission/distribution system. These losses are inherent, unavoidable consequences of power delivery and appear as additional electrical load requiring the generators to generate additional power to compensate these losses. For a typical HV transmission system losses are in the range of 2% on average, while electrical losses experienced in LV distribution system such as UDN are in the range of 6% on average of the total energy consumed. Power losses in the distribution system vary greatly as a function of network configuration, DG locations and outputs, and customer locations and demand. It can be divided into two categories: real power losses causes by the resistance of the network components and reactive power losses causes by the network reactive elements. Due to the magnitude of losses experienced in UDN, real power losses attract more attention for the UDNO as it reduces the efficiency of supplying energy to customers. At the same time reactive power losses are no less important due to the fact that reactive power flow in the network needs to be maintained to ensure sufficient voltage levels.

A number of studies have indicated that the problem of DG allocation and sizing should be approached with caution [112,150,151]. If DG units are sized and located inappropriately in a UDN it can lead to greater network losses. Therefore, most of the studies refer to: DG optimal capacity sizing, DG placement and DG capacity evaluation. Although the studies suggest a wide variety of objectives and constraints related to connection of DG into UDN, two main approaches are used: finding optimal locations for a defined DG capacity and finding optimal capacity at defined locations. Out of all benefits and objectives of DG implementation in a UDN, the idea of employing DG plants for network loss reduction needs special attention [114]. In determining the requirements for the ideal arrangement for allocating losses it is important to remember that the cost of losses constitutes a large part of a UDN operating costs. With this in mind the requirements for the ideal arrangement for allocating losses can be summarised as follows [112]:

- Losses must be allocated so as to reflect the true cost that each customer imposes on the network with respect to cost of losses.
- The loss allocation method must be accurate and equitable. It must avoid or minimise cross subsidies between customers and between different time of use.
- The loss allocation method must be consistent and utilise metered data.
- The method must be simple, easy to understand and implement.

Real power losses ($I^2R$) are proportional to the resistance R of the power path and the loading current $I^2$ which is proportional to the load supplied. Unlike central plants, DGs are located near the load point at consumer sites and as a consequence the resistance in the current path is much lower than that between central power generating plants and electrical load points at consumer sites. Active and reactive power injection by the DGs at the consumers sites to supply local load will reduce loading of transmission/distribution systems relieving heavily loaded lines leading to more reduction in power loss.

In [113], it was demonstrated that loss reduction depends on DG penetration, technology dispersion, location and reactive power control. The value of this benefit can be substantial in some cases where UDN losses are very high. Although loss reduction calculations can be done using power flow calculations, the real power loss in a UDN is given by

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} \left[ \propto_{ij} \left( P_i P_j + Q_i Q_j \right) + \beta_{ij} \left( Q_i P_j + P_i Q_j \right) \right] \qquad (2.4)$$

$$\propto_{ij} = \frac{r_{ij}}{V_i V_j} cos(\delta_i - \delta_j) \qquad (2.5)$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j} sin(\delta_i - \delta_j) \qquad (2.6)$$

$$P_i = P_{DGi} - P_{DGi} \ \ \& \ \ Q_i = Q_{DGi} - Q_{Di} \qquad (2.7)$$

$P_{DGi}$ & $Q_{DGi}$ are injection powers of DG to the network busses

$P_{Di}$ & $Q_{Di}$ are the loads demand

$P_i$ & $Q_i$ are the active and reactive power of the buses

In some cases with certain loading levels (especially with light loads), the DG might result in increasing the power losses compared to situations for which DG is not used. Fig. 2.14

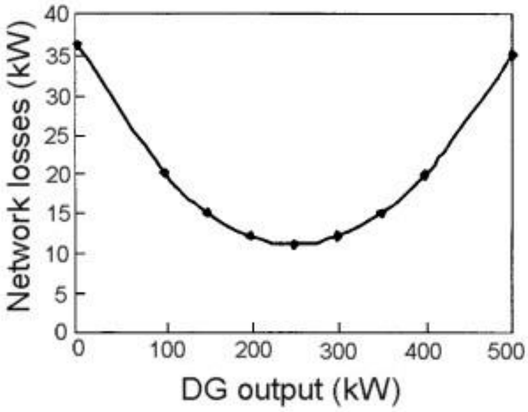


**Fig. 2.14 Variation of network losses with DG output (source [112])**

The location of the connection, the type of DG technology and the size of the DG units are the most important factors in the application of DG for loss minimisation in UDN. In reality the choice of the best site, size and most suitable DG technology may not be always possible due to the various constraints e.g the most suitable size of particular DG technology is not available in the market.

### 2.4.3 UDN & DG Economic & Environmental Efficiency

Electricity generation is still dominated by large centrally located power plants, which is the embodiment of technological practice, performing little better today than it did in the 1980s. This centralised system is extremely wasteful and environmentally damaging. Big centralised electrical power generating stations waste around two thirds of the energy contain in the fuels they use by throwing away waste heat in cooling towers and then in the electrical transmission and distribution. So around 65% of the energy is lost before it even reaches consumers. If that wasted energy is used it would make a very large contribution to reduction of greenhouse gas emission and improve energy security supply. Technological advance over the past 30 years introduce a way of electricity generation and supply which is completely different. By seeing the supply system as a whole and locating energy generation close to consumption point, it is possible to utilise both electrical and thermal energy with efficiency in some cases reaching up to 85%.This system would work together with renewable energy sources towards more efficient end use. This highly efficient, decentralised approach is better for the environment, more secure and gives better value for money than investment in a centralised power generation systems. A wide spread of DG units across the UDN can result in economic benefits for the network that include: savings on transmission and distribution losses and removal of local bottlenecks in the network. The economic benefits or cost for the UDN depend on the penetration level of DG. With low or moderate penetration of DG in a UDN, costs savings can be substantial while with very high penetration of DG capacity the network hardware may need to be reinforced specially if significant quantities of electricity is transported through the network. CHP technologies can be very flexible in their operation and as a consequence a CHP plants can operate during periods of high electricity prices and then be switched off during low-price periods. DG units operating in CHP mode have the possibility of generating and using both heat and electricity creating additional economic opportunities. In some cases DG may also be in a better position to use low-cost fuel such as landfill. Some DG plants are portable and easily installed which allows system capacity to be expanded readily to take advantage of anticipated high energy prices. CHP generation is economically attractive for SMEs located in the cities because of its high fuel efficiency and low incremental capital costs for heat-recovery equipment. On average these costs for the SMEs and household consumers may constitute to around 15% of total electricity costs over a period of three to four years [Declan Rayan, Temp Technology Limited., Personal communication, June 2014]. DG units conveniently located and with more efficient use of primary energy resources and waste heat enables more efficient exploration of available energy sources with better greenhouse gas emission efficiency. Apart from well known energy benefits brought by adopting CHP technologies, a larger penetration of DG in the form of CHP technologies into urban areas rises new environmental issues. In terms of total emission such as for greenhouse gas, CHP systems can perform much better than traditional separate power and heat (SHP) production, owning to the energy saving characteristics intrinsic to the CHP technology [115] On the other hand, unfortunately, the local emission of hazardous pollutants such as $NO_x$, CO, $CO_2$, and particulate matter generated by CHP systems can dramatically increase with respect to the SPH generation. [116] The issue is particularly challenging when high penetration of CHP generation occur in urban areas, where air quality standards are very high and the pollutants dispersion may be difficult due to the density and configuration of the buildings.

With respect to central SHP generation, small-scale DG units have a few disadvantages that include: there is a more limited selection of fuels and technologies to generate electricity; the smaller generators used in DG units cost more per kilowatt to build than larger plants used in central generating stations; costs of fuel delivery for the DG plants are usually higher; unless run in CHP mode, the small DG units operates at lower fuel conversion efficiency than those in central power stations; in some cases high capital cost prevent them from being competitive with network supply electricity; high environmental standard of air quality in an urban area can limit benefit of emission efficiency of DG/CHP technologies. In order to achieve high economic and environmental efficiency of DG plants installed in urban areas, a more detailed approach has to be employed to analyse impact of a DG versus SPH generation technologies.

## 2.5 Modelling Multiple Energy Supply

Key economic and environmental benefit potential of the installation of DG at customers sites in urban area lies in the opportunity to utilise locally the waste heat from conversion of primary fuel to electricity in small scale CHP systems. These systems are expected to play a significant role in the local energy generation in developing countries [117]. At present, the current policy of DG installation into UDN has focused on connection rather than integration. Typically DGs have been connected in UDN with a fit and forget approach, based on the legacy of a passive nature of UDN. Under this practice at present DG plants are not visible to the power system. Without active management, DG plants have functions required for the network support and security activities; therefore centralised generation capacity must be retained to perform these functions**.** With growing pressure to increase DG penetration into the distribution network, a passive fit and forget approach will lead to rising costs for DG plants connection and operation of the network and ultimately impact on the speed of DG adoption as energy supplier. The active energy system represents the system that incorporates DGs capacities and the demand side fully participates to both energy market and system management. In a case where DGs and the demand side will be able to take responsibility for delivery of system support services taking over the role of central generation, that will allow DGs to displace not only energy produced by central generation but also its controllability and capacity. To achieve this, UDNs operating practice will need to change from passive to active shifting from traditional central control operational management to a new distributed control paradigm, including significant contribution of demand side necessary to enhance the control capability of the network. In this situation heat demand consideration is important due to the fact that the CHP generation will play an important role in energy supply in urban areas. Consequently, heat load adds a further dimension to the problem related to energy management in urban area. To deal with this problem the possible solution is to improve energy management by employing concepts known in the literature as virtual power plant (VPP), microgrid and energy hub [36].

### 2.5.1 Virtual Power Plant

The future of UDNs is expected to involve an increasing level of wide-scale distributed generation and variation of energy demand and in addition integration of new information and communication technology in every aspect of the UDN operation. Future UDN represents the system capacities with DGs and demand side fully integrated into the UDN operation under a decentralised concept which allows DG to participate in the network management [118]. The virtual plant (VPP) structure employed in urban area are formed by a mix of DGs, storage and load units in a particular supply area that behaves as large central generators or loads [119]. It integrates the operation of the supply and demand side assets to meet customer demand for energy services in both the short and long term[120]. VPP is an energy management system, tasked to aggregate different DGs, either for the purpose of energy trading or to provide network ancillary services. It establishes suitable interfaces among local components, an adequate generation management strategy, and optimal use of the available capacity. Having these properties, VPPs become a visible form of flexible customer – oriented energy services provision in the urban area [36]. The VPP concept can facilitate decentralisation of UDN with a large number of small scale DGs. Another application of VPP is managing and scheduling of different types of energy generation and demand such as electricity and heat as described [121, 122] The principal strategic objective of the VPP is to supply the energy needs for consumer services, while minimising the operational and investment risk associated with peak generation, baseload power plants and transmission/distribution facilities**.** The ability and co-optimisation of energy resources in real-time to shape the load, also promises to improve UDN reliability by adding capability to manage transmission and distribution congestion. In addition, the VPP concept will significantly reduce greenhouse gas emission primarily by facilitating the orderly integration of DG resources into the UDN operation.

### 2.5.2 Microgrid

The increase of distributed generation in energy supply systems combined with emerging technologies, particularly in the area of energy storage and controls are making the concept of a microgrid a technical reality. The fundamental concept of any microgrid can be defined as system or a group of distributed and interconnected energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the power system. It serves some or all the energy needs of participating users and in addition it can provide optimised benefits that include: reduced energy costs, increased overall energy efficiency, enhanced generation flexibility, improved environmental performance and local electric system reliability. The key distinguishing feature of a microgrid is local control thereby exercising control over the power quality and reliability delivered to the end-use consumers [123]. In addition a microgrid is a regionally limited energy system and it can continuously operate in off or on-network mode, as well as in dual mode by changing the network connection status. This implies that the connection point between microgrid and the network may not necessarily be active all the time. However, present distribution network operational codes require that all DG units operate as single units and must shut down during times of the network power outages. [IEEE 1547]

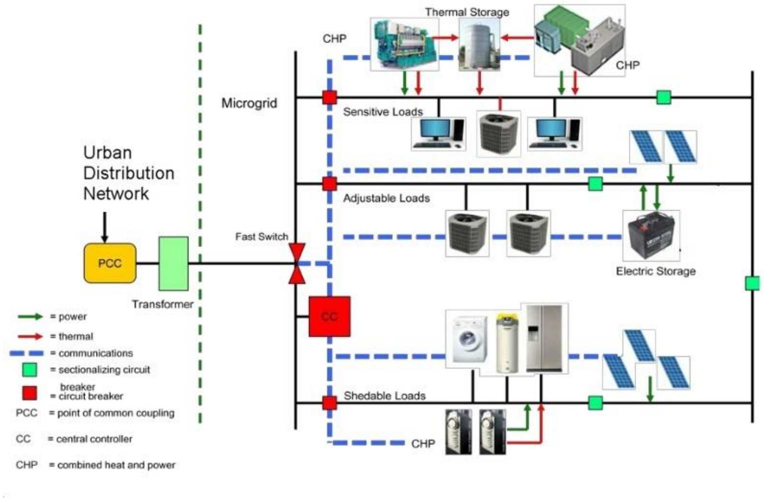


**Fig 2.15 Microgrid arrangement normally applied in urban area (adapted from [125])**

The schematic of microgrid shown above generally reflect the type of components and capabilities normally associated with microgrids. In reality, microgrids can be configured in many different ways and the specific components, operational capabilities and design adopted will vary with local environmental, energy market conditions and the energy performance requirements of local loads.

A main objectives of microgrids is to integrate and combine the benefits of both conventional and non-conventional or renewable and other low carbon generation technologies such as high efficiency CHP based systems. At present there are number of SME sites worldwide with on-site DG and off-network operational capability [221, 222]. DGs installed on these sites normally cover the energy demand of the site, for the simple reason to avoid possible generation and demand imbalance in the case of off-network scenarios. For this sites, the network connection is a backup solution in the case that one or more on-site DGs are out of operation [124].

In general microgrids are mostly a customised solution for the energy requirements of connected loads and it is very unlikely that any two systems will use the exact same energy generation technologies or configurations. As it is described in [125], important variables for determining microgrid design and technology will include: the type, level and density of demand on-site thermal energy, the type and level of electrical demand considered uninterruptable (i.e. affecting the amount of capacity that must be available at all times), the local utility energy tariffs, requirements for interconnection and interaction with the existing electric network and the local availability of fuel supply.

### 2.5.3 Energy Hub

Energy efficiency have been one of the major concerns over three decades among the energy supply companies and customers in urban areas. These concerns have experienced unprecented growth over the past two decades. That could be attributable to policies that establish high specific energy saving targets to be achieved. Liberalisation of energy supply that started in urban areas two decades ago created an environment for a new type of energy supply management, the so-called energy hub. SMEs and residential consumers in cities require various forms of energy services provided by a different infrastructure [126]. Coal, petroleum products, biomass and network-bounded energy carriers such as electricity, natural gas and district heating are normally used as energy carriers. Until recently the different energy supply infrastructures are most often operated and considered independently. Combining these infrastructure can bring benefits related to the energy supply for the network and consumers located in urban areas. Synergy effects among various energy supply networks can be achieved by taking advantages of their specific qualities, e.g electricity can be transmitted over long distance with comparably low losses, natural gas can be stored employing relatively simple and cheap technology. An energy hub can be seen as a system installed at customer site (such as SMEs) where different energy carriers can be converted, conditioned and stored. It facilitates an interface between different energy infrastructures such as natural gas, electricity and loads. The energy hub consists of two basic elements: direct connections and converters [127]. Direct connections are used to deliver an input power directly to the point of use without converting. Converter elements are used to change particular energy carriers into other suitable energy form required by customers. One of frequent converters employed in an energy hub located in urban area consists of combustion engine, gas turbine and fuel cells as component of CHP system.

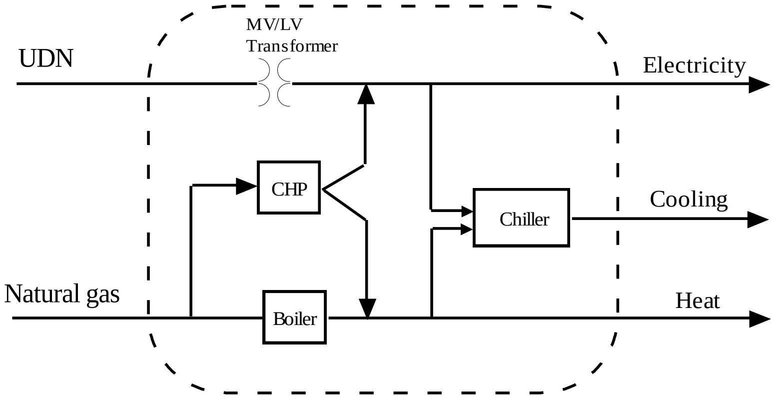


**Fig.2.16 Energy Hub (adapted from [126])**

The energy hub is a typical example with no limitation to the size and application related to energy management. SMEs, multi-apartment buildings as well as bounded geographical area such as entire urban districts can be modelled as an energy hub. In typical urban SMEs, the energy hub consumes electric power and gas and provides energy to its electric load and thermal load. For energy conversion the energy hub normally contains a CHP unit and a boiler. The CHP unit converts the energy contained in natural gas into electrical and thermal energy. Depending on the prices of energy and load profiles, the CHP plant is utilised differently. At high prices of electricity, the electric load is supplied from CHP plant and thermal energy produced in the same process is used to supply thermal load. At electricity low prices, the electric load is supplied directly from UDN and the gas is used to generate thermal energy via site boiler. This redundancy increases the reliability of the supply and at the same time create environment for optimisation of energy inputs using criteria that include: cost, greenhouse gas emission and availability. The energy hub is considered as profit-maximising energy generation that converts a certain number of energy inputs required by consumers. Besides, the energy hub provides operational flexibility in the sense that certain energy output can be provided by using different energy carriers. Another more evident aspect of operational flexibility is that the energy hub can be kept idle if input and output prices are such that it would not be profitable to operate it. In today energy markets, fluctuating energy prices and the related financial risk have gained significant importance. In coming years, the volatility of energy prices in expected to increase further due to intermittent infeed from renewable energy sources, increasing scarcity of fossil fuels and rising speculative trade with energy commodities. Therefore, the volatility of prices will become an essential factor to consider in investment decision making. Competition and efficiency are key words in the deregulated energy market and they are in close association with environment and economy. An environmentally and economically strong energy supply system would sustain competition.

## 2.6 Optimal Sizing and Siting of CHP Plant in UDN

Recent years have seen a trend towards the development and deployment of DG due to government targets, initiatives and increased availability of small capacity generation technologies. Electrical power generation from DG is playing an increasing role in the supply of electricity in liberalised electricity markets. The nature of the DG connected to the UDN is a small plant (usually ≤ 1MW) in a form of CHP generation mode limited central control, connected at low or medium voltage level. CHP plant serving SMEs and in some cases domestic consumers, form the back bone of the on-site energy generation capacity in an urban area, replacing existing on-site thermal energy plant and substituting to a large extent, the commercial electricity supply. The traditional structure of a UDN is, in most cases, characterised by the radial layout of the network that consists of many LV feeders, which can include one or more branches [66]. The introduction of generating sources into the distribution system can significantly impact the operating state and dynamics of transmission and distribution systems. These impacts may manifest themselves either positively or negatively, depending on the distribution network operating condition and the DG characteristics. On account of achieving maximum benefits for the network, DG must be reliable, dispatchable, of the right size and connected at correct locations [128, 129]. A proper placement and sizing of CHP plant plays a very important role since power flows at the interface substations and throughout the networks depend on geographic distribution of all generation sources with respect to demand, irrespective of the voltage at the connection point. Siting and sizing of CHP plant installed by SMEs or other electricity consumers having existing electricity supply from the UDN is a very complex task considering a high number of options in terms of sites and units available and the need to account for load profile for full year and generation and associated uncertainties. From the UDNO perspective the connection of a CHP generation in a UDN requires in-depth technical analysis. By performing technical analysis, the UDNO is normally concerned to maintain the UDN power quality and to ensure that operation of the CHP scheme does not cause a problem for nearby electricity users. In particular the UDNO should establish the following: voltage levels are kept within statutory limits, the fault ratings of switchgear and cables are not exceeded and the network protection system correspond to the new situation. In order to obtain optimal size and location of a CHP plant connected in the UDN, Fig 2.17 outlines an optimisation procedure.

The connection of a CHP unit to the UDN will inevitably result in some changes to the characteristics of the network. The network must operate within a narrow range of technical constraints to ensure efficient and safe operation of network equipment and quality of supply i.e.

Voltage operational tolerance limits at all busses

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad (2.8)$$

where $V_i^{min}$ and $V_i^{max}$ are the lower and upper bound of voltage $V_i$ of bus i around the rated value

The thermal capacity of a line or transformer, also sets a limit to the maximum apparent power (MVA) transfer :

$$|S_t| \leq S_t^{max} \qquad (2.9)$$

where $S_t$ is the apparent power and $S_t^{max}$ is the thermal limit.

The connection of CHP generation rises network fault current at all network locations with the impact being dependent on generation impedance. The fault level constraints given by the fault capacity $I^{CAP}$ of each set of switchgear at bus i.

$$|I_i^f| \leq |I_i^{CAP}| \qquad (2.10)$$

In addition to assessment of technical constraints mentioned above it is equally important to carry out an initial feasibility study using the best possible assessment of the potential CHP scheme developer‘s future energy consumption. CHP plants are traditionally sized by reference to base load heat demand. Connecting CHP plants into UDN will generate observable impacts on the network power flow, protection and voltage regulation particularly where generator capacity is comparable to local demand

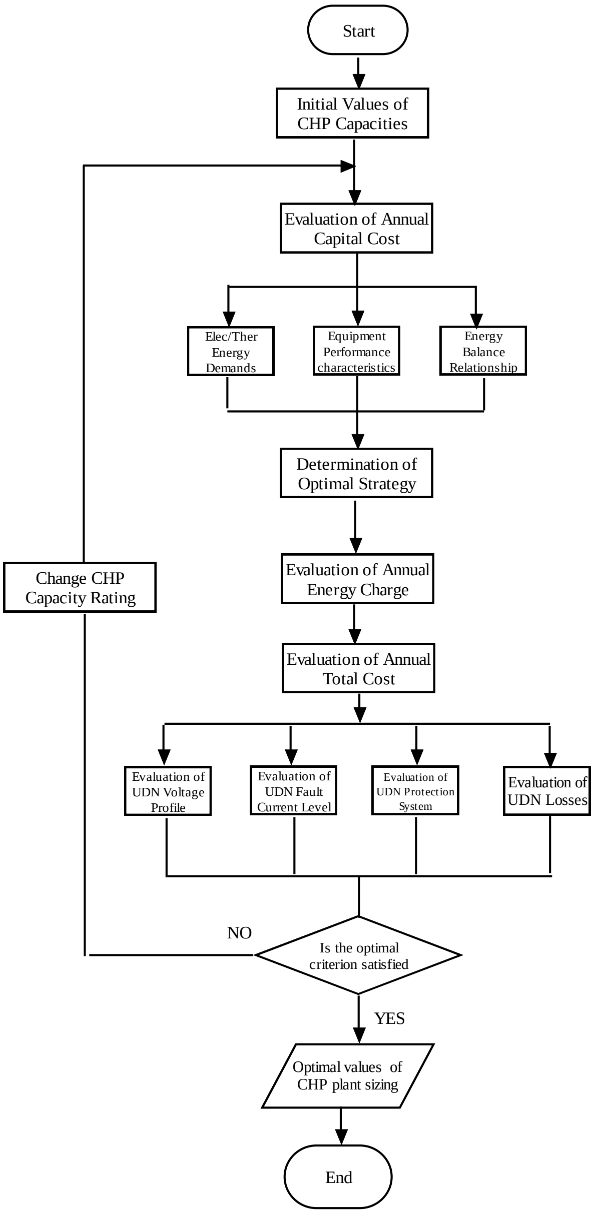


**Fig 2.17 Algorithm of determining CHP plant’s size (adapted from [66])**

and specifically where export occurs. Where there are negative impacts a range of options exist to mitigate them. However, under current commercial arrangements the CHP scheme developer will largely bear the cost of the network upgrades needed to rectify negative impacts caused by CHP plant connection [2]. Therefore the optimal size of a CHP plant installed at a consumers site in an urban area is determined mainly by the plant operational strategy and type of the plant connection to the UDN. When considering the connection of a CHP plant to the network, the UDNO normally considers more than one connection options. In order to determine the most appropriate connection method required to facilitate connection of CHP plant into the UDN, the UDNP/UDNO applies the LCTA principle described in detail in Chapter 6.

## 2.7 Impact of DG Connection Policy on CHP Generation

The penetration of DG and electricity from DG is increasing in most European electricity markets. A transition towards a more sustainable electricity supply may be expected in the coming years. Besides technological changes in DG, electricity markets are undergoing institutional transition. To improve economic efficiency and improve service to the consumers, electricity markets are being liberalised, leading to the introduction of competition and opening of the markets for new entrants. Therefore, a number of policy goals can be distinguished that drive the growth of DG, and these goals include: security of supply, a competitive energy system, environmental protection and energy efficiency improvements [130, 131]. Normally DG facilities are connected to distribution networks at low and medium voltage levels; often at a site that were not originally intended to connect power generation facilities. As a consequence they can create several problems for the distribution networks in terms of stability and power quality; particularly when large amounts of DG are connected or DG is connected to weak networks. [130]

The primary objectives of the network connection policy from the network operator point of view regarding DG connection is to ensure that in the short term, the network will be efficiently operated and that, in the long-term it follows the path of least cost development. Short term effects are caused by balancing the system at the operational time scale, and the interaction of DG with network voltage and stability. Long term effects are related to the contribution that DG can make to the adequacy of the system in terms of its operational capability to meet peak load with high operational reliability and economic/environmental efficiency. In the context of network operation and expansion, this requires some form of coordination between DG and the network development as the optimisation of the network operation in isolation from DG would almost certainly not meet the above objectives. The policies adopted by network operators should reflect the location of DG connection and the specific nature of DG operation. Different DG technologies have different operating patterns that could be described as firm, non firm or a mix of firm and non firm [132]. In determining the value of DG to the UDN, the benefits and costs of a specific DG project must be individually assessed, as benefits may become costs depending on specific details and location of the DG connection under consideration. As such, determining the overall value of DG to the UDNO requires in depth analysis of the proposed DG connection and the cost of the changes to the UDN architecture due to the DG connection.

The value of DG to the developer can be defined as a balance between costs of the DG unit, fuel, maintenance and installation and the benefits that can be obtained from the DG installation e.g. reduced energy costs, increase in security of supply and potentially reduced carbon footprint. In a case where the developer of DG has significant constant demand for heat and cooling, it is worthwhile to consider the CHP generation technology option. CHP generation is an efficient, clean and reliable approach to generate electrical and thermal energy from a single fuel source by recovering the waste heat for another beneficial purposes. Customer – owned CHP plants are normally connected in parallel to the network and are designed to provide some or all of the onsite electricity needs. In some cases, excess power is exported to the network [133]. In the case where the developer is seeking to connect a CHP system to the network it must meet the procedural and technical requirements of the local network operator. These requirements include: network upgrades, operating restrictions and application procedures that may create barriers for some CHP system connection to the network. If connection procedures are overly expensive in proportion to the size of the CHP generation project, they can overwhelm the project cost to the point of making the CHP system uneconomical. One of the most important factor in assessing the value of a DG/CHP system to a developer is the connection and pricing policy of the network to which the DG/CHP system is going to be connected. Ideally, the network operator should use its connection and pricing policy to encourage DG/CHP system connection at a location that offer the optimal benefits to the network and discourage DG/CHP system connection at a location where that connection would increase the cost of the network operation and upgrade [134].

## 2.8 LCTA Method for CHP Generation Connection

The distribution network business is dominated by capital cost and operates in a near monopolistic or highly restricted competitive environment [24]. In general, the cost is an important attribute in the distribution network planning. Almost invariably one of the planner’s main goals is to minimise overall cost associated with connection of DG. When considering the method of connection for a DG or group of DGs into the UDN, the UDNO will consider more than one connection method. The LCTA principle is defined as the solution which is technically acceptable and which results in the least cost being incurred by the UDNO in implementing the solution and which facilitates the long term development of the electricity network in the area. According to [2] any costs incurred by the network in providing a infrastructure for connection of a DG which are deemed by UDNO to be over and above the LCTA solution are borne in full by the customers or developer. The UDNO may specify a connection method which deviates from a strict application and in the case when a number of DGs are being processed at a same time in the same network area, the LCTA principle applies to the entire group of DGs, not to individual DG developers. LCTA principle must be promoted and justified in light of the UDNOs broader duty to ensure wide long term network development and future capacity of DGs connections into the UDN. In the event of the network operator pursuing such a non-LCTA connection method, the applicant would only be liable for a charge based on the LCTA solution. [2] Another issue that can significantly influence the cost of a DG connection is whether connection charges should reflect only costs exclusively associated with making the new connection or also include the additional costs which are indirectly associated with any reinforcement of the network. In other words, cost of DG connection based on shallow or deep connection cost [24]. When connecting a DG to the UDN, the DG developer normally should consider costs such as: shallow/deep connection costs, distribution deep reinforcements, pass through costs, internal network requirements and distribution code compliance costs [2]. An CHP system developers shall be charged for the connection to the UDN on the same basis as a final customer. Their connection charge shall be based on their electrical power maximum import capacity (MIC) with the exception of any additional costs required in relation to the provision of export meters which shall be charged in full to them. Where and existing customer has an agreed electrical power MIC such that it now becomes an exporting CHP producer, this customer shall be charged for connection that has not already been recovered via use of UDN system [223]. An essential condition to develop competition and penetration of DG in UDN is open access on a non-discriminatory basis. The central issues in the concept of the open access is setting adequate costs for UDN services as this affects future siting of DG, network operating costs and quality of delivery of electricity. Under such a scenario, there is ever growing pressure for all assets and labour associated with DG connection into UDN to the clearly identifed and assigned efficiently and equitably to all parties avoiding temporal or cross-subsidies.

## 2.9 Regression analysis

Regression analysis is a statistical technique for estimating the relationship among variables. The relationship is expressed in the form of an equation or a model. Multiple regression analysis is a powerful statistical that is used for forecasting the unknown (dependent) value of a variable from the known value of two or more variables also known as predictors (independent). Multiple regression analysis base optimisation procedure, shown in Fig. 2.18, provides an opportunity to incorporate any detrimental operational constraints that can be seen by the UDNO and CHP system developer as critical regarding the CHP system connection into the UDN. It includes many techniques for modelling and analysing several variables when the focus is on the relationship between dependent variables and one or more independent variables. More specifically regression analysis helps to understand how the typical value of the dependent variable changes when any one of the independent variable is varied while the other independent variables is held fixed. It is also used to understand which among the independent variables are correlated to the dependent variable and to explore the nature of these relationships.

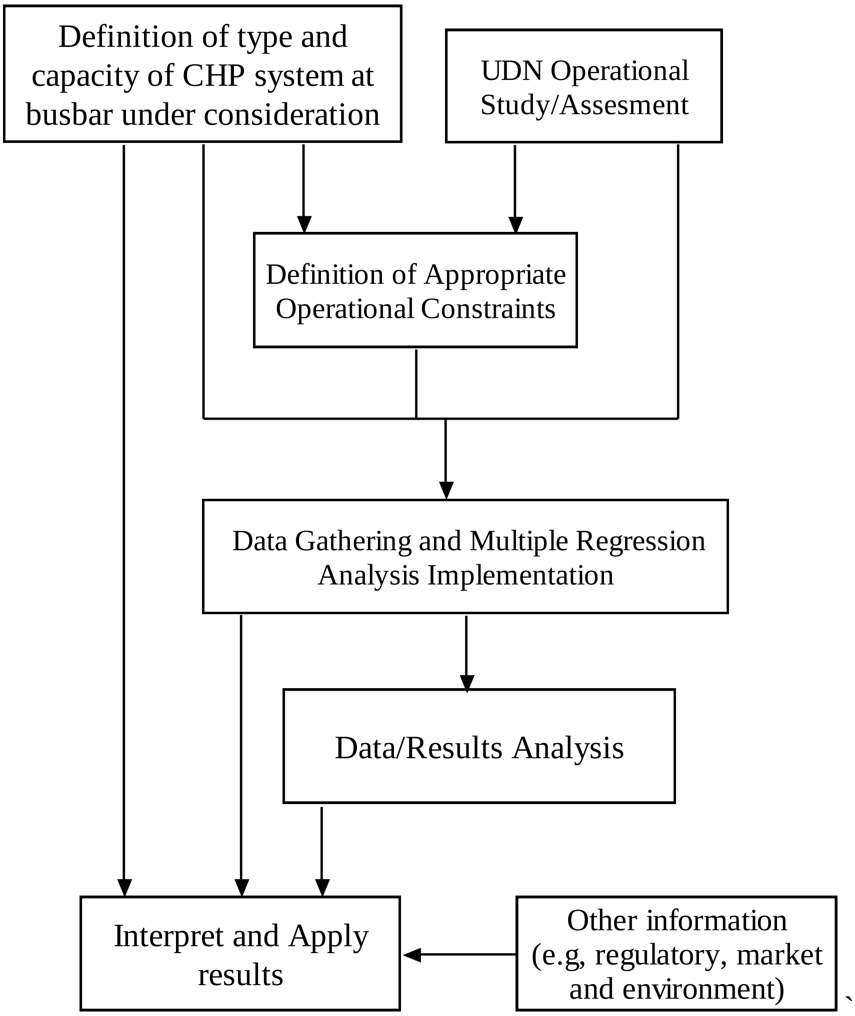


**Fig 2.18 Multiple regression analysis based optimisation procedure**

Regression analysis is widely used for prediction and forecasting. Also it is used to understand which among the independent variables are related to the dependent variables and to explore the forms of these relationship. A multiple regression model that describes this relationship is specified as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots\cdots + \beta_m x_m + \varepsilon \qquad (2.11)$$

where :

y – is the dependent variable

$x_j$, j=1,2,…..,m represent m different independent variables

$\beta_0$ – is the intercept ( value when all the independent variables are 0)

$\beta_j$ , j=1.2,……,m represent the corresponding m regression coefficients termed as partial regression coefficients because they measure the change in a particular $x_i$ holding the other m-1 X variables constant

ε – is the random error, usually assumed to be normally distributed with mean zero and variance $\sigma^2$

Regression analysis attempts to model the relationship between two or more explanatory variables and response variables by fitting a linear equation to observed data. Every value of the independent variable X is associated with a value of the dependent variable Y. Multiple regression analysis model enable us to assess the relationship between the response variable and each of the predictors adjusting for the remaining predictors.

In order to determine multiple regression coefficients, the method of least squares estimation is most frequently used [135]. Assume that n>m observations are available, and let $X_{ij}$ denote i$^{th}$ observation or level of variable $X_j$.

The observations are: ( $x_{i1}, x_{i1}, \dots, x_{i1}, y_i$), i = 1,2,. . . . . ,n and n > m and each observations are model (2.12)

$$Y_i = \beta_0 + \sum_{j=1}^{m} \beta_j x_{ij} + \epsilon_i \qquad i= 1,2, . . . ,n \qquad (2.12)$$

The least squares function is

$$L = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} \left(y_i - \beta_0 - \sum_{i=1}^{m} \hat{\beta}_j x_{ij}\right)^2 \qquad (2.13)$$

The aim is to minimise L with respect to $\beta_0, \beta_1, \ldots \beta_m$ and the least squares estimates of $\beta_0, \beta_1, \ldots \beta_m$ must satisfy the following

$$\left.\frac{\partial L}{\partial \beta_0}\right|_{\beta 0, \beta 1, \ldots \beta m} = -2\sum_{i=1}^{n} \left(y_i - \beta_0 - \sum_{i=1}^{m} \hat{\beta}_j x_{ij}\right) = 0 \qquad (2.14a)$$

and

$$\left.\frac{\partial L}{\partial \beta_j}\right|_{\beta 0, \beta 1, \ldots \beta m} = -2\sum_{i=1}^{n} \left(y_i - \beta_0 - \sum_{i=1}^{m} \hat{\beta}_j x_{ij}\right) x_{ij} = 0 \qquad (2.14b)$$

where j=1,2,.....m

Simplifying this system of equations is as shown below.

$$n\hat{\beta}_0 + \hat{\beta}_1 \sum_{i=1}^{n} x_{i1} + \hat{\beta}_2 \sum_{i=1}^{n} x_{i2} + \cdots\cdots + \hat{\beta}_m \sum_{i=1}^{n} x_{im} = \sum_{i=1}^{n} y_i$$

$$\hat{\beta}_0 \sum_{i=1}^{n} x_{i1} + \hat{\beta}_1 \sum_{i=1}^{n} x_{i1}^2 + \hat{\beta}_2 \sum_{i=1}^{n} x_{i1}x_{i2} + \cdots\cdots + \hat{\beta}_m \sum_{i=1}^{n} x_{i1}x_{im}$$

$$= \sum_{i=1}^{n} x_{i1}y_i$$

$$\hat{\beta}_0 \sum_{i=1}^{n} x_{im} + \hat{\beta}_1 \sum_{i=1}^{n} x_{im}x_{i1} + \hat{\beta}_2 \sum_{i=1}^{n} x_{im}x_{i2} + \cdots\cdots + \hat{\beta}_m \sum_{i=1}^{n} X_{im}^2$$

$$= \sum_{i=1}^{n} x_{im}y_i$$

(2.15)

At this system there are p = m+1 normal equations, one for each of the unknown regression coefficients. The solution to the normal equations are the least squares estimators of the regression coefficient $\beta_0$, $\beta_1$, . . . $\beta_m$ . The system of equations shown above can be resolved by any method appropriate for solving a system of linear equations.

In fitting a multiple regression model that facilitate a large amount of data, it is much more convenient to express the mathematical operations using matrix notation shown in Appendix 9 [135, 136].

The general form of a multiple regression analysis employed in this study incorporate two independent variables can be written as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \qquad (2.16)$$

where $\beta_0$, $\beta_1$ and $\beta_2$ are constants, $X_1$ , $X_2$ are the independent variables, and Y is the dependent variable. The graph of an equation describing multiple regression model with two independent variable is a plane in three-dimensional space shown in Fig. 2.19

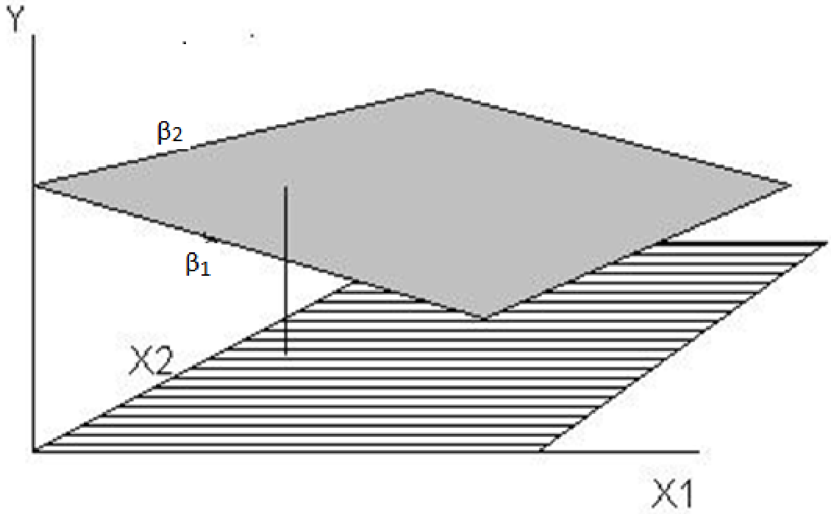


**Fig. 2.19 A typical Multiple Regression Plane for the model described in equation 2.16.**

In these case studies, data generated for multiple regression analysis are generated by power flow and short circuit analysis perform by power system analysing software package ERAC. Data is generated by performing a number of case studies using different sizes of CHP plant connected at busbars under the investigation. In each case power flow and fault current analysis are performed and data are collected for a number of busbars marked by UDNO that are close to violating of the constraints defined above. Data used as predictor $X_1$ in this multiple regression analysis is the per-unit value of voltage level at the busbar selected by UDNO as the most critical regarding the voltage profile concern and in a similar way predictors $X_2$ is the magnitude of fault current at the busbar selected by UDNO as the most critical regarding the fault current level. Once a multiple regression model has been created it can be checked how good it is (in terms of predictive ability) by analysing number of coefficients generated by the model and these are described below [135].

The first coefficient to be examined is the coefficient of multiple determination ($R^2$) which by definition is the ratio of the regression sum of squares (SSR) to the total sum of squares (SST) where:

$$SSR = \sum\left(\hat{Y} - \bar{Y}\right)^2 \qquad (2.17)$$

$$SST = \sum(Y - \bar{Y})^2 \qquad (2.18)$$

$$R^2 = \frac{SSR}{SST} = \frac{\sum(\hat{Y} - \bar{Y})^2}{\sum(Y - \bar{Y})^2} \qquad (2.19)$$

The $R^2$ is the proportion of the total variation in the observed value of the response variable (in this case size of the CHP plant) that is explained by the multiple linear regression in the predictor variables $X_1$ and $X_2$ (in this case magnitude of the voltage level and fault current level respectively at particular busbar selected by

UDNP/UDNO). It is always lies between 0 and 1 and it is a descriptive measure of the usefulness of the multiple regression model for making prediction. If magnitude of $R^2$ is near 0 it shows that the multiple regression model is not useful for generating predictions, whereas magnitude of $R^2$ close to 1 indicate that the multiple regression model is very useful for generating predictions. In a case when $R^2$ is equal 1, there is an precise linear relationship between Y and $X_1$ and $X_2$.

The second coefficient, normally the F-test statistic, will allow us to determine multiple regression model statistically significant predictive capability that is whether the variable, voltage level magnitude at a particular busbar selected by UNDP/UNDO ($X_1$) and fault current level at particular busbar selected by the UDNP/UDNO ($X_2$) taken together are useful for predicting size of CHP plant (Y) connected at busbar where CHP plant is going to be connected. In a case where $\beta_1$ and $\beta_2$ are equal to zero then the predictors $X_1$ and $X_2$ generate no input about the conditional distribution of the response variable

Therefore $X_1$ and $X_2$ taken together are inadequate input variables for predict Y. In this case SSR tend to be small and SSE tends to be large relative to SST. In a case when $\beta_1$ and $\beta_2$ are not zero then $X_1$ and $X_2$ are suitable for predicting the Y, and the SSR tends to be large and the SSE tends to be small relative to the SST.

$$F - statistic = \frac{MSR}{MSE} \qquad (2.20)$$

where:

$$MSR = \frac{SSR}{k} \quad \text{- mean square for regression} \qquad (2.21)$$

$$MSE = \frac{SSE}{n-(k+1))} \quad \text{- mean square for error} \qquad (2.22)$$

The F – statistics value will range from zero to an arbitrarily large number. A small value of significance F confirms the validity of the multiple regression model output.

The P – value of coefficient ($\beta_1$ , $\beta_2$ and $\beta_0$ ) provide the possibility that these are valid results which did not occur by chance. Lower P- values mean that the likelihood that $\beta_1$ , $\beta_2$ and $\beta_0$ are valid. A low p-value less then 0.05 indicates that null hypothesis can be rejected. Low P-value suggest that changes in the predictors (voltage and fault current ) value are related to changes in the response variable (size of CHP plant ). On the other hand a larger P-value suggest that changes in the predictors are not associated with changes in response variable.

The significance of the slope of the regression line is determined from the t-statistics. It is essentially a test to determine if the regression model is working. If the slope is considerably different than zero, then a multiple regression model can be used to predict the dependent variable Y (size of CHP plant) for any value of the independent variable $X_1$ and $X_2$ representing the magnitude of the voltage profile and magnitude of fault current at any selected busbars by the UDNP/UNDO. In a case when the slope is zero, multiple regression has no prediction capacity because for every value of $X_1$ and $X_2$, the prediction for the Y would be the same. Knowing the value of the $X_1$ and $X_2$ would not improve multiple regression model capacity to predict the Y.

In order to predict new observations with greater insight into interrelatedness between and within sets of variables, a number statistical estimation methods including correlation and test for significance of regression are used to complement multiple regression analysis. The multiple regression, complemented with the statistical estimations, make possible to predict new observation in a more detailed and realistic way. Compared with other statistical methods, the multiple regression method allows us to analyse a complex array of variables, providing greater assurance that some synthesizing conclusion can be achieved with less error and more validity than if variables were analysed in isolation. Multiple regression offers greater flexibility and options for analysis that extent and enrich other statistical methods [137,138,139].

## 2.10 Summary

In this section a literature review was presented as a summary of the prior work and interpretation in order to support the main objectives of this thesis. A detail review is presented of the most relevant published work related to the impact of distributed generation on an distribution network. Analysis of this published work is based on the fact that small-scale distributed generation technologies are fast replacing large centralised power generation in liberalised markets. EU DG directives and national initiatives are promoting development of DG technology in urban areas in particular in the form of CHP generation technology. At present, the key barrier holding CHP generation development in urban area is the up-front capital cost of CHP plant connection to the network caused by non-consistent interconnection standards. These standards are based on case-by-case approach of apprising DG/CHP plants connection risk the sterilisation of UDN through the inappropriate sizing or location of DG/CHP plants. The ability of determining maximum capacity at a given location over a UDN according to the LCTA principle provides a means of planning and managing DG/CHP plants connection whilst limiting the risk of UDN sterilisation. While a number of options exist to mitigate adverse impacts, under current commercial arrangements the developer will largely bear the financial responsibility for their implementation. Much work has been done on the technical and economic implications of DG/CHP technology connection in UDN and the need for new kind of planning methodology for dispatching of DG/CHP systems has been recognised, but there is no evidence that new methodology has been developed. The gaps in existing UDN planning methodology are manifested in lack of simple and flexible mathematical methods that can be used in determining the size of DG/CHP plant to be connected at a particular location in a UDN according LCTA principle. The objectives of this thesis is to identify and quantify any adverse impacts on the security and quality of power supply in UDN initiated by connection of DG/CHP plants. Using this data in a mathematical method based on multiple regression analysis complemented with appropriate statistical estimation, it will be possible to determine maximum size of DG/CHP plant that can be connected at any particular point in UDN without causing adverse impacts, prevent sterilisation of the network and without substantial cost of a network equipment upgrade.

# Chapter 3 Integration of CHP Generation into the UDN

## 3.1. Siting and Mode of Operation

Integration of CHP generation into the UDN is a planning process that evaluates a number of different options for meeting existing/future energy/electricity demands. That further involves the selection of the optimal solution with respect to siting, sizing and operational mode of CHP plant that minimises the cost of energy/electricity supply while meeting reliability needs and other objectives in an urban area. With traditional urban energy supply planning, the following considerations are taken into account by the planners: the demand to be met, the reliability to be achieved and government policies and regulations in place at the time. In a case of CHP plant integration, the planners normally attempt to take the traditional planning approach several steps further. These steps include [141]:

- Evaluate all options, from both the supply and demand sides, in a impartial and consistent manner,
- Minimise costs to all participants (not just cost to the service companies),
- Create a flexible plan that permits adjustment in response to change in operational circumstances.

In order to maximise the benefits and minimise the cost of CHP plant integration into UDN, the planner in addition to the above considerations takes a number of other constraints into consideration. These constraints are investigated in the following paragraphs below. Analysis is performed on a 34 busbar UDN resembling a part of the network of Cork City.

Most UDN networks or parts of network are unique. The vast variation in UDN design tend to make it particularly difficult to standardize CHP plants installation, as every UDN will have its own requirements and limitations based on its own unique design and operational mode. As with the growing number of acceptable connection applications for CHP plants, concerns related to siting and mode of operation of the CHP plants are evolving. Optimal locations for CHP plants can be defined in terms of the extent to which the CHP plant electrical output will decrease line loading, real power losses and reactive power losses, which combined will also postpone network equipment upgrades. General analytical methods that address concerns related to identification of the optimal connection location of CHP plant in UDN are presented in [142, 2]. In the case where penetration of CHP generation capacity is low, potential for optimised line loading and line low losses is very promising but diminish as the installed capacity of CHP generation is increased. For a CHP plant with a capacity capable of supplying load in full to the feeder where it is connected and in addition able to export electrical power to the network, additional considerations of equal importance have to be addressed. The new considerations create situations in which CHP plants interact with the operation of the UDN. These new considerations include:

- Power Flow Management,
- Impact of CHP generation capacity on UDN losses,
- UDN control requirements in the presence of CHP generation.

CHP plant installed in UDN normally operate in one of two modes: base load or load following constant voltage [97]. From the UDNO perspective the best location for CHP plant location is the end of a feeder where the network voltage magnitude is at lowest point and normally has the greatest variations. To provide maximum voltage support to the network the CHP plant should operate as a P-V bus such that voltage is constant and output varies as necessary to maintain the voltage level set by the UDNO. Due to the fact that load fluctuation in urban areas is dynamic, for the CHP plant to follow the load in P-V mode has impacts on the CHP plant generator wear and tear. The second mode of operation of CHP units is the mode where the plant is run as base load generator with set output level. A disadvantage of this mode is the negative impact on equipment used for voltage control such as capacitor banks. The benefit gained by operating a CHP plant in this mode is that the plant generator will not experience greater wear and tear as it follows dynamic load fluctuations. In order to achieve greater operational benefits from CHP plant connected to UDN, it is important to analyse and determine the siting and operational mode of CHP plant.

### 3.1.1 Power Flow Management in UDN with CHP Generation

In the case where the capacity of CHP plant exceeds local load, the CHP plant will inject power into the UDN leading to the following possibilities [97]:

1) The connected load between the CHP plant and the feeder is greater (or equal) to the total power injected by the plant into the UDN. This scenario produces situations where the loading of the equipment upstream of the connection point is reduced, and power flow continues from the HV/MV substation toward the end of the feeder. For a certain part of the UDN (as a consequence of CHP plant installation) power flow should be reduced within the UDN lines as it supplies power to local loads and thereby reduces line losses. In addition, in some cases it is also possible that a CHP plant output could increase the power flow of a specific line. If existent UDN equipment have already power flow approaching its nominal ratings, a connection of CHP unit might caused overload, increase fault

current and cause nuisance tripping that could happen even under normal operating conditions.

2) The load between the CHP plant and the end of the feeder is less than power injected by the plant into the UDN. In this case the upstream equipment from CHP plant connection point will experience a reduction in load. However in both cases, the loading on the HV/MV substation is lessened, which in turn generates potential benefits for postponement of the substation equipment and some upstream network equipment installation. Balanced with this benefit there are a number of constraints that include: an increase in requirements for protection as a result of bi-directional power flow, voltage profile and fault current level and a potential for the increased loading of the equipment close to the connection point of the CHP plant into the UDN.

### 3.1. 2 UDN Control Requirements in UDN with Presence of CHP generation

All UDNOs maintain a detailed database describing the electrical characteristics of their UDN [2]. This data are used to analyse the network behaviour under different loading conditions and network configurations during events such as scheduled/unscheduled maintenance or during particular faults on the network. The connection of a CHP plant to the network will inevitably result in some changes to the characteristics of the network. To evaluate the possible consequences caused by connection of the CHP plant in the UDN, the UDNO will perform some network studies with CHP plant included in the network model. In performing these studies, the UDNO will determine whether the connection of the CHP plant proposed would result in any of the network planning criteria being exceeded. These criteria include: thermal ratings of the equipment; unacceptable voltage rise; fault level limits of the existing equipment ; losses; voltage stability and network protection adequacy. As well as performing analysis of the network under normal operating conditions the UDNO will also study the network under a number of contingency cases. The impacts of CHP generation on UDN operation outlined above raise a number of issues relevant to UDN control and the concept of a urban distribution network operational management. From a UDNO perspective, the control requirements resulting from the impacts of CHP generation connection into UDN are listed in [97]:

- Controlling CHP plant for the specified voltage profile (if operating in P-V bus mode),
- Controlling CHP plant to not exceed UDN line or equipment capacity limits,
- Detecting a line fault and reconfigure the network to best utilise available CHP plants, and if necessary disconnect CHP plant from the network,
- Detecting a CHP plant fault or out-of limits condition and disconnect.

In terms of current application of CHP generation in an UDN, a UDNO will require that the above control requirements be set during the planning process of CHP plant integration into UDN. At present the only active control that UDNO has is the ULTC position on the HV side on the transformer in the HV/MV substation supplying a number of UDN feeders. It has been established that at this stage a certain level of CHP generation penetration has been facilitated without the requirement of innovative control in many UDNs due to the robustness and the redundancy of the networks. Even with that amount of CHP generation connected, the networks have remained largely passive. With greater energy cost and progressively stringent environmental laws, urban energy consumers are required to streamline their energy consumption from CHP based onsite generation. This scenarios demands a degree of the control for the following network operational constraints, [144]: power flow, voltage profile, fault level, losses, greenhouse gas emission and economic performance.

### 3.1.2.1 Effect of CHP Generation on UDN Voltage Profile

In traditional UDN, voltage profile is controlled mainly by the ULTC positioned on the HV side of the transformer in the HV/MV substation continually. In order to minimise operation of the ULTC the fix tap changer (FIXTC) position on the MV/LV transformer normally sited on the consumer site is determined by the UDNO base on power flow analysis performed for various load consumption scenarios. Finally to complement these two methods of voltage profile control, at some points in the UDN a requirement for customers with a heavy reactive power demand to introduce power factor correction facilities as shown in Fig 3.1

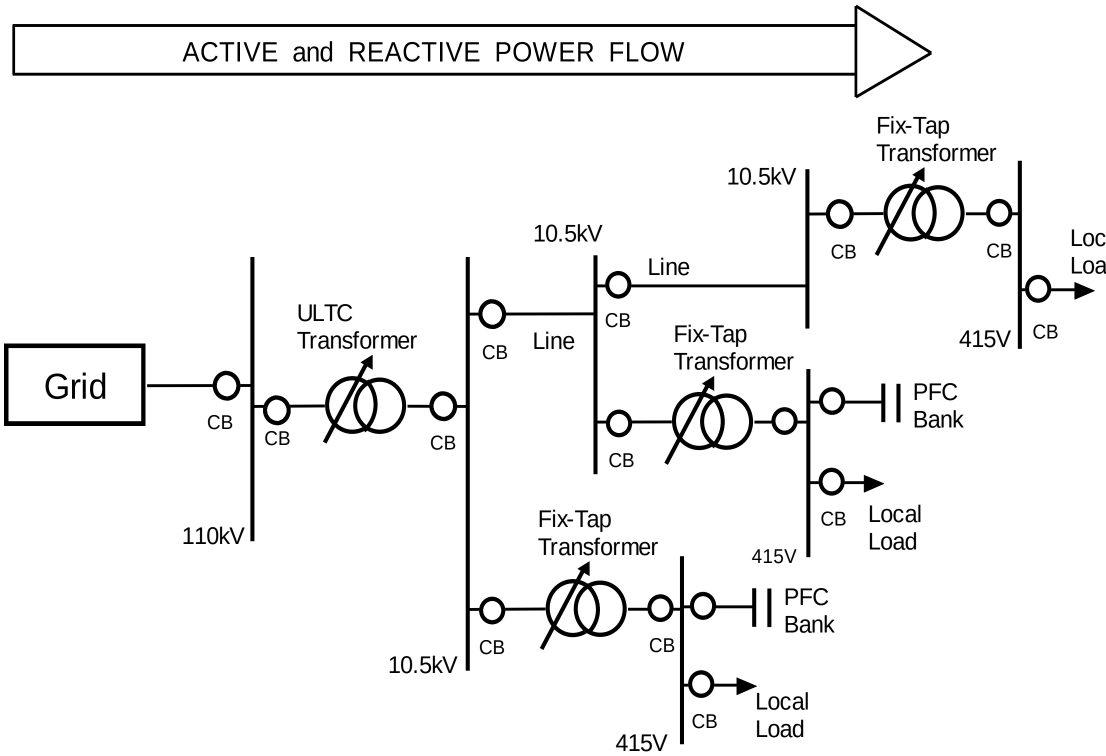


Fig. 3.1 **Typical UDN with Voltage Control Profile Facilities**

The first and last method can be seen as continuous modes while FIXTC can be seen as a static method of voltage profile control in the UDN. The values must be kept within national standard limits at each bus and it is given

$$V_{mini} < V_i < V_{maxi} \qquad (3.1)$$

CHP plants, being sited within UDN and therefore close to or an at site of consumers' site are well suited to provide voltage support. To analyse and understand the impact of CHP plant in a mainly passive UDN, the simple two bus network is created as shown in Fig. 3.2

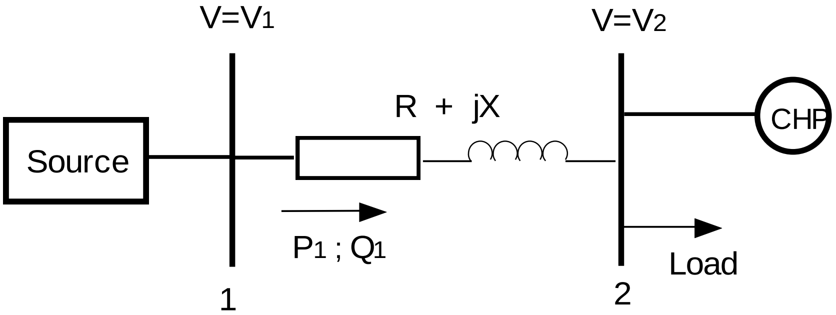


**Fig 3.2 Two bus feeder with CHP plant connected**

Using the network above and a simple network theory [143, 24], it is possible to develop an approximate expression for the voltage magnitude at the receiving end busbar $V_2$ in terms of the sending-end voltage $V_1$ and the given network parameters.

$$V_2 = V_1 - \frac{RP_1 + XQ_1}{\sqrt{3}V_1} \qquad (3.2)$$

In a passive UDN, the active $P_1$ and reactive power $Q_1$ flow in the direction shown in Fig 3.2 and creates a volt drop between the sending and receiving busbars as can be estimated using (3.2). The connection of CHP plant to such a feeder reduces the amount of active power $P_I$ that normally is supplied from the source and hence reduce the volt drop experienced between busbars 1 and 2. If the CHP plant generates at unity power factor (UPF), it will have only a small impact on the reactive power $Q_1$ supplied from the source corresponding to a reduction in reactive power losses across the conductor. In the case where the active power generation by the CHP plant exceeds the local demand, it will reverse the direction of the $P_I$ in Fig 3. 2 If the reverse flow of active power is of significant magnitude, it can overcome the volt drop caused by $XQ_I$ in (3.2) and will give rise to the net voltage rise between busbars 1 and 2 in Fig 3.2 In order to facilitate the voltage level corresponding to the national standard at any point of the UDN, the UDNO has the number of methods to mitigate adverse voltage variations. The methods that are at present used by the UDNO to mitigate voltage variations are listed in [145,106] and these are: voltage reduction at a feeding substation; allow the generator to import greater reactive power; in-line voltage regulator; increase the size of the conductors; the generator(s) reduce power output

#### 3.1.2.2. Effect of CHP Generation on UDN Fault Level

The UDN traditional role is to distribute energy from the transmission system to the various customers. It usually operates at two voltage levels, MV and LV and is characterised by design maximum fault current, i.e short-circuit capacity. A CHP plant is normally equipped with a synchronous generator and IC engine as a prime mover with rating of between 100kW and 1MW. When connected at a customer site that can cause an increase of fault levels throughout the network and in particular close to the point of the CHP plant connection. The fault level rise depends on the capacity/penetration of CHP generation. Detailed assessment of the impact that the CHP plant might have on the fault currents is very challenging as the impact largely depends on a number of factors that include: the technology of CHP plant; its operation mode; interface of the plant and the network voltage level prior to the fault. When a fault occurs in the UDN a fault current will flow to the fault location. The fault current comprises the current from connected generation and from rotating load such as motors at customers' sites [146]. The switchgear in the UDN and the switchgear facilitating

CHP plant must be rated to withstand the effects of the new combined fault current level. This fault is detected by the protection system and will be cleaned by circuit breakers or fuses. Therefore, one of the most important aspects of planning and operating an UDN is the design of protection that handles fault conditions. Circuit breakers capability and settings of protective relays that were previously designed for the UDN without CHP generations connected may not safely and appropriately coordinate to manage a fault in the UDN with CHP plant connected. To eliminate that possibility, the magnitude of fault current must be within limits:

$$I_{Fault}^{Min} < I_{Fault}^{Rated} < I_{Fault}^{Max} \quad (3.3)$$

In the presence of multiple fault current sources within the UDN, the total fault current is the vector sum of all contributions that include: upstream network, local generation and motor loads. The value of the short-circuit current is determined through the use of the impedance in the basic equation (3.4).

$$I = \frac{E}{Z} \quad (3.4)$$

Where E is the system driving voltage and Z is the impedance of the network from the fault point back to and including source or sources of a fault current. The value of the impedance is determined with regard to the basis of rating for the device or equipment under consideration [147]. In UDN the maximum fault level typically occurs at the busbar at the infeeding substation due to the large contribution from the HV transmission system. In a case when a CHP plant is connected to the UDN, the fault current is due to:

- The upstream network,
- The CHP plant generation,
- The large motors if these are connected into UDN

In order to determine the contribution to the total fault current from various sources and the total fault current in the UDN, the simple three busbar network shown in Fig.3.3a can be used for illustration [148]

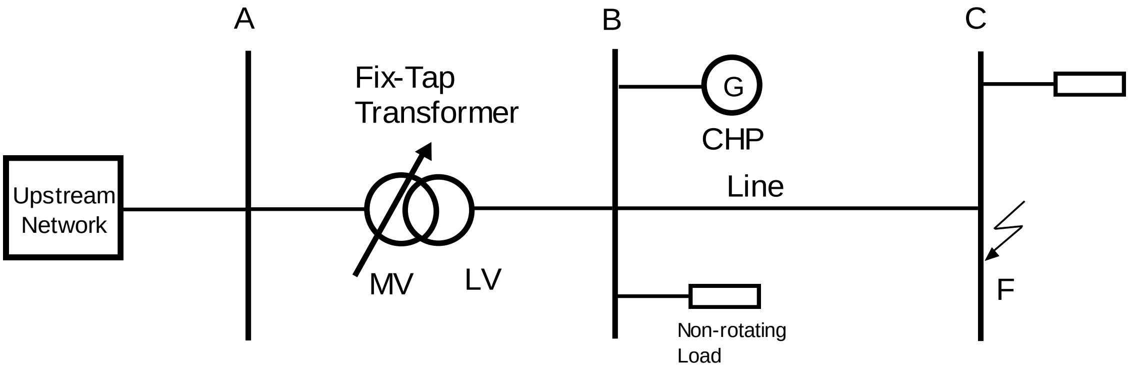


**Fig. 3.3a Three busbar network**

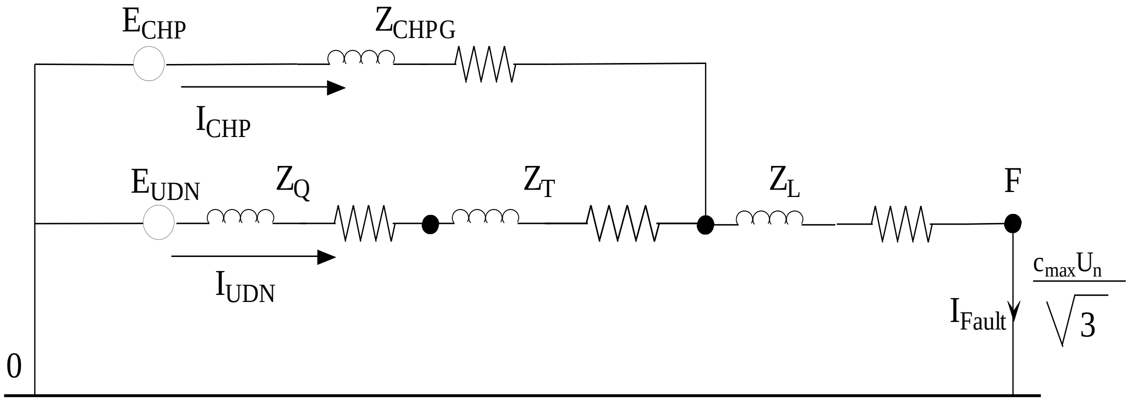


**Fig. 3.3b Single line diagram corresponding to the network shown in Fig 3.3a**

The contribution from the upstream network is determined based on [166]:

$$I_{\substack{Fault\\UDN}} = \frac{c_{max}E_n}{\sqrt{3}(Z_Q+Z_T+Z_L+Z_F)} \qquad (3.5)$$

where: $Z_Q$ - is the impedance of upstream network at the connection point A

$Z_T$ - The impedance of transformer

$Z_L$ – Line impedance

$Z_F$ - Fault point impedance

$c_{max}$ – voltage factor for calculating the maximum fault current

(e.g. for MV ≈1.1)

Contribution from the CHP plant is determined based on [33]:

$$I_{\underset{CHP}{Fault}} = \frac{c_{max}E_n}{\sqrt{3}(Z_{CHPG}+Z_L+Z_F)} \qquad (3.6)$$

where: $Z_{CHPG}$ - is the impedance of CHP plant generator

In addition to the rating of the equipment effected by increased fault current, the UDNO and the CHP plant developer must take into account the following concerns [149]:

- Failure of interrupting device,
- Undetected fault,
- Changing the reach of protective relays,
- Recloser setting,
- Safety,
- Adequacy of the network,
- Implication of unit commitment.

In order to minimise the adverse impact of the concerns mentioned above the fault analysis should be done prior to the connection of CHP plant. A protection system and associated circuit interruption may need to be upgraded or replaced. In some cases, entirely new protective relay settings and upgraded circuit breakers may be needed. Once the circuit breakers are in place and relay settings have been implemented, there may be some operating and planning implications imposed by the changing current. This is a complicated issue which depends on the type of the customer, the size and the operating intention of the CHP plant. All approaches to allocate the responsibility and the cost of these changes should be on the basis of simple and fair market for every customer and the network utility. The identification of what is fair and what is simple has not been done for the case of fault currents due to added CHP plant. These issues are needed to guarantee safety and reliability of the system which should be covered by the owner of the CHP plant.

#### 3.1.2.3 Effect of CHP generation on UDN Losses

Energy losses have been and will remain as one of the metrics used to assess an UDN performance. The fact that a high proportion of the UDN in the developing world is over 30 years old and has a high contribution to the network losses (average of 7%). Therefore, the minimisation of energy losses is and will be an important focus for UDNOs in liberalised energy markets [150]. The growing interest in recent times in CHP generation as a means of energy supply for SMEs located in an urban area is substantial. If it is utilised correctly through optimal accommodation and through incentives/economic/environmental signals could create an opportunity for substantial reduction in energy losses. As pointed out in [151], traditionally the CHP units have to some extent been regarded as passive negative loads with the main purposes of generating energy for the urban consumers and not disturbing the operation of the UDN. When evaluating the operational performance of a CHP plant connected into the UDN, more aspects than the annual energy production must be taken into account. In a UDN where the penetration of CHP generations is low, the CHP units are located close to load centers and there is a large coincidence between load and the CHP plant energy output, the CHP units can contribute to the reduction of the total UDN losses. In order to increase the reduction of UDN losses, the CHP plant output profile in time should reasonably match that of the local load demand. In the case when power from the CHP plants connected to the MV or LV levels of the UDN has to be exported to the HV transmission system (because the local CHP plant generation exceeds the local demand) the total power system losses caused by transport of that energy is greater than if the power were produced at a power plant directly connected to the transmission system.

To analyse the overall impact of CHP generation on losses, several scenarios with different CHP generations penetration and concentration levels are considered. CHP generation impacts on the UDN losses are measured as the difference between losses in the considered scenario and losses in the base UDN without CHP plants. The results obtained are presented through different means that show the UDN losses change versus CHP generations penetration and concentration levels.

In the context of urban environment, CHP generation can be considered as taking power to the load. The amount of that losses depends on the magnitude of the current flow and the resistance of the network component on the current path. Therefore, the network losses can be reduced by reducing either the current or resistance or both. If CHP plant is used to provide energy locally to the load, network losses can be reduced because of the decrease in current flow in some part of the network. In order to evaluate and allocate losses in UDN without CHP generation, the method used is based on ac power flow analysis. The schematic of the network shown in Fig. 3.4 is used to determine network losses based on the algorithm described in [152].

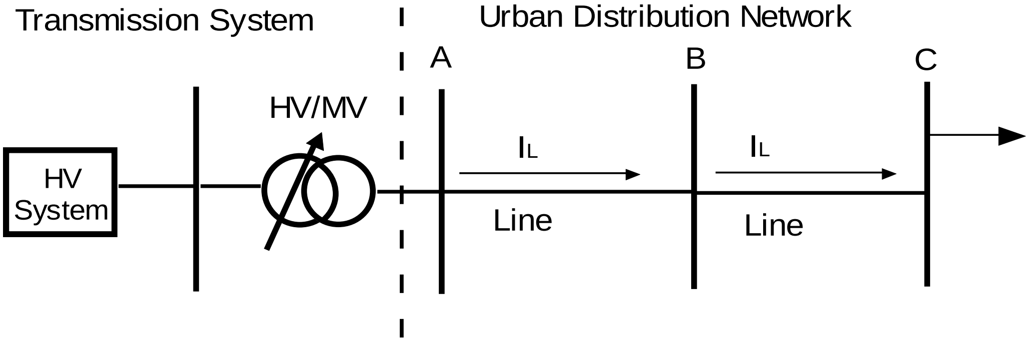


**Fig.3.4 Single line diagram of the system to illustrate active and reactive power losses**

Losses which concern the UDNO on the feeder shown in Fig.3.4 are equal to the product of line current squared times the line resistance. Therefore line loss equation for the three phase system is defined as:

$$Loss_{AC} = \frac{r * L_{AC}(P_L^2 + Q_L^2)}{3V_P^2} \qquad (3.7)$$

r – line resistance per metre

L – length of line

$P_L$ – Active power transport through line

$Q_L$ – Reactive power transmitted through line

$V_p$ – phase voltage

In a case where the CHP unit is connected the losses are determined using the schematic of three busbar network shown in Fig. 3.5

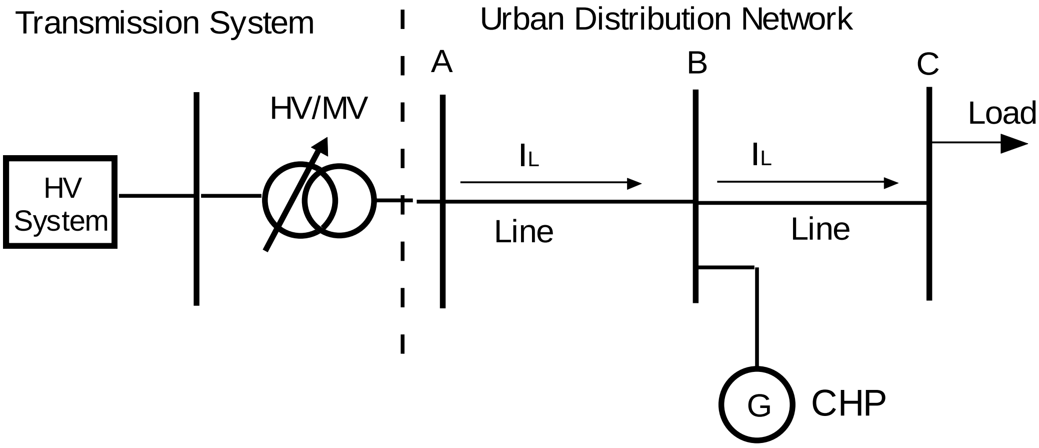


**Fig.3.5 Single line diagram of the system with CHP plant connected to illustrate active and reactive power losses**

The complex power supplied by the CHP plant equals to $S_{CHP} = P_{CHP} + jQ_{CHP}$. Thus, CHP plant output current is given as:

$$I_{CHP} = \frac{(P_{CHP} - jQ_{CHP})}{3V_P} \qquad (3.8)$$

The losses with the integration of CHP plant is a combination of the following parts:

- Losses from HV/MV substation to the CHP plant location (AB section)
- Losses from CHP plant connection to the load (BC section)

From the diagram shown in Fig. 3.5 it can be seen that $I_{AB} = I_{BC} - I_{CHP}$.

The current flows in section BC is the $I_L$ which is the same magnitude as in case without CHP plant connected. Therefore the expression for line losses from busbar B to busbar C is given as:

$$Loss_{BC} = \frac{r(L_{AC} - L_{AB})\left(P_L^2 + Q_L^2\right)}{3V_P^2} \qquad (3.9)$$

Expression for line losses from busbar A to CHP plant connection is given as:

$$Loss_{AB} = \frac{rL_{AB}\left(P_L^2 + Q_L^2 + P_{CHP}^2 - Q_{CHP}^2 - 2P_L P_{CHP} - 2Q_L Q_{CHP}\right)}{3V_P^2} \qquad (3.10)$$

Total line losses in the feeder shown in Fig. 3.5 are given by :

$$Loss_{Total} = Loss_{AB} + Loss_{BC} \qquad (3.11)$$

The assumption that CHP generation will always reduce UDN losses is not valid [153]. From a number of studies it can be concluded that CHP plant will contribute to the reduction of UDN losses when CHP plant output reduces power flows across the UDN. This is likely to happen when the CHP generation penetration and concentration is relatively low. The studies also indicated that increase in UDN losses will follow a high penetration and high concentration of CHP generation in the UDN . Finally, specific location analysis of a part of a UDN, and CHP plant operation as a function of time will have to indicate whether CHP generation will increase or decrease the losses in a particular part of UDN.

### 3.2 Environmental – Economic Impact

Although CHP generation is recognised by many researchers for its energy-savings and environmental and economic benefits, a method has not been fully developed to quantify non-energy related benefits such as transmission and distribution or to evaluate who will benefit and to what extent from the CHP generation installation in urban area. CHP generation installed in an urban area can be seen as facilities that generate three different products: thermal energy, electricity and energy efficiency resource that manifests as a reduction for additional electricity generated by central power generation stations and as a consequence reduced electrical losses in UDN [145]. CHP systems up to 1MW are found across all sectors, but they normally serve as energy sources for SMEs and institutional sectors very well. In that context these products manifested themselves as benefits to the CHP scheme developer, UDN utility and to society as a whole. Valuing these benefits has not always been straight forward, and the energy efficiency CHP resource has been filled with questions about appropriate valuation. Nevertheless CHP generation is often thought of as an energy efficient energy generation. However it is not static like some energy resources but offers benefits to the UDN beyond just reduced consumption and demand. CHP system developers chose to implement a CHP system as a means of energy supply because it will cost them less to meet their onsite energy needs compared to purchasing separate heat and power. The efficiency benefits of getting more useful energy out of a fuel are accompanied by the ability to accommodate multiple fuels. In addition the amount of energy that can be generated by the CHP plant may exceed energy needed by the CHP owner, creating an opportunity to sell excess electricity to the network for profit if such an option is available. The flexibility of a CHP plants allows the plant developer to tailor the design and use of the CHP plant to respond to real time market. CHP plant can also be built much faster than most other alternative types of energy generation. The actual installation time of CHP plant within urban area is less than that of centralised power generation plan, reducing the cost and risk of the network assets and allowing them to more tightly link generation supply with customer demand [155]. The economic viability of CHP generation is based on the several methods that include: the internal rate of return (IRR), the net present value (NPV), the payback time and operating costs [156, 157].

Once a developer of a CHP scheme is satisfied with the approximate payback period, a simple procedure of economic feasibility may be estimated using chart shown in Fig. 3.6 The capital cost is based on the size and type of system design while the operating cost includes normal operation and maintenance costs, fuel costs and also electrical costs. Having the potential to play a major role as a complement or alternative to energy supply, CHP generation system with operational efficiency and flexibility yield real economic benefits to the CHP generation developer and UDN utility. The increasing dispersion of CHP generation within urban areas calls for deeper analysis aimed at evaluating the sustainability of local energy generation and its environmental impact [159]. In particular CHP generation technologies enable enhanced energy efficiency and thus greenhouse emission saving with respect to the conventional separate heat and power (SHP) generation. Since CHP generation reduces actual fuel used to generate energy for on-site needs and as an consequence emission of greenhouse gases are reduced as well. Emissions are reduced directly by fuel reduction gain by CHP generation at the point of energy consumption on the UDN and in addition avoiding the UDN losses and excess generation needed to mitigate the UDN and transmission system losses.

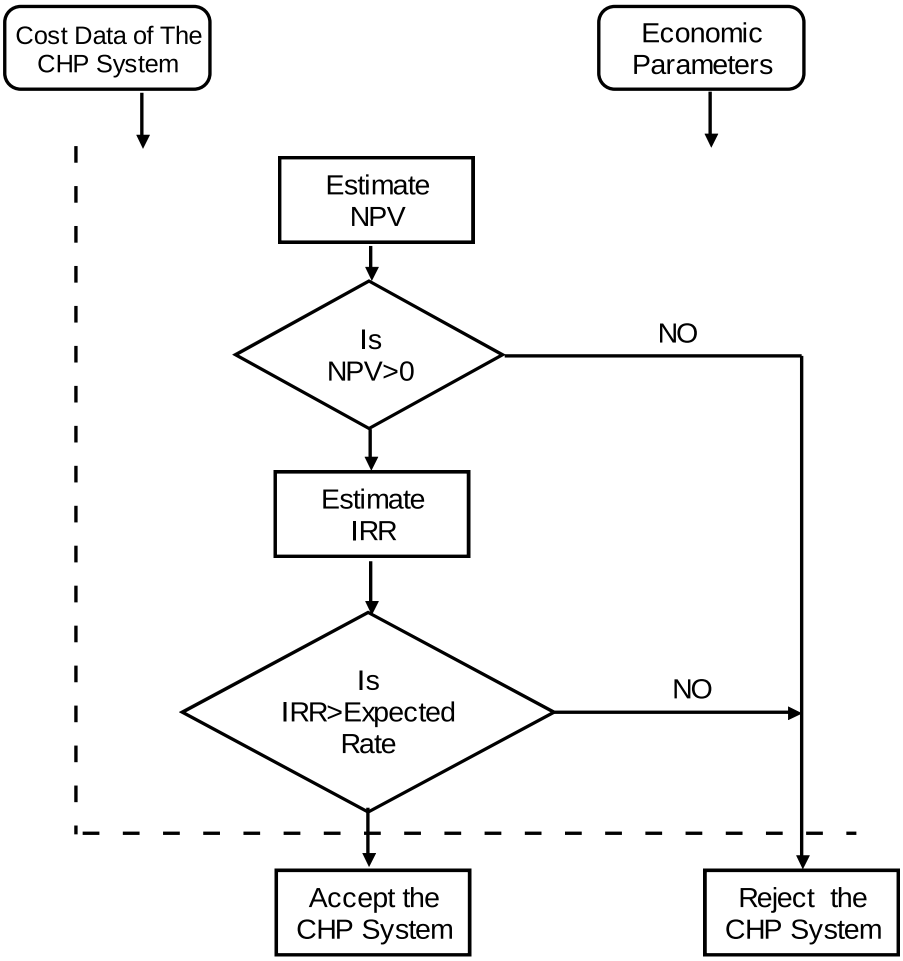


**Fig. 3.6 Flowchart of CHP Plant Economic Analysis (adopted from [158])**

With CHP generation being the most popular alternative energy supply for SMEs located in urban areas, where air quality standards are often stringent because of the high population density and in many cases with environmental assessment tending to be conservative thus leaving reduced margins, the development of CHP generation in most cases is very limited. These limitations demand a detailed evaluation of the CHP generation at the planning stage. Hence, the environmental assessment of CHP generation has to be carried out not only on the basis on the full load performance but in time operating conditions. This aspect is even more relevant considering that the CHP plants can be controlled to achieve specific objectives of thermal and electrical load tracking. For that reason, the expected increasing penetration of CHP generation into urban areas brings new important issues for both regulators and energy service planners and these include local and global emission as described in [160, 161].

The evaluation of the impact of CHP plant installation on local emission is well-documented and if equipment technology has been specified, then the data can be obtained from the equipment manufacturer. In a case of global or remote emissions displacement calculations, the procedure is not as straightforward as the local emissions calculations. The determination of remote emissions needs a model based on a complex algorithm which includes: what type of generation will be displaced, price, location, emissions limits, integrated within national framework in order to determine how and when electrical generation is dispatched.

For the purpose of this document data used for emissions calculations shown in Fig.3.7 are based on annual energy output of CHP plant located at Rochestown Park Hotel in Cork City. Full performance analysis of the CHP plant can be found in Appendix 7 and [115]. To quantify the emission savings of a CHP plant can be determined by subtracting the emission generated by CHP plant from the emission generated by SHP generation for the same amount of energy delivered to the consumers. These calculations are based on the following algorithm described in detail in [115, 162].

$$E_S = (E_{thermal} + E_{elec}) - E_{CHP\ emission} \qquad (3.12)$$

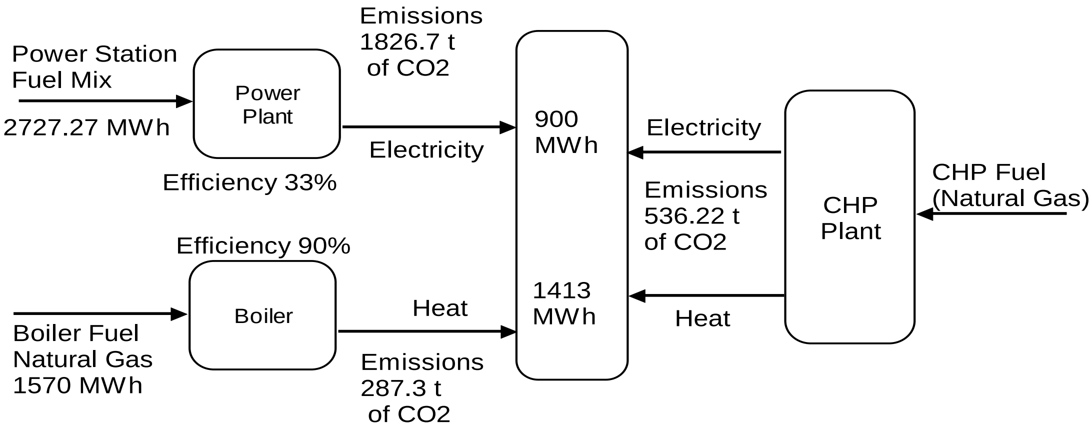


**Fig.3.7 Typical $CO_2$ Emission: CHP generation versus SHP generation**

$E_S$ – $CO_2$ emission savings

$E_{thermal}$ - $CO_2$ emission generated by separate heat production

$E_{electricity}$ - $CO_2$ emission generated by separate electricity production

$E_{CHP\ emission}$ - $CO_2$ emission generated by CHP generation

Radical changes occurred in the energy supply in urban areas in the last two decades with a clear trend towards shifting part of the energy generation from large centralised plants to relatively small decentralised privately owned CHP plants. The diffusion of CHP generation in urban area can bring substantial improvements: in energy efficiency, primary fuel and emission savings as well economic benefits, with respect to the separate generation of electricity in the centralised power system and thermal energy in local boilers.

## 3.3 UDN Performance (Test Case)

In general all UDNOs maintain detailed databases describing the electrical characteristics of the their networks. This data can be used to analyse the network response to in any operational events and network configurations, during maintenance and in the event of a particular network failure. Prior to the connection of CHP plant at any point in the UDN, the UDNO normally performs a number of preliminary operational tests such as load flow and fault current analysis in order to establish the existing network operational constraints that could be adversely influenced by the new CHP plant connection. After establishing the existing network operational constraints, based on the analytical and statistical analysis of the results obtained from a number of tests that include load flow and fault level analysis perform by the ERAC power analysing software will allow the UDNO to define the size and operational pattern of the CHP plant that is intended to be connected at a particular location in the UDN. The methodology for this preliminary test is tested on a 34 busbar network resembling the part of UDN of Cork City shown in Fig.3.8 These preliminary tests focus on the feeder containing six 10.5 kV busbars (B2; B11; B12; B13; B14; B15) and seven 0.4kV busbars connected to the busbars listed above with four CHP systems connected at 0.4 kV busbars ( B11-2; B12-1; B13-1; B15-2). Load flow and fault level calculation are performed using ERAC power analysing software. These calculations are performed with the following assumptions that CHP plant with output of 750kW and 250kVAr is connected on low voltage busbar B14-1 and local load connected on three busbars (B15-1; B15-2 and B14-1) while will vary according to six scenarios according defined by UDNO and shown in Table.3.1

**Table 3.1 Loading scenarios**

| Busbar ID | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|
| B14-1 | 200kW<br>65kVAr | 400kW<br>130kVAr | 500kW<br>170kVAr | 600kW<br>200kVAr | 800kW<br>270kVAr | 950kW<br>310kVAr |
| B15-1 | 320kW<br>100kVAr | 640kW<br>220kVAr | 800kW<br>270kVAr | 960kW<br>320kVAr | 1280kW<br>400kVAr | 1420kW<br>455kVAr |
| B15-2 | 200kW<br>65kVAr | 400kW<br>130kVAr | 500kW<br>170kVAr | 600kW<br>200kVAr | 800kW<br>270kVAr | 950kW<br>310kVAr |

For each scenario, the calculations are performed for two situations where CHP plant connected on busbar B14-1 and B11-1 respectively when CHP plant is OFF and ON. [Note: results obtained for situation when CHP plant is connected on B11-1 are presented in Appendix 10]. Results from these calculations are used to assess the main technical constraints that are normally encountered when assessment of the CHP connection into the UDN is performed. These assessments include:

- Voltage profile assessment,
- Fault level assessment,
- Equipment thermal limits assessment,
- Network power loss assessment.

The outcomes of these assessments are evaluated and limitations related to the size, operational arrangement of CHP plant are determined for a particular location in the UDN where the CHP plant is connected. In addition to the above mentioned evaluation, the network reinforcement cost, network losses and network capacity replacement value related to the CHP plant integration needs to be evaluated. These costs are evaluated in light of the network technical standards listed in Appendix 3, against which the UDN is planned and operated. When those standard are met, the connection costs are evaluated in line with the LCTA principle explain in Chapter 6. In this test case it is expected that connection of CHP plant at busbar B14-1 will result in some changes to the operational characteristics of the network. Results obtained from the load flow and fault level studies performed on the network that is shown in Fig.3.8.

The connection of CHP plant generator will tend to increase local voltage levels on the network close to the point where CHP plant is connected. This voltage rise can be in conflict with the UDN operational practice, particularly in circumstances where CHP plant is connected at a busbar used to supply customer load and where CHP plant exceeds the local electrical energy demand. Results obtained by the Load flow analysis shown in Table 3.2 shows voltage profile on a number of busbars under observation:

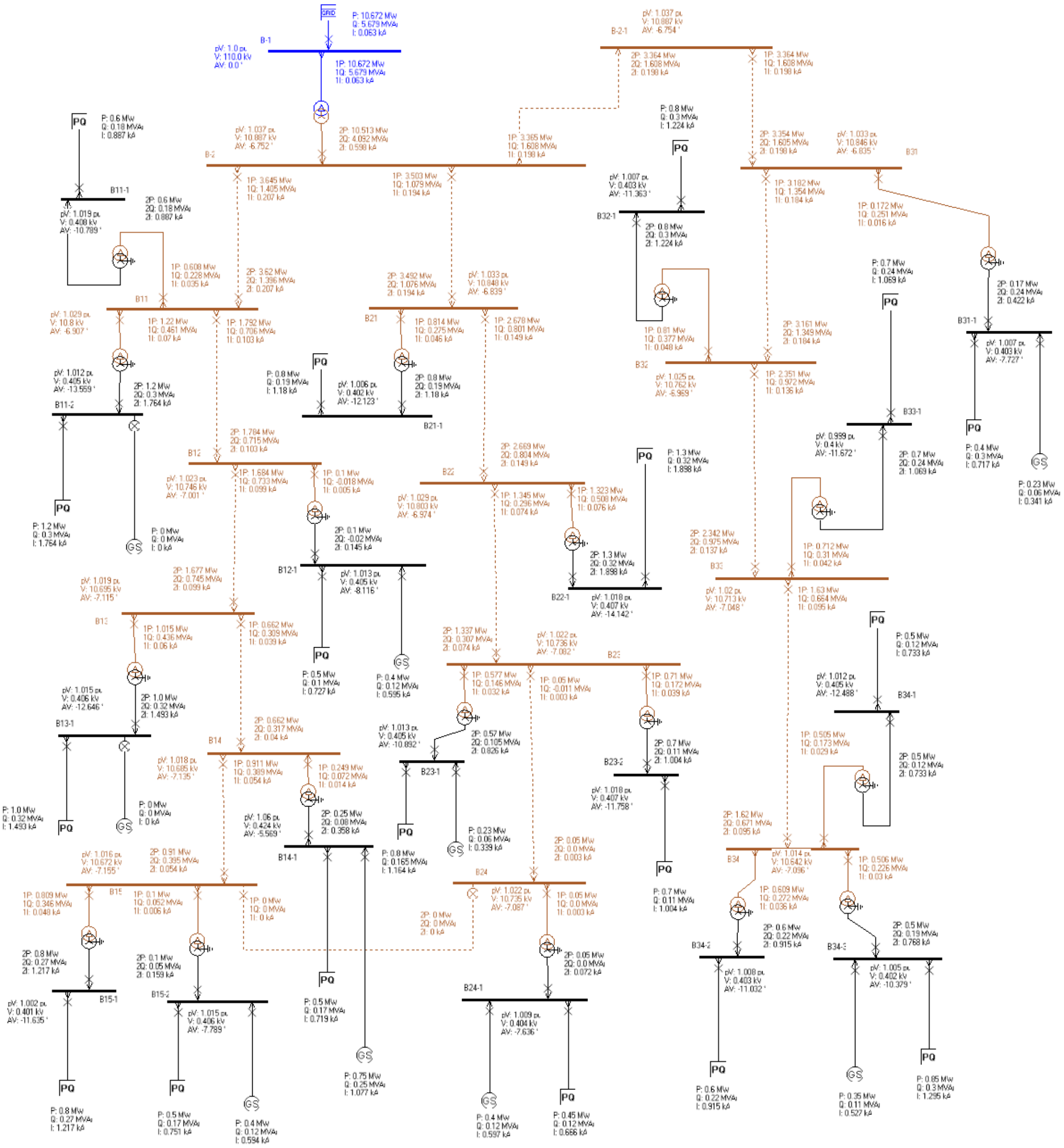


**Fig 3.8 Part of Urban Distribution Network (UDN) under test (see Appendix 6 for the network equipment specification)**

**Table 3.2 Voltage profile on the busbars under analysis**

| Busbar | CASE 1 | | CASE 2 | | CASE 3 | | CASE 4 | | CASE 5 | | CASE 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | V (kV) | | V (kV) | | V (kV) | | V (kV) | | V (kV) | | V (kV) | |
| | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON |
| B2 | 10.93 | 10.989 | 10.856 | 10.925 | 10.813 | 10.887 | 10.769 | 10.85 | 10.669 | 10.765 | 10.597 | 10.706 |
| B11 | 10.853 | 10.93 | 10.759 | 10.847 | 10.706 | 10.8 | 10.652 | 10.754 | 10.529 | 10.648 | 10.442 | 10.575 |
| B12 | 10.81 | 10.909 | 10.694 | 10.805 | 10.628 | 10.746 | 10.561 | 10.688 | 10.41 | 10.556 | 10.305 | 10.468 |
| B13 | 10.771 | 10.89 | 10.631 | 10.764 | 10.553 | 10.695 | 10.474 | 10.625 | 10.296 | 10.469 | 10.172 | 10.364 |
| B14 | 10.767 | 10.894 | 10.617 | 10.76 | 10.534 | 10.685 | 10.449 | 10.61 | 10.259 | 10.444 | 10.127 | 10.332 |
| B15 | 10.765 | 10.893 | 10.608 | 10.751 | 10.52 | 10.672 | 10.432 | 10.593 | 10.232 | 10.418 | 10.095 | 10.301 |
| B21 | 10.891 | 10.95 | 10.816 | 10.885 | 10.773 | 10.848 | 10.729 | 10.81 | 10.628 | 10.725 | 10.556 | 10.666 |
| B31 | 10.889 | 10.948 | 10.814 | 10.884 | 10.771 | 10.846 | 10.728 | 10.809 | 10.626 | 10.723 | 10.555 | 10.664 |

These results are showing voltage profile on eight selected critical busbars under six scenarios representing different loading conditions in both situations when CHP plant is OFF and ON. Using these results, the UDNO will be in a position to advise what is the voltage profile that can be allowed on the particular selected busbars with CHP plant connected. These results and method and how they are used are discussed in more detail in section 3.4. In Chapter 4 the outcome of this analysis will be used as data in the procedure used to determine optimal size of the CHP plant that can be connected at any busbar in question.

One of the effects of connection of CHP plant into the UDN is an increase of fault levels close to the point of CHP plant connection. The magnitude of the fault current that can be accepted is normally determined by the rating of the switchgear in the area of the CHP plant connection. Results obtained from fault level analysis are shown in Table 3.3 and Table 3.4

**Table 3.3 Three Phase Fault Current on busbars under analysis- CHP plant OFF**

| Three Phase Fault Table | | CHP OFF | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Case 1 | | Case 2 | | Case 3 | | Case 4 | | Case5 | | Case 6 | |
| Busbar ID | Specified Rating (kA) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) |
| B-2 | 13.746 | 3.567 | 25.949 | 3.565 | 25.934 | 3.565 | 25.934 | 3.561 | 25.905 | 3.560 | 25.898 | 3.558 | 25.883 |
| B21 | 13.746 | 3.403 | 24.756 | 3.400 | 24.734 | 3.398 | 24.719 | 3.396 | 24.705 | 3.391 | 24.668 | 3.388 | 24.646 |
| B31 | 13.746 | 3.392 | 24.675 | 3.389 | 24.654 | 3.387 | 24.639 | 3.385 | 24.625 | 3.380 | 24.588 | 3.377 | 24.566 |
| B11 | 13.746 | 3.250 | 23.642 | 3.248 | 23.628 | 3.247 | 23.621 | 3.247 | 23.621 | 3.244 | 23.599 | 3.243 | 23.592 |
| B12 | 13.746 | 2.901 | 21.104 | 2.899 | 21.089 | 2.897 | 21.075 | 2.896 | 21.067 | 2.894 | 21.053 | 2.892 | 21.038 |
| B13 | 13.746 | 2.569 | 18.688 | 2.566 | 18.667 | 2.565 | 18.659 | 2.564 | 18.652 | 2.561 | 18.630 | 2.558 | 18.608 |
| B14 | 13.746 | 2.441 | 17.757 | 2.438 | 17.736 | 2.437 | 17.728 | 2.435 | 17.714 | 2.432 | 17.692 | 2.430 | 17.677 |
| B15 | 13.746 | 2.325 | 16.913 | 2.322 | 16.892 | 2.320 | 16.877 | 2.318 | 16.863 | 2.314 | 16.833 | 2.311 | 16.812 |

**Table 3.4 Three Phase Fault Current on busbars under analysis- CHP plant ON**

| Three Phase Fault Table | | CHP ON | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Case 1 | | Case 2 | | Case 3 | | Case 4 | | Case5 | | Case 6 | |
| Busbar ID | Specified Rating (kA) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) |
| B-2 | 13.746 | 3.811 | 27.724 | 3.800 | 27.644 | 3.799 | 27.614 | 3.799 | 27.60 | 3.783 | 27.520 | 3.776 | 27.470 |
| B21 | 13.746 | 3.625 | 26.370 | 3.615 | 26.298 | 3.610 | 26.261 | 3.605 | 26.225 | 3.593 | 26.138 | 3.584 | 26.072 |
| B31 | 13.746 | 3.612 | 26.276 | 3.603 | 26.210 | 3.597 | 26.167 | 3.592 | 26.130 | 3.580 | 26.043 | 3.572 | 25.985 |
| B11 | 13.746 | 3.502 | 25.476 | 3.493 | 25.410 | 3.488 | 25.374 | 3.483 | 25.337 | 3.471 | 25.250 | 3.463 | 25.192 |
| B12 | 13.746 | 3.159 | 22.981 | 3.149 | 22.908 | 3.143 | 22.864 | 3.138 | 22.828 | 3.125 | 22.733 | 3.115 | 22.660 |
| B13 | 13.746 | 2.831 | 20.594 | 2.820 | 20.514 | 2.814 | 20.471 | 2.808 | 20.427 | 2.795 | 20.333 | 2.785 | 20.260 |
| B14 | 13.746 | 2.704 | 19.671 | 2.694 | 19.598 | 2.687 | 19.547 | 2.681 | 19.503 | 2.668 | 19.409 | 2.658 | 19.336 |
| B15 | 13.746 | 2.566 | 18.667 | 2.556 | 18.594 | 2.549 | 18.543 | 2.543 | 18.499 | 2.530 | 18.405 | 2.520 | 18.332 |

These results show contribution of connected CHP plant to a fault level at a number of critical busbar selected by the UDNO under different loading scenarios. These results could be used to determine the impact on protection and breaking UDN facilities and corresponding cost allocated to the CHP plant developer. In Section 3.4 detailed account of fault analysis will be given and result of these preliminary fault analysis combined with voltage profile preliminary analysis results will be used in determining optimal size of CHP plant at any busbar in question in line with LCTA principle explained in chapter four.

In the last two decades, one of the important issues appearing in de-regulated electricity markets is allocation of power losses in MV/LV network. It becomes a very significant issue as losses in a UDN are in the range 3-6%. The impact of CHP plant connection on electrical energy losses in the UDN is estimated by calculating the power losses for several cases representing different load consumption levels on a number of busbars in the feeder. This analysis is performed with one load flow calculation for each case. Results extracted from load flow analysis indicated the total amount of power losses for two different scenarios (CHP plant OFF and CHP plant ON) in the feeder under observation are shown in Table 3.5

**Table 3.5 Total Losses on the Feeder Under Analysis**

| Total Losses in (MW) | | | | | | |
|---|---|---|---|---|---|---|
| Scenarios | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
| TL CHP OFF | 0.075 | 0.108 | 0.132 | 0.161 | 0.240 | 0.303 |
| TL CHP ON | 0.064 | 0.080 | 0.095 | 0.114 | 0.169 | 0.213 |

TL CHP OFF – Total Losses CHP plant at B14-1 is OFF

TL CHP ON – Total Losses CHP plant at B14-1 is ON

## 3.4 Discussion

Traditional UDN is radial in nature characterised by a single source feeding a network of downstream feeders. Existing UDNs traditionally have not been designed to accept high penetration of CHP generation. Technical challenges that are encountered during the process of accommodating CHP generation in the UDN can, in some cases incur high reinforcement costs. Considering the main technical issues, the CHP plant connection costs are associated with upgrading of the UDN assets. With solid growth of CHP generation in the UDN a large amount of investment is needed to upgrade current UDN assets when the UDNO uses the traditional fit and forget method, that is seen as a passive network operational mode. When considering the method of connection of CHP plant or a number of CHP plants in the UDN, the UDNO considers a number of connection options. To determine the most appropriate connection option the UDNP/UDNO evaluates number of connection options according to the technical standards against which the UDN is planned and operated. When those standard are met, UDNO considers the capital cost of the equipment needed to facilitate the connection of the CHP plant or a number of CHP plants. In the case of the connection of a number of CHP plants in the UDN being processed at the same time, the LCTA principle applies to the entire group of CHP plants, not to an individual applicant [2]. In order to fulfil the LCTA principle a number of operational preliminary tests conducted on the UDN shows that CHP plant connection into the UDN affects the existing UDN in a number of ways [163]. From the results obtained from the test introduced above, it can be seen that CHP plant connection can create impacts on the technical and in some cases safety features of the UDN. Also the CHP plant connection contributes to voltage rise, fault current level, voltage control and increase/reduction of losses in the UDN. Load flow and fault level analysis are the basic tools for the UDNO in order to estimate the robustness of steady state operation of the UDN. In addition to that estimation, the operational pattern of the CHP plant must be taken into account and these patterns [2, 163, 24] will be analysed in detail in Chapter 5. These analysis will include:

i) Operate in parallel with feeder where CHP plant is designated to supply a large part of the load with fixed real and reactive power output referred to as a PQ node,
ii) Have power output at a specific power factor referred to as P (cos $\phi$) node,
iii) Have output power at a specified terminal voltage referred as a PV node,
iv) Dispatchable,
v) Non-dispatchable,
vi) Firm connection,
vii) Non-firm connection.

Based on the results obtained from load flow, fault level analysis and the analysis related to the operational pattern of the CHP plant connected in UDN, the following can be observed.

UDNOs have a statutory obligation under the Electricity Supply Regulation Act corresponding to EN 50160 provide electricity to customers within fix statutory limits +/- 10% of in EU countries of nominal voltage at any time. Typically a UDN is regulated at the HV/MV substation. Regulation is normally performed using an on-load tap changer (OLTC) on the HV side of the HV/MV transformer. The OLTC is controlled by an Automatic Voltage Control (AVC) scheme normally incorporated some form of voltage line-drop compensation. On a traditional UDN feeder, the voltage level will drop with distance from the HV/MV substation. However, the voltage level at all parts of the feeder is kept within specified limits simply by maintaining a high level on the busbar close to the source substation so that the voltage level on the far end of the feeder is kept within the limits under any operational power flow. Connecting CHP plant in the UDN will affect the power flow and consequently the voltage profile on a number of busbars in the feeder Fig 3.9

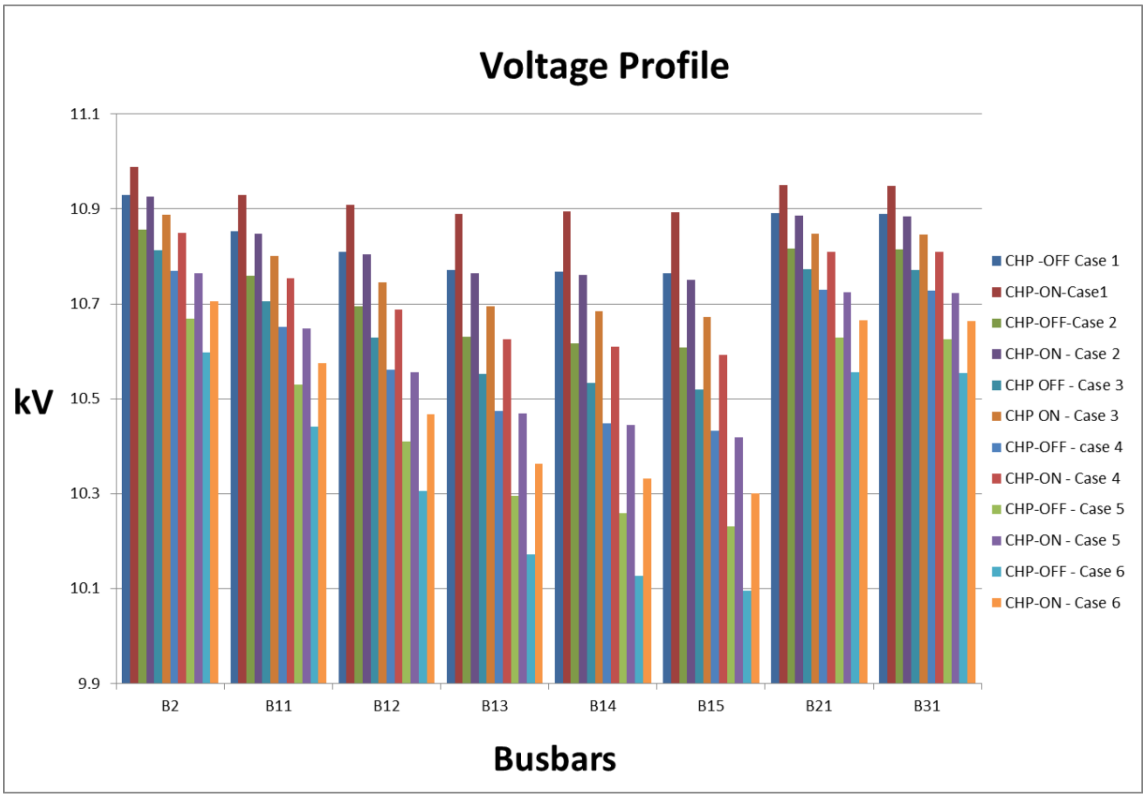


**Fig 3.9 Voltage profile on the busbars under analysis**

From the load flow analysis it can be seen that busbars B15, B14 and B13 experience voltage rise due to the CHP plant connected at B14-1. This effect on voltage profile caused by the connection of CHP plant at some point in the feeder could be in conflict with UDNO's statutory obligation towards the electricity consumers. Analysis outline above is able to analyse different operational/loading scenarios generating results that will allow UDNO to determine which feeders/busbars are critical and in need of voltage profile support in case of CHP connection. To support the statutory voltage requirements each UDNO will have its own practice on voltage control. In general these practices are similar in nature but differ in detail due to the different local factors that has to be taken into account. To deal with a new situation the UDNO has to take its own view related to the following setting that include:

- appropriate tap changer set points,
- bandwidth setting and
- time delays of OLTCs operation.

Connecting a CHP plant to the UDN has the effect on the fault levels in the UDN close to the point of connection of the CHP plant in Fig 3.10. From the fault level analysis it can be seen that busbars B15, B14, B13 and B12 experience fault level rise due to CHP plant connected at B14-1. The extent of the fault level that can be safely accommodated by an UDN is typically determined by the fault level rating of the switchgear in the area of the point of the CHP plant connection. The fault contribution from a small CHP plant is not large, but aggregate contributions of many small units can increase fault level up to the point where mal-operation of protection and breaking devices can be expected. In the event of short circuit in the UDN all generators will contribute to the fault level. Switchgear in the UDN and switchgear of the CHP plant must be rated to withstand the effects of the new combined fault level. As the point where the CHP plant becomes more remote from the HV/MV substation the intervening impedance will lower the grid fault contribution. But connection of CHP plant will tend to raise fault level at least locally. If the fault levels increase beyond the rating of existing UDN switchgear, the switchgear must be upgraded or replaced. Normally, CHP plants would not be permitted to push maximum fault level beyond the UDN and equipment designed fault level. At the same time, the absolute fault level margin of the installed CHP plant may not be easily determined, due to the uncertain knowledge of fault contribution from other secondary sources. In a case when contribution to the fault level from the CHP plant is determined, the developer of CHP plant may be required to contribute to the cost of network assets in order to accommodate the increase in the fault level associated with connection of the new CHP plant.

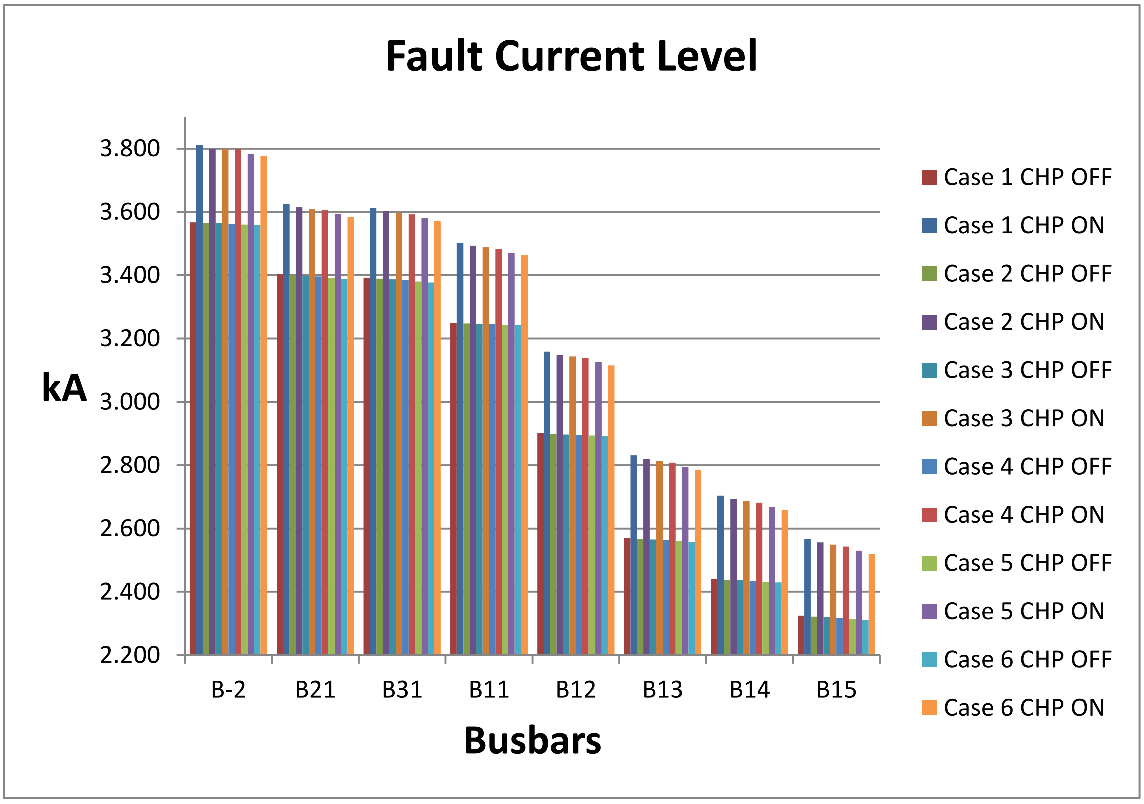


**Fig. 3.10 Three Phase Fault Current on busbars under analysis- CHP plant OFF/ON**

As pointed out in [164], transmission and distribution of electricity is still a monopoly unlike generation and sale of electricity. The cost of these services need to be minimised and allocated to the network users, namely through network use tariffs. Among other costs, power losses produced by UDN are one of the costs that need to be estimated and allocated among each UDN user. Power losses can represent a considerable percentage in UDN operation. However, similar to any other cost they must be balanced against other cost and objectives and therefore their absolute minimisation may not be always desirable. Therefore power losses are usually seen by the UDNO as a commercial issue in the planning process dealing with the connection of CHP plant into the network. During this stage of the planning process deviation of power losses produced in the

UDN as a consequences of CHP plant connection are not considered as a barrier of the degree that can hinder connection of CHP plant. The impact of CHP plant on UDN losses is determined from data obtained from power flow analysis. The impact of CHP plant connected in UDN mainly depends on the location, size and pattern of operation of CHP plant and UDN characteristics. Normally connecting the CHP plant into the busbar in the UDN will reduce power losses produced by the UDN as can be seen from Table 3.5 and Fig 3.11 These losses will be reduced even further until the CHP plant reaches load demand consumption from the same busbar or feeder area where the CHP plant is connected. In the case when CHP plant power injection capacity increases beyond the load consumption on the same busbar where the CHP plant is connected, the losses of the UDN begin to rise. Power loss determination in the UDN has two main problems: the inconsistency between losses and the delivered power, which complicates the determination of the impact magnitude of each user of the network losses. Tests described above are designed to highlight the challenges that must be overcome in the process of the integration of CHP plant into the UDN. A particular emphasis in the tests were placed on the need to shift the network planning and operating practices away from the fit and forget policy of connecting CHP plant to the UDN and operating the network through active management of UDN. Some of the opportunities that could be exploited in support of the integration and hence greater penetration of CHP generation into the UDN are also examined. Connecting the CHP plant to the existing UDN suggests an increase in the direct (investment) cost in the UDN assests. Under shallow connection [2] cost responsibility can suggest an increase in capital expenditures of the UDNO. Under a deep connection [2] cost responsibilities are passed-through to the developer of the CHP plant (as can be seen in Chapter 6).

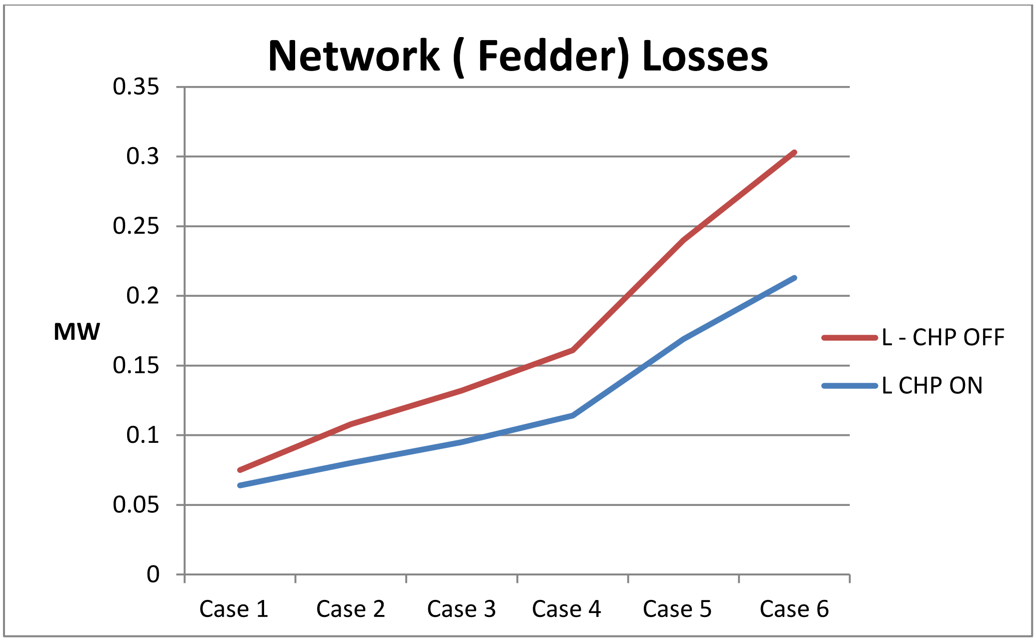


**Fig 3.11 Feeder Losses with CHP plant OFF/ON**

The CHP systems come with different sizes and with different mode of operation and are usually connected across the UDN. This creates many new problems concerning network operation. To deal with these problems, UDNOs must have concrete guidelines and standards that CHP developers can follow.

In general, the connection of CHP plant in the UDN improves the connection of CHP plant in the UDN, reduces losses and improves voltage profile. The loss reduction depends on the power injection capacity and network characteristics. If the UDN is not properly set up and the power injection from the CHP plant is high, this might cause local over-voltage and increased short-circuit currents. At present, CHP generation provides only a very small portion of total electricity demand in the UDNs. In this test case the existing penetration level of CHP generation relative to average load demand is 16.3%. In order to maximise penetration of CHP generation as a means of energy supply in light of LCTA principle, before establishing a plan for CHP generation development in a specific UDN, the UDNO must perform a number of different analysis designed for power systems analysis incorporating different operational patterns of CHP plant outlined above. In this test case, the UDNO from the results outlined above is based on the following assumption: that the CHP plant will operate for most of the day and that it will operate in PQ mode. UDNO can identify most critical points in the network which will be affected by the connection of a new CHP plant. Taking into account all limiting factors it is obvious for the UDNO the most critical points in the network are busbars: B15, B14 and B13. The constraint that is most vivid is voltage rise caused by the connection of the new CHP plant. In some cases voltage rise exceeds 3.5% of the voltage level observed under average load. From the results above, other constraints such as fault level and power losses are not so significant and could be seen as minor obstacles to the CHP plant connection at B14. In order to facilitate maximum penetration of CHP generation in the network, UDNO (based on the results of the analysis outlined above) will determine the limit of voltage level, fault level and power losses that cannot be exceeded for every critical point in the network. The magnitude of those limits are dependent on a number of factors: existing UDN operational assets well-being, future forecast of CHP generation development in the network (area), willingness of CHP developer to participate in network assets upgrade. Having these estimated results and using these as data in multiple regression analysis, the UDNO and the CHP plant developer can determine the size of the CHP plant that can cause least impact on the network at any particular point of interest and from the same analysis it can be seen which constraints are violated.

## 3.5 Conclusion

This chapter has presented an overview of the key issues concerning the integration of CHP plant into the UDN. The most interested participants for these issues include: UDN planners and operators, CHP plant developers and UDN electricity consumers.

Performing these preliminary tests and analysis on the network, provide a chance to the UDNO to determine the optimum size and location of the CHP plant that can be connected in the UDN feeder of interest under the LCTA principle. In addition, results obtained from the above analysis allowed the UDNO to indicate cost allocation associated with the connection of CHP plant.

The costs of integration and benefits of CHP generation are likely to be UDN specific. The impacts are driven by a set of parameters that include: CHP generation penetration level, distribution of CHP plants across the UDN, CHP plant sizes, correlation between CHP plant output and load, UDN characteristics, UDN headroom, UDN reinforcement costs and UDN structures. The aim of this chapter is to provide a framework and methodology for estimation of magnitude of adverse impacts and benefits instigated by the connection of CHP plant in the UDN from the studies on the network shown in Fig 3.8. The chapter also highlights the key impacts which will affect the integration costs of the CHP plant into the UDN.

# Chapter 4 Optimal Capacity Allocation of CHP Generation in a UDN

## 4.1 Development of the Optimisation for a CHP Generation Plant Allocation in UDN

Recent research has shown that urban areas are responsible for nearly two-thirds of global primary energy consumption [167, 168]. As a result, there is a growing interest in improving the energy efficiency of urban areas so that environmental impacts are reduced while at a same time maintaining economic opportunity and quality of life. One of the most significant areas of improvement is the integration of energy sources such as electrical and thermal energy supply. A CHP generation is one of the few technologies that can provide a substantial short or medium term impact on the energy efficiency in urban areas and therefore can make a positive contribution to the environmental policies of the EU. Use of CHP generation as a means of energy supply in urban area could significantly change the paradigm of electrical energy management in the UDN. It converts the traditionally passive network into an active one and therefore impacts the flow of power and voltage conditions at customers and the UDN equipment. These impacts may manifest themselves either positively or negatively depending on the UDN operating characteristics and CHP plant characteristics. The impacts of the CHP plant on UDN operational characteristics, such as: voltage profile, fault level, losses and stability requirements needs to be properly estimated. The problem of CHP plant allocation and sizing is of great importance for the UDN planner and UDNO. The installation of CHP plant at non-optimal places can result in having an outcome opposite to the desired. For that reason the use of an optimisation method capable of specifying the best solution for a given UDN can be very beneficial for the UDNP/UDNO especially when dealing with the increase of CHP generation penetration that is happening at present in urban areas.

In liberalised energy supply markets development of an optimisation framework for a CHP generation plant allocation in the urban area is an absolutely vital tool for urban utility operators. The optimisation framework is based on the idea of evaluating all CHP generation plant issues regarding many operational scenarios related to energy supply of SMEs (likely developer of CHP generation) in regulated UDN. A CHP plant value function is proposed to enable UDN planners and strategist to measure the impact of the CHP plant on all aspects of UDN operational performance. This optimisation framework make possible for a UDNO to formulate its response to the CHP plant developer regarding the impact of CHP plant on number of the UDN key strategic issues that include [169]:

- How much CHP generation will appear in the UDN,
- What impact will the CHP generation have on the technical performance of the network,
- What impact will the CHP generation plant have on the environmental and financial performance of the UDN,
- What changes in the technical design and commercial practice in the UDN will be effective to accommodate CHP generation.

These issues can introduce limits on the size of the CHP plants and as consequences of these limits restrict the overall efficiency of the urban energy system, potentially making it difficult to achieved anticipated energy efficiency and greenhouse gas restriction objectives. The aim of this optimisation framework is to recognize how such issues might quantitatively affect the performance of urban energy system. Fig 4.1 shows a optimisation framework incorporating, technical, environmental, economic and regulatory constraints affected by the CHP plant connection.

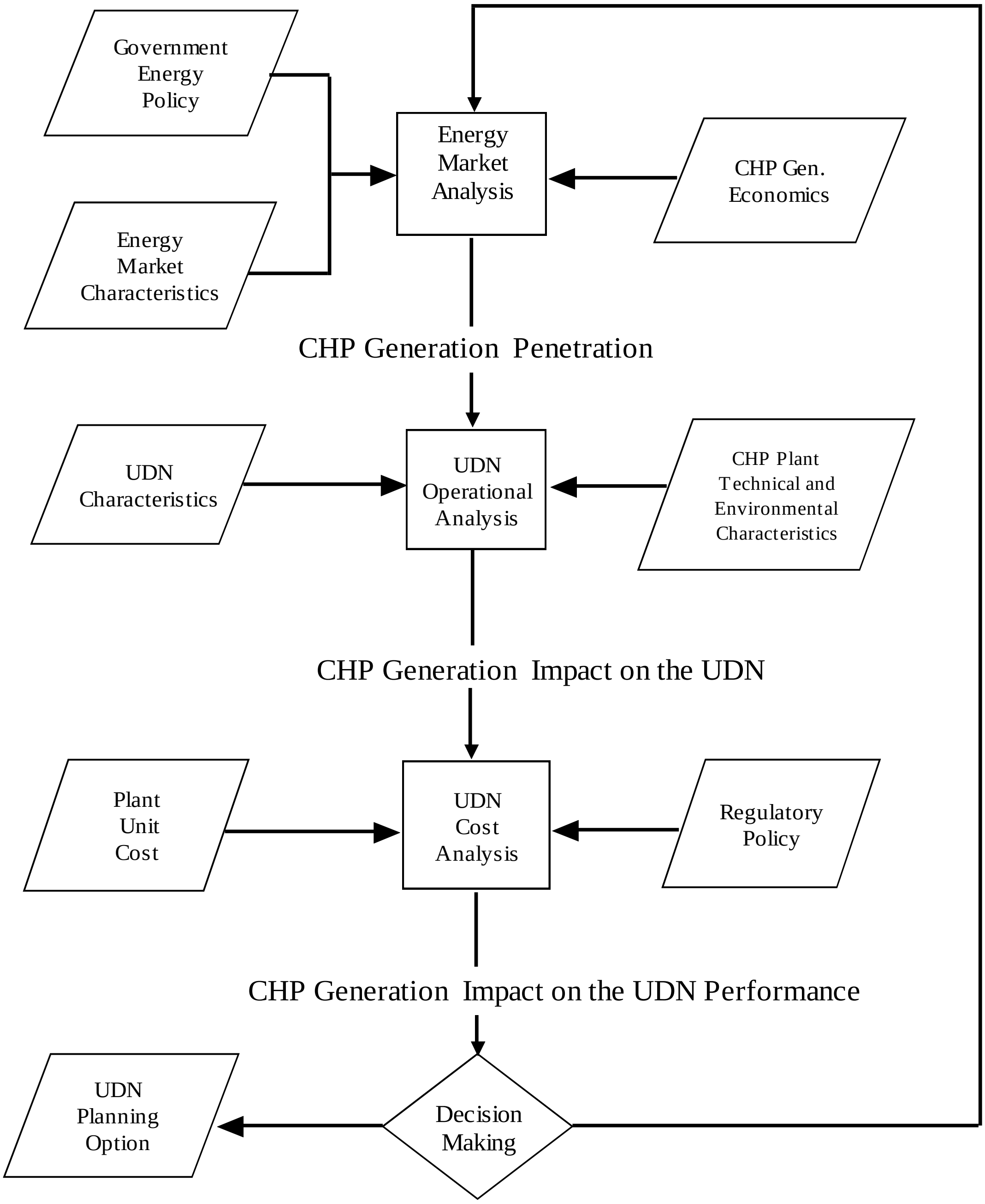


**Fig 4.1 Broad CHP Plant Connection Framework Analysis ( adapted from [169])**

All these constraints must be systematically investigated before CHP system connection can be effectively followed. In order to do that a number of specifics regarding the constraints must be examined in detail and these include:

- Understanding the CHP generation technological impact on urban energy supply
- Assessing the kind of CHP generation penetration in the UDN
- Quantifying the power quality problems introduced by CHP system integration

- Development of planning procedures for integration of CHP system into the UDN
- Designing interface between the CHP system and existing UDN
- Flexibility quantification introduced by CHP system connection
- Defining new operational characteristics of the UDN

With these examinations completed, the framework can be used for modelling the impact of CHP system on the UDN performance and in addition to fulfil an important task for the UDNP that consists of finding optimal siting and sizing of CHP systems for a given network so that cost of the CHP plant connection and the investment for the UDN upgrades can be minimised and in some case deferred.

### 4.1.1 Objective Functions

The main objectives of the methodology employed to maximise of penetration of DGs/CHPs system in a UDN are based on the maximisation of the amount energy secured per euro of investment by making the best use of the existing UDN assets and available energy resources explain in detail in chapter 6. This is done subject to the economic, environmental and most importantly technical constraints on the network. From the point of view of the UDNP/UNDO and their responsibility, the optimisation is carried out primarily to utilise the available capacity optimally and to facilitate increasing penetration of DG/CHP systems, while at a same time maintaining the standard of supply to the electricity consumers. In most realistic optimisation problems, particularly those applicable in energy supply systems, there are more than one objective function which should be optimised at the same time. In general every multi-objective optimisation problem consists of several objectives and several equality and inequality constraints. The objectives such as low losses, minimum cost, high degree of reliability and maximum environmental benefits which are the most important objectives in DGs/CHPs planning process. From the CHP generation developer and the network planner, these objectives can be summarised under three categories and these are: economical, reliability and environmental protection optimisation objectives shown below [172]

Optimisation objectives:

➢ Economical

- Increased CHP plant efficiency
- Reduce installation and maintenance cost
- Least cost for the UDN assets upgrade
- Increased UDN operational efficiency

➢ Reliability

- Adequacy of the UDN voltage profile
- The UDN power flow balance
- Adequacy of the UDN capacity adequacy
- The UDN power quality

➢ Energy savings and environmental protection

- Reduce the UDN (power system) losses
- Maximise the capacity of installed CHP system
- Greenhouse gas emission reduction

To determine the relative importance of each optimisation objective a broad strategic framework analysis shown in Fig 4.1 should be performed. The issues involved in setting optimisation objectives in order to maximise penetration of CHP generation into the UDN include: perspective on energy market characteristics; UDN technical characteristics and UDN operational economical characteristics.

The process of achieving these objectives can be described with common objectives functions outlined below:

- Minimisation of the investment cost:

$$minF_{cost} = min\left[\sum_{i=1}^{N_{CHP}} (C_{i1} + C_{i2})\, P_{CHPi}\right] \qquad (4.1)$$

Where $N_{CHP}$ is the total number of busbars to install CHP plants, $P_{CHPi}$ is the rated electrical power output of CHPs installed at each busbar, $C_{i1}$ and $C_{i2}$ are installation and equipment costs ( normally €/MW) of CHPs unit installed at each busbar i.

- Maximise consumers energy savings

$$maxF_{Energy\ Savings} = \max\left(\sum_{i=1}^{M} E_i\right) \qquad (4.2)$$

where: M is the number of customers with CHP plant at each busbar i, $E_i$ energy savings of each customers supplied from busbar i.

- Maximise the capacity of the connected CHP generation in the entire network under consideration of the local UDNO.

$$maxF_{CHP\ Cap} = max \sum P_{CHP} \qquad (4.3)$$

where: $P_{CHP}$ is active electrical power output of CHP plants in the UDN.

- Minimise UDN/Grid losses

$$\min F_{UDN/Grid} = minP_{losses} \qquad (4.4)$$

where: $P_{losses}$ is UDN/Grid losses due to size and location of CHP plants (see section 6.2.4)

### 4.1.2. Constraints

The new situation created by high penetration of DG/CHP system into a UDN creates a number of problems for UDNP/UDNO including: operational, safety, environmental and economic performance of the network. The increased share of DG/CHP generation influences the planning and operation of the UDN. DG/CHP plants are typically connected to the UDN at low voltage. Not being designed to connect power generation systems, the connection of DG/CHP systems can create problems regarding stability and power quality of supply. A major problem with DG/CHP plants connected into the UDN is that these units operate independently of the local network energy demand posing a challenge for UDNP/UDNO. In addition CHP plant that could be centrally dispatched is intended to operate in response to the thermal energy demand of the local installation rather than the needs of the UDN electrical energy demand. The more DG/CHP plants connected to a UDN the bigger the challenges of planning and operating is imposed on the UDNP/UDNO. Network constraints hampering the connection of DG/CHP plants can be solved to a certain extent by reinforcing the capacity of the UDN. But, from an economic point of view this is not always attractive as it may require large, long-term investment. However, in the real world all constraints such as UDN and DG/CHP plant technical and operational constraints, environmental and economic constraints should be considered because they reduce the feasible space for installation of the DG/CHP facilities:

#### 4.1.2.1. Pattern of Customer Energy Demand

In general, energy consumption has been recognised as one of the most important indicator in describing economic growth and society development. There is a strong two-way relationship between energy consumption and economic development and therefore understanding energy consumption patterns is extremely important for optimisation of utility energy distribution assets and efficient application of energy generation. In the case of electricity supply in urban areas, consumers expects to receive continuous service with properly regulated voltage and frequency. With a load that varies in size, time of use of service (diversity), period of use (load factor), service voltage, power factor, instantaneous peak, location and requirement that load be supplied at any time makes it necessary for supply authority to provide facilities for the maximum energy requirements of consumers. Thus, the nature of electricity demand dictates the type, size and timing of supply needs. Electricity demand in urban area is dynamic in nature and varies significantly from moment to moment, hour to hour, day to day and season to season. But changes in electricity demand levels in an urban area are generally predictable and have daily, weakly and seasonal pattern as described below [171]:

- Daily patterns:

Demand levels rise through the day and tend to be highest during a block of hours referred to as "on-peak" which usually occurs between 7:00 am and 10:00pm on weekdays

- Weekly patterns:

Demand levels are generally lowest between 10:00 pm and 7:00 pm on weekdays . This is usually referred as "off-peak".

- Seasonal patterns:

Demand levels during the summer and winter months tend to be higher than demand levels during the spring assuming that demand for space conditioning (heat or cooling) is low. The annual peak of hourly, daily and monthly demand typically occurs during the winter or summer.

Due to the lack of any significant capacity energy storage facilities the system operators must match electricity demand with supply in real time, with very tight tolerance at all times. Any significant imbalance could cause the network instability or severe voltage and frequency fluctuations and cause failures within the network. Electricity supply capacity is sized to match the network peak demand with some margin of error and allowance for contingency. Network operators generally plan to use the least expensive distribution and generating capacity at any time. With regard to the consumers with desire to install a CHP system, energy demand pattern will be a significant factor in determining the size and the connection method of the system into the UDN.

#### 4.1.2.2. Short Circuit Level

When it is proposed to connect DG/CHP plant into the UDN, consideration must be given to the contribution of the new DG/CHP plant towards the short-current levels on the UDN. In the case of a short–circuit fault in the UDN all generators connected into the UDN will contribute to the fault current as shown in Fig. 4.2. Depending on characteristics such as the existing penetration level of DG/CHP plants in the UDN, the location and size of DG/CHP plant, protection system may lose coordination with new DG/CHP plant connected into the UDN. Circuit breaker capabilities and settings of protective devices that were previously designed for the UDN may not safely and properly manage the faults in the UDN with new DG/CHP plant connected. Normally short circuit current estimation is done using statistical analysis of size of new DG/CHP plant output and load variation at busbar under consideration. This estimation analysis could be used as on-line assessment of short-circuit current to assist an UDNP/UDNO to avoid/mitigate undesired operational conditions. The safe operation of the DG/CHP plant operation in the UDN depend upon accurate assessment of the short-fault current contributions made by all plants operating in UDN at instant of the short-circuit fault in the network.

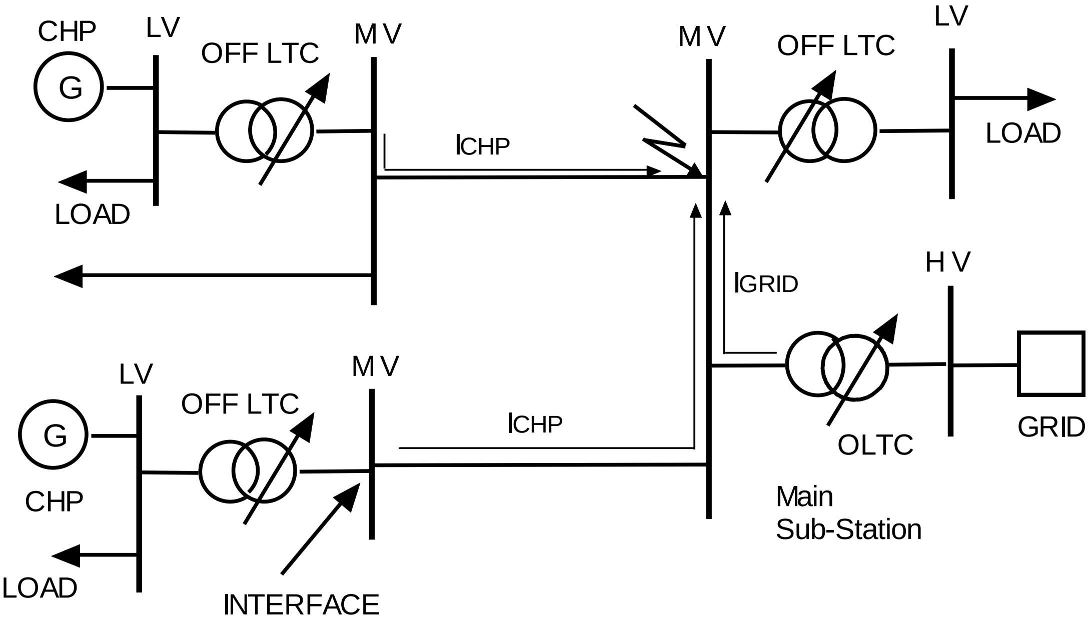


**Fig. 4.2 Schematic illustration of CHP plants contribution to fault current level (adapted from [172])**

In order to minimise and in some case eliminate the cost for the upgrading of protection and interrupting devices in the UDN the following limitation described by equations (4.5) and (4.6) must be observed.

$$I_{SC,i}^{with\ DG/CHP} \leq I_{SC,i}^{Rated} \quad (4.5)$$

$$S_{SC,i}^{with\ DG/CHP} \leq S_{SC,i}^{Rated} \quad (4.6)$$

where:

- $I_{SC,i}^{with\ DG/CHP}$ and $I_{SC,i}^{Rated}$ are the calculated short circuit current at the bus i and its rated value respectively.
- $S_{SC,i}^{with\ DG/CHP}$ and $S_{SC,i}^{Rated}$ are the calculated short circuit VA at bus i and its rated value respectively

### 4.1.2.3. Voltage Rise Level

Growing customer demand for high power quality in urban area due to the use of sophisticated electrical equipment puts an extra responsibility on UDNO to provide quality of the supply within the parameters set down by the network regulator. A key feature of supply quality in a UDN is the optimum application of voltage levels at all points in the network. The voltage of the UDN is normally regulated by using an online tap-changing transformer as shown in Fig.4.3

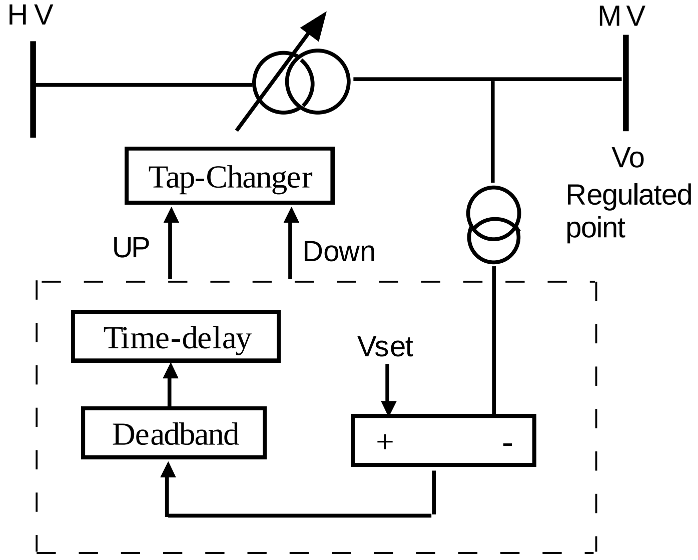


**Fig. 4.3 Typical OLTC arrangement in UDN (adapted from [173])**

Normally restricted to one method of voltage control, the UDNO (prior to allowing the connection of DG/CHP plant into the UDN) will ensure that the voltage level along the feeder/network correspond to the level given in equation 4.7 will not be violated for any operating scenarios characterised by [106]

$$V_{min} \leq V_{Level}^{DG/CHP} \leq V_{max} \qquad (4.7)$$

where $V_{min}$ and $V_{max}$ are the minimum and maximum of voltage limits, respectively determined by UDNP/UDNO for every busbar in the network.

For the distribution system with load and a CHP plant connected at a low voltage busbar shown in Figure 4.4, the size of the CHP plant is determined based on constraint shown in equation (4.7) for four operational scenarios:

- Maximum CHP generation and maximum load
- Maximum CHP generation and minimum load
- No CHP generation and maximum load
- No CHP generation and minimum load

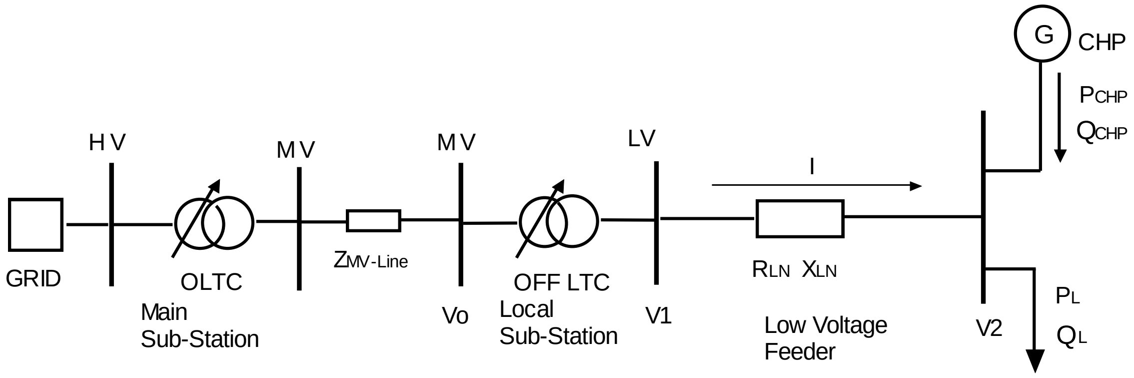


**Fig. 4.4 Single line diagram of UDN feeder with CHP plant connected (adapted from [173])**

The volt drop on the feeder shown above is determined by the equation:

$$\Delta U = V_1 - V_2 = \frac{R_{LN}(P_{L}-P_{CHP})+X_{LN}\left(Q_L-(\pm Q_{CHP})\right)}{V_2} \quad (4.8)$$

Prior to the connection of CHP plant at a particular feeder the UDNP/UDNO will carry out analysis for every operational scenarios outlined above and determine the maximum size of the CHP plant that can be connected into the UDN based on voltage level constraint determine during preliminary studies.

#### 4.1.2.4 UDN Losses

Energy losses in a UDN can represent a considerable cost and represent the key element of the UDN operational efficiency. The connection of a large amount of CHP generation in UDNs is transforming the networks from what were traditionally energy delivery networks to networks that both deliver and harvest energy. However, similar to any other cost they must be balanced against other cost and objectives. The losses considered by the UDNO are losses which are dependent on the power flows in the network. As connection of the CHP plant into the UDN is bound to effect power flow of the UDN and especially associated UDN feeder, the losses of the UDN and that feeder will in turn be affected as well. Recent studies have shown that connection of DG/CHP plants normally contribute to the reduction of network losses but also in some rare instances can cause an increase in losses magnitude shown in Fig.2.14 and described in [174,112]. The magnitude of losses depends on factors that include: location of DG/CHP plants, the relative magnitude in difference between the DG/CHP plants generation and the topology of the network/feeder under consideration. Prior to the determination of the losses in the UDN, the power flow analysis has to be performed. At the end of that analysis the power flow (and consequently the current) through each network component become available. The total active/reactive losses of the network can be determined by the summation of losses due to individual network components which can be calculated using basic equations:

$$P_{loss} = \sum_{i=1}^{N} P_{Gi} - \sum_{k=1}^{M} P_{Lk} \qquad (4.9)$$

$$Q_{loss} = \sum_{i=1}^{N} Q_{Gi} - \sum_{k=1}^{M} Q_{Lk} \qquad (4.10)$$

where:

$P_{Gi}$ , $Q_{Gi}$ , are the output of active/reactive power of i<sup>th</sup> generator including grid supply respectively

$P_{Lk}$ , $Q_{Lk}$ are the active/reactive power of k<sup>th</sup> load connected to the network respectively

N number of generators including grid supply and M are the number of loads connected to the network.

### 4.1.2.5. Environmental – Economic Impact

CHP generation represents established reliable and cost-effective technologies that are already making a significant contribution to meeting electrical and thermal energy demand in urban areas. In general, adoption of CHP generation as a means of energy supply can decrease in absolute terms, the primary energy consumption with respect to the SPH generation [159,175]. On a small-scale level this occurs also due to the fact that the energy generation systems can be managed more efficiently when privately owned. Understanding the technical impact of CHP systems has been one of the main priorities of the UDNPs/UDNOs in the last two decades. However, it has been recognised by the energy industry regulators, developers and UDNO that DG/CHP systems may also generate impacts of different nature. The increased penetration of CHP generation within urban areas calls for deeper analyses intended at evaluating the sustainability of energy generation and its environmental impact. In particular, CHP generation enable enhanced energy efficiency and thus greenhouse gas emission savings with respect to the conventional separate heat and electricity generation. However, the CHP generation could radically worsen the air quality on a local level in urban area. Moreover, in urban areas the air quality regulation could be quite strict because of the high population density, thus calling for a thorough environmental impact assessment at the planning stage of CHP plant development. Consequently, the likely increase in development of CHP systems in urban areas generates new important issues for both policy makers and energy system planners. From the policy the major issue consisting of establishing emission limits for CHP plant installation whereas energy planners are called to evaluate the additional local environmental impact of the CHP system. In this matter the main concern for CHP plant developers refer to the additional cost of abatement systems that could decrease the CHP plant overall profitability or to the additional cost brought by potential future policy regulation demanding to internalise the external cost from emission limit in urban area.

From the UDNO point of view, strategically siting of DG/CHP plant close to the point of energy consumption reduces stress on the UDN assets and in addition to that can avoid or defer investment and reduce maintenance cost for the UDN. The value of strategically sited DG/CHP system for certain parts of the UDN can be immediately apparent and impactful to a UDNO which knows exactly where its most constrained UDN assets are. In some cases there is a risk that connection of new DG/CHP plant will impact adversely on the UDN operation and accordingly it must be evaluated carefully by the UDNO [172]. Where there are negative impacts, a range of options exist to alleviate them, however, under current commercial arrangement the DG/CHP system developer will mainly bear the cost of alleviation. The cost required to mitigate negative impacts caused by CHP plant connection can make potential CHP system connection less attractive. Quantifying the impacts on UDN cost as a result of DG/CHP plant connection is a complex task and requires a number of simulations. To quantify the impact of DG/CHP system connection on operational cost of the UDN, number of concerns from different perspective has to be analyse in detail and include those initiated by: regulators, UDNOs and the DG/CHP systems developer.

### 4.1.3 Mathematical Formulation of the Optimisation Model

As illustrated in a number of publications listed in previous chapters, planning and development of new architecture of the UDN is concerned with two main goals and these are: maximisation of the benefits brought by the CHP system connection and minimise problems caused by CHP plant connection. This subject requests not only for technical solutions but for a combined solution incorporating economic and environmental constraints helped with the UDN operational standardisation [77]. In order to simplify and make more transparent the optimisation model regarding the optimal sizing at specific location of the CHP plant in the UDN, we can refer to the network under analysis with:

- N-1 voltage observable nodes ( assumed equal to the number of busbars of the network without HV busbar at main substation)
- $N_{branches}$ number of branches ( cables or overhead lines)
- $N_{OLTC}$ (transformers equipped with off-line tap changer facility)
- $N_L$ ( number of busbars with load connected)
- $N_{CHP}$ number of CHP systems connected in the UDN owned by single customer

In order to maximise the penetration of CHP systems in the UDN in an optimal way an appropriate management of the CHP system and the UDN must be realised. To achieve this through mathematically formulated optimisation model apart from the general constraints explained earlier the observation of the following constraints are absolutely vital and must be taken into account.

- ➢ The minimisation of the busbars (normally MV) voltage deviation with respect to the rated value $\bar{V}$ determined by the UDNP/UDNO

$$min_{P_{CHP}Q_{CHP}n_{OLTC}}\sum_{i=1}^{N-1}|V_i-\bar{V}| \qquad (4.11)$$

- The minimisation of the power generation cost C at every period t, taking into account cost $C_{CHP,j}$ of the j-th CHP plant output $P_j$ considered constant in time interval Δt, and price $C_{grid}$ of energy $P_{grid}$ Δt imported from the network

$$min_{P_{CHP}Q_{CHP}n_{OLTC}}C=C_{grid}P_{grid}\Delta t+\sum_{j=1}^{N_{CHP}}C_{P,j}\,P_j\Delta t \qquad (4.12)$$

- The minimisation of losses $P_{losses}$ in the system

$$min_{P_{CHP}Q_{CHP}n_{OLTC}}P_{loss}=min\sum_{l=1}^{N_{br}}I_l\,R_l^2 \qquad (4.13)$$

where $N_{br}$ is the number of branches , $R_l$, is the l-th branch resistance and $I_l$ is the l-th branch current.

The aim of this optimisation model is the minimisation of the linear combination of the three components namely, the absolute value of the deviations of each j-th CHP plant active power output $P_j$ respect to corresponding predefined maximum efficiency value $\bar{P_J}$ , the system losses and the absolute value of the voltage deviation at each i-th under observation with respect to the predetermined value $\bar{V}$. The expression incorporated all three components can be written as:

$$min_{P_{CHP}Q_{CHP}n_{OLTC}}\left(\sum_{j=1}^{N_{CHP}}\propto\left|P_j-\bar{P_j}\right|+\beta P_{loss}+\sum_{i=1}^{N}\gamma|V_i-\bar{V}|\right) \qquad (4.14)$$

where coefficient α, β and γ are the weights of the multiple objective function optimisation problem. The value of the weights is determined by the UDNP/UDNO based on physical and operational nature of the UDN. This problem is solved by power flow procedures of three-phase power flow calculations regarding the deviations of CHP system active power outputs $\Delta\bar{P}_j - P_j^{k-1}$ , the magnitude of $P_{loss}$ and the deviation of the voltages at every monitored bus $\Delta\bar{V}_i - V_i^{k-1}$ are obtained. The value of the equation (4.14) at the iteration k is then evaluated by linearizing the voltage and power loss function with reference to the control variable variations such as $P_{CHP}, Q_{CHP}, n_{OLTC}$

$|\Delta V_i| = K_{ip}\Delta P + K_{iQ}\Delta Q + K_{in}\Delta n$ (4.15) for every bus i except slack bus

$$\Delta P_{loss} = H_{P_{loss}P}\Delta P + H_{P_{loss}Q}\Delta + H_{P_{loss}n}\Delta n \qquad (4.16)$$

where:

ΔP, ΔQ and the Δn are the vectors of the variations of CHP plant P and Q operating levels as well as the OLTC position of transformers in the network.

$K_{iP}$, $K_{iQ}$, and $K_{in}$ are the vectors of sensitivity coefficient of the voltage variations at the network busses .

$H_{P_{loss}P},\ H_{P_{loss}Q},\ H_{P_{loss}n},$ are the vectors of sensitivity coefficient of active UDN losses.

#### 4.1.3.1 Constraints of mathematical optimisation model

In creating the mathematical optimisation model the following constraints ought to be taken into account and these include:

- Off Line tap-changer (OLTC) position n are constrained to assume integer values limited at real number of available taps on tap-changer. Such limits are taken into account by means of upper and lower bounds shown by equation 4.16. The upper and lower limits of the magnitude of the OLTC namely on the transformer between the CHP system and the UDN.

$$lower\ bound\ _{OLTC} \leq n_{OLTC} \leq upper\ bound_{OLTC} \quad (4.17)$$

- Limits in voltage magnitude in all the busbars and the power transfer capacity limits through the network branches and also power transfer capacity from the high voltage (HV) transmission system.

- CHP plants capability constraints regarding the CHP plant active power output limits. In particular active power output limits is implemented as upper and lower boundaries.

$$lower\ bound\ _{CHP_j} \leq P_j \leq upper\ bound_{CHP_j} \quad (4.18)$$

While the reactive power export/import limits are imposed indirectly through a power factor constraints.

- Limits on the power exchange of the CHP system with the network is constrained to the respect of the condition that can be described with equation (4.19)

$$P_{CHP,min} \leq P_{CHP} \leq P_{CHP,max} \quad (4.19)$$

It mainly characterizes the constraints introduced by capacity of the interface transformer or connection. $P_{cp}$ indicates the active power exchanged with the UDN. It could be both imported or exported depending of the operational condition of the site network where CHP plant is connected. Power at connection point between the UDN and the site network when CHP plant(s) at site network are ON can be described by the energy balance equation (4.20)

$$P_{cp} = \sum_{l=1}^{N_L} P_l + P_{loss} - \sum_{j=1}^{N_{CHP}} P_j \qquad (4.20)$$

where:

- $P_{cp}$ is the power at connection point between the UDN and the site network
- $P_l$ is the power consumed by the load connected at the site network
- $P_j$ is the power output from CHP plant(s) connected at the site network

➢ The network assets thermal capacity limit constrains the current in each UDN component. This is a stand-alone constraint, introducing that magnitude of the network current must not exceed rated current of any network component. It is described by the equation:

$$I_i^{Rated} \geq I_{UDN_i}^{max} + \sum_{i=1}^{N} I_{CHP_i}^{max} \qquad (4.21)$$

where:

$I_{UDN}^{max}$ is the maximum current contributed by the network

$\sum_{i=1}^{N} I_{CHP_i}^{max}$ maximum current contributed by CHP systems

$I_i^{Rated}$ is the maximum rated current of any network component

Under normal network operational voltage and power factor level allowed that the current flowing through any network component can be converted directly into the active power flow for that particular network component.

## 4.2 Case Study

An initial feasibility study is designed to provide an estimate of the various impacts (described above) that could be generated by CHP system development in an urban area. Once the energy and cost data have been collected and tabulated the next stage of the initial feasibility study is to select a potentially suitable CHP scheme. Sizing of a CHP system intended to be installed in an urban area is usually based on thermal energy demand of the CHP system installation site. Depending on the heat to power ratio of the site energy demands, sizing to match the thermal energy requirements will result in a scheme that may offer a surplus of electricity generation or may require top-up electricity supplies from the UDN. The export/import of the electricity then becomes a key issue in determining the cost of CHP plant connection into the UDN. Connection costs of a CHP system can make up a significant proportion of the project cost and may therefore have a major impact on the financial viability of a CHP system development. These costs are project specific and will be driven by the operational characteristics of the CHP system and the local UDN. Specifically, factors such as the location of the CHP scheme, connection voltage level, type of connection, size of the CHP system capacity and the capacity of the existing UDN will all be likely to have an impact on the connection costs.

To evaluate the possible consequences of these changes for this exercise a 34 bus HV/MV/LV network was created as shown in Fig 3.8 resembling a real part of a UDN. At LV busbar No B14-1, the CHP plant was connected and for this analysis the output of the CHP plant was changed in 20 increments of the CHP plant Table 4.1 and at the same time load drawn from the feeder is kept at operational minimum. Fault current level (three phase short circuit) at LV busbar B14-1 and the voltage level at MV busbar B15 were obtained from ERAC power analysis software and tabulated (Table 1). In carrying out these simulation studies, the UDNO will be particularly interested to see what level the connection of the proposed CHP system would result in change of fault current level and voltage profile at any point of the network.

Using data obtained from ERAC software in a multiple regression analysis technique, the UDNP and UDNO are in a position to determine the size of a CHP plant that can be connected at busbar B14-1 based on allowable changes of fault current and voltage profile. In addition the multiple regression analysis technique can determine to what degree the network parameters can impact on the size of the proposed CHP plant [135, 139].

Table 4.1  Power Flow and Fault Analyses Results from ERACS

| No. | Y | X1 | X2 | No. | Y | X1 | X2 |
|---|---|---|---|---|---|---|---|
| 1 | 100 | 1.0370 | 24.281 | 11 | 500 | 1.0435 | 24.969 |
| 2 | 150 | 1.0378 | 24.372 | 12 | 550 | 1.0441 | 25.027 |
| 3 | 200 | 1.0387 | 24.455 | 13 | 600 | 1.0450 | 25.114 |
| 4 | 250 | 1.0394 | 24.536 | 14 | 620 | 1.0452 | 25.124 |
| 5 | 300 | 1.0403 | 24.632 | 15 | 650 | 1.0457 | 25.200 |
| 6 | 350 | 1.0412 | 24.726 | 16 | 700 | 1.0465 | 25.284 |
| 7 | 380 | 1.0417 | 24.776 | 17 | 750 | 1.0470 | 25.337 |
| 8 | 400 | 1.0418 | 24.788 | 18 | 800 | 1.0478 | 25.419 |
| 9 | 450 | 1.0427 | 24.879 | 19 | 850 | 1.0485 | 25.500 |
| 10 | 480 | 1.0431 | 24.927 | 20 | 900 | 1.0490 | 25.546 |

The variables in Table 4.1 are described below:

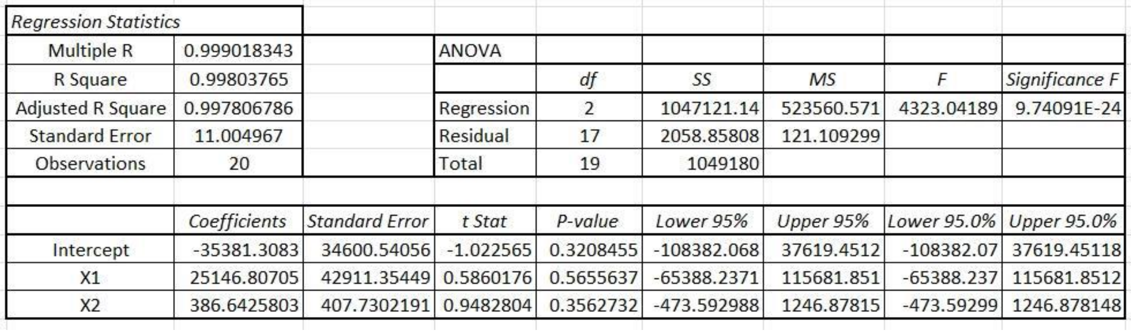
Y:  Input from the CHP plant in kW

X1:  Voltage level at B15 in per unit values

X2:  Three-phase SC current values B14-1 in kA

Using the data from Table I and performing the multiple regression analysis in EXCEL the following results are summarised in Table 4. 2.

Table 4.2  Multiple Regression Analysis Results



| *Regression Statistics* | |
|---|---|
| Multiple R | 0.999018343 |
| R Square | 0.99803765 |
| Adjusted R Square | 0.997806786 |
| Standard Error | 11.004967 |
| Observations | 20 |

| ANOVA | | | | | |
|---|---|---|---|---|---|
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 2 | 1047121.14 | 523560.571 | 4323.04189 | 9.74091E-24 |
| Residual | 17 | 2058.85808 | 121.109299 | | |
| Total | 19 | 1049180 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | -35381.3083 | 34600.54056 | -1.022565 | 0.3208455 | -108382.068 | 37619.4512 | -108382.07 | 37619.45118 |
| X1 | 25146.80705 | 42911.35449 | 0.5860176 | 0.5655637 | -65388.2371 | 115681.851 | -65388.237 | 115681.8512 |
| X2 | 386.6425803 | 407.7302191 | 0.9482804 | 0.3562732 | -473.592988 | 1246.87815 | -473.59299 | 1246.878148 |

Based on the initial feasibility study of the network and energy demand at a particular site presented in Chapter 3, the UDNP and UDNO are in position to determine the fault current and voltage levels that cannot be exceed without violating LCTA principles. Evaluation of these operational constraints are based on the results of load flow and fault current level analysis and systematic operational observation of network/feeder/busbar of interest. In this case the UDNP/UDNO identified two critical busbars constrained with a voltage level of 1.04 per unit at busbar B15 and short-circuit current level of 25 kA on busbar B14-1. Combining these values with results obtained by multiple regression analysis and fitting the multiple regression prediction equation corresponding to the two regressors:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 \qquad (4.22)$$

Using the value of the multiple regression coefficients from Table 4.2 where: $\beta_0$ = -34393.952 ; $\beta_1$ = 23764.6579 and $\beta_2$ = 404.8277 the estimated size of CHP plant can be determined as follows:

$$\hat{Y} = -35381.308 + 25146.807 * 1.04 + 386.643 * 25 \approx 437.4\ kW$$

Prior to proceeding to further analysis regarding the estimation of the CHP plant the validity of multiple regression model need to be examined. In order to do that the magnitude of the following parameters of multiple regression, explained in detail in [135, 139, 136], has to be analysed and these are: R Square value , Significance F test, t-test Statistic and P-value. The F test, R Square value and level of significant obtained validated multiple regression selection and established multiple regression model confidence.

With the obtained estimated size of electrical power output of CHP plant the next step is the selection of CHP plant with size that is available on the market. Having determined the CHP plant electrical output which is in this case 420kW, it is straight forward to determine the plant thermal output by simply multiplying the electrical output with the heat to power ratio that is be specific for every size and every type of the CHP generation plant. In this case it is assume that heat to power ratio of the plant is 1.3 resulting in thermal output of 546 kW.

Depending on the CHP system and the UDN connection circumstances this methodology can be used in other environments such as these with technical, economic and environmental constraints so long as they can be numerically described.

In addition, in a case when any operational parameter of the wider UDN are correlated with impacts of the CHP system connection on the UDN operational parameters, they can be used as a regressors (if this can be numerically described) in order to estimate the optimal size of the CHP system to be connected.

## 4.3 Discussion

Long term planning of the UDNs is an essential part of the activities of a UDNPs/UDNOs. Its main purpose is to determine the optimum network arrangements and its corresponding investments to obtain maximum benefits. But from the CHP system developer point of view one of the most important aspects of the CHP plant installation is to provide an economic but safe connection to the UDN.

To sustain the forecast of penetration rate of CHP systems in the UDN according to the goals of UDNOs and the CHP system developers, the appropriate tools need to be developed in order to estimate the size of CHP plant that can be connected in the UDN according to the LCTA principle. The current UDN infrastructures in most cases were not originally built to accommodate a substantial proportion of CHP generation within the network. To provide a situation where optimum capacity of CHP system can be connected according the LCTA principle, first difficulties for the UNDP/UDNO and the CHP system developer are related to technical improvements to ensure high degree of UDN operational consistency. To overcome these technical difficulties a number of issues has to be constrained as described earlier in this chapter and these include: network capacity, voltage profile, fault current level losses and ancillary services. In addition on constrain that is closely associated with technical issues is cost of connection and operation of CHP system.

Results shown in the case study determine the optimum size of the CHP system connected causing minimum violation of two most important constraints imposed by the UDNO. This case study is performed on the network shown in Fig. 3.8 with CHP system connected on B14-1 and load on each busbar is set at minimum operational limits resembling the worst network operational scenarios. The CHP size is changed in 20 increment shown in Table 1 and results of power flow and fault analysis from ERAC power system analysis software are recorded for number of the network busbars. In order to estimate optimal size of CHP plant to be connected on B14-1, the voltage profile at busbar B15 and fault current level at busbar B14-1 is selected by UDNO as outcome of preliminary studies describe in Chapter 3. Results for all twenty increment are tabulated and multiple regression analysis is performed with results shown in Table 4. 2. These results are used in the multiple regression prediction equation (4.22) and results obtain for the optimum size of CHP plant is 437.4 kW of electrical output. Obviously that size of CHP plant is not available commercially and the normal practice is to take next less one. In this case size of the CHP plant that is selected corresponding to 420kW electrical output that matching thermal output of 546 kW. To make sure that results obtained in this analysis are valid the number of attributes of data used in multiple regression analysis and also results of multiple regression needs to be examined. Looking the values of $X_1$ and $X_2$ it can be seen that they are highly correlated. When performing multiple regression analysis high degree of correlation between predictors $X_1$ (voltage) and $X_2$ (fault current level) will cause multicollinearity [176]. In this situation the coefficient estimates of the multiple regression may change erratically in response to small changes in the input data. The presence of multicollinearity does not reduce the predictive power of the multiple regression model as a whole, it only affects valuation regarding individual predictors.

Selecting a value of the electrical output of 420kW for the CHP plant obtained in this case study correspond to the expected value of the plant. With a high degree of correlation between the predictors, a multiple regression model may not give valid results regarding the estimations of impact of individual predictor on predicted variable in this case size of electrical output of the CHP plant. But for the UDNP/UDNO and CHP plant developer both estimation are equally important. The first estimation regarding the size of the plant is probably more important for the CHP plant developer due to fact that size of the plant will have immediate impact on environmental, operational and more importantly on the financial aspect of the whole project. The second estimation dealing with impact of individual predictors on the predicted value is more important to UDNP/UDNO due to the fact that this information will help the UDNP to define what action in terms of the network improvements to provide the plant connection according the LCTA principle. In the case study performed above it can be seen that value of t-statistics is very small and the value of P-value exceed 0.05. These values indicate how individual predictors impact the predicted value. The impact of this negative feature of the multiple regression model regarding different sensitivity analysis will be discussed in detail in the following chapters.

To rectify this problem caused by multicollinearity, especially if there is a high interest in the effects of individual predictors on predicted parameters, a number of actions can be applied [135, 139, 136]. In this case the most visible action that can be used to rectify negative impact of multiclinearity is to increase the amount of sample data. More data will produce more precise parameter estimates. Equally applied action is to leave the model as it is and simply realised that multicollinearity is present and be aware of multicollinearity consequences in the overall optimisation model.

Results from the feasibility studies and multiple regression analysis obtained on a case by case basis are essential in order to provide technically sound and economically efficient connection of the CHP plant into the UDN according to the LCTA principle, the UDNP/UDNO must design each connection on a case by case basis. To make full use of these results the additional analysis dealing with: different network and CHP plant operational scenarios and sensitivity analysis associated with the network technical constraints effecting LCTA connection principle are performed in the next two chapters.

## 4.4 Conclusion

Connection of a CHP scheme to a UDN fundamentally alters the operation of the network. There will be evident impacts on the UDN power flow, protection and voltage regulation particularly where generator capacity is comparable to local demand and specially where export occurs. There is a risk that new connection will impact adversely on the quality and security of local electricity supplies and therefore they must be evaluated carefully by the UDNP/UDNO and CHP system developer in order to achieve optimal CHP plant capacity allocation in the UDN.

Using the results obtained by ERAC power analysing software normally presented in Excel format and the same results incorporate into multiple regression analysis algorithm will give a good estimation of electrical output that can be connected at a particular busbar of the UDN. Equally important results of the multiple regression analysis will indicate the degree of technical constraints violation caused by the CHP system connection.

This chapter outlines methods that can assist in planning the CHP system development and connection in the UDN by allowing the UDNP/UDNO and CHP system developer to minimise the system connection cost and maximise the benefit of CHP system development. To achieve this and fully utilise results from this chapter the full and open collaboration between UDNP/UDNO and CHP developer is essential. Cost of connection of the CHP plant may be influenced by number of factors that are usually affected by the network technical constraints and environmental regulations. Methods described in this chapter can equally be applied using any other technical, economic and environmental constraints that can have an impact on CHP plant size connected in the UDN.

# Chapter 5 UDN and Operational Setting for CHP Generation

## 5.1 Introduction

The connection of CHP generation has lead to a change in the characteristics of the UDN. If increasing levels of CHP generation are to be accommodated in existing UDN, then there should be a change regarding the planning and design of the operational setting for CHP generation connection into the UDN. The traditional approach employed by the UDNP/UDNO regarding the connection of CHP generation is on a first come, first served basis which is becoming obsolete as the volume of applications for CHP generation increases. To meet that increase the alternative approach employed by UDNP/UDNO regarding the connection of CHP generation is to permit access to the UDN only on an integrated operational access mode. Under an integrated operational access mode agreement, the amount of output at which the CHP system can always operate without violating any of the UDN operational constraints is determined. Special consideration is paid to energy prosumer, an entity that resonates with the energy market in various forms. While UDNOs may not have direct control over prosumers' energy management, they can attempt to guide and manage prosumer development through the use of different connection operational setting strategies. This can include supporting (or preventing) prosumers from selling power to the network and in addition it also include more UDN structural reforms, such as creating new regulatory setting that allow UDNOs to develop new operational access modes as the prosumers number increases. In order to determine the most appropriate prosumer CHP system engagement method, UDNO should adopt a step-by-step methodology to assess the current network/prosumers operational situation and based on that, put in place suitable operational settings for CHP generation.

This chapter presents the description and analysis of possible changes in operational settings of the UDN and CHP system proposed by the UDNP/UDNO in order to maximise the size and benefits of the CHP system connection for both utility and CHP system developer (prosumer). In addition to that, and in the light of these changes, the techno-economic and environmental impacts of CHP generation on UDN operations are discussed and analysed.

### 5.1.1 UDN and Operational Setting for CHP Generation

Connection of CHP generation into the UDN introduces the need for a change in the network operational setting in order to maximise the network performance. These changes deal mainly with basic assumptions under which networks are normally designed and operated, particularly with respect to voltage control, protection and behaviour following a contingency situation. In order to maximise the benefits of CHP plant connection into the UDN, the UNDP/UDNO must deal with a number of network operational settings issues and these include [177, 178]:

- Two key protection issues are whether the CHP plant will increase fault levels and whether the CHP plant will make high impedance faults difficult to detect.
- A CHP plant with an appropriate size at the right location can provide voltage support on a radial UDN network MV feeder. However reverse power flow may lead to excessive voltage rise. In that case the location and size of the CHP plant will influence its ability to support the UDN voltage control system.
- Islanding can raise safety concerns. It can be avoided by an appropriate CHP plant connection management. However islanding may be more acceptable to the loss of power if it allows supply to be maintained to high value loads. At present is no provision for the CHP to operate in island mode.

The ability of a CHP plant to allow network expansion to be postponed depends on a strong correlation with demand on the feeder. Schedulable CHP plant may be able to follow load subject to ramping limits and other objectives. Non-schedulable CHP plant must depend on correlation between the plant output and feeder demand.

Prior to the connection of the CHP plant, the UDNO only has to consider the effect of supply from the main HV/MV substation on the operational settings. CHP plants introduce energy sources in the UDN where they had not existed before. As the UDN provides the main conduit for the distribution of electricity, the UDNP/UDNO main challenge is to be able to estimate the network operational settings in order to ensure that the principle objectives are achieved. Operational settings of the UDN regarding the installation of CHP plant must be evaluated on an individual basis because of the variation in CHP plant size and because the impact on the UDN can be location specific.

### 5.1.2 Capacity

In order to operate reliably and safely UDNs must be equipped for significant dynamics in electrical load demand and also a significant increase in future electricity demand. This challenge must be met in a cost effective manner and without undue environmental impact. It is also important that this can be delivered without compromising network protection or the security of supply. The primary objective of performance management of the UDN is to ensure that the degradation in the network performance is within acceptable bounds due to the CHP plant connection. Therefore, from the UDNP/UDNO perspective it is extremely important to estimate the available capacity of the UDN in terms of CHP systems penetration without violating network operational constraints beyond the point where additional investments required for the UDN assets upgrade are not feasible. The technique used to evaluate the UDN capacity consists in iteratively increasing the CHP system output in a given bus until the UDN operating limits are violated [179]. The aim of this technique is to evaluate the UDN capacity with respect to technical and environmental constraints. The technical constraints are based on load flow analysis of the network of interest while environmental constraints are based on comparisons between the CHP system vs SHP generation presented in section 5.2.2. After that, the next bus is investigated using the same method shown in algorithm Fig 5.1.

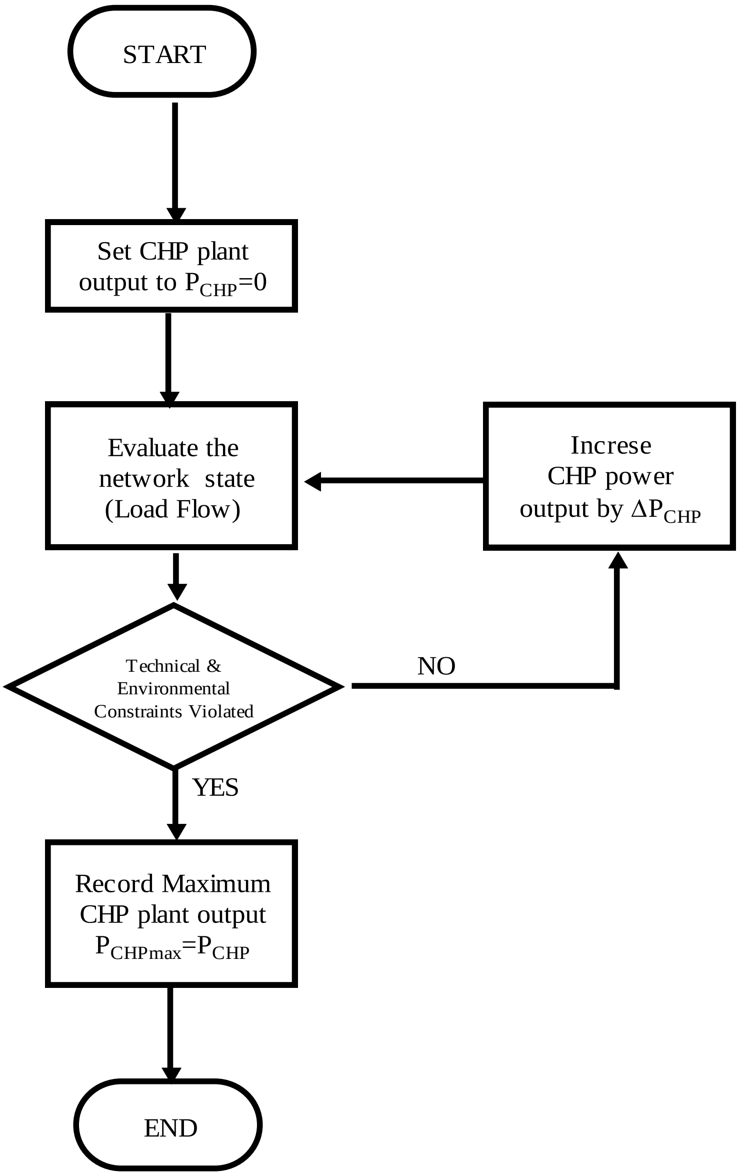


Fig 5.1 UDN Capacity Evaluation Algorithm (adapted from [179])

The study ends when all busses of a given UDN are checked. In order to evaluate the impact of increasing power injection into the UDN, CHP plant output is normally simulated by means of negative load (PQ Load flow representation) with average power injection of a 50kW step. The CHP plant power factor is assumed to comply with the UDN code which is normally between 0.92 – 1.05 which prevents CHP plants from exceeding local voltage. The technical constraints considered by UDNP/UDNO concern the operation of the UDN and include: the thermal limits of the network components, steady-state voltage limits, rapid voltage change, short-circuit capacity limits and environmental limits. The magnitude of these constraints with respect to the network capacity that can be violated by connection of new CHP plant at a particular location of the network are determined by UDNO during the on-going network analysis explained in Chapter 3.

### 5.1.3 Siting restriction

Due to the complexity of the problem and the fact that at present most UDNOs have little experience of a large number of CHP plants connected, few effective planning/operational procedures are in place to understand and minimise CHP plant siting restrictions in the process of connection into the UDN. Today UDNOs have their own standards for ensuring that interconnected generators are compatible with the network operational standard and other purposes. Each utility also has its own policy, procedure and contract terms for interconnection of distributed generation into the UDN. Integration of CHP generation into the UDN creates significant technical, environmental and economic challenges for UDNOs and CHP system developers. Even with potential benefits, such as reduction of losses, planning issues, the regulatory structure and the availability of resources (financial, space and fuel) have restricted, in many cases, the UDNOs and CHP system developers' ability to accommodate CHP plant at particular sites in urban areas. The increased penetration of CHP generation as a means of energy supply in urban areas has been subjected to number of constraints and it rises important questions as to whether the traditional fit – and – forget approach is still adequate. The typical siting restriction confronting the UDNP/UDNO and CHP developer when seeking connection to the network are subjected to a number of constraints that can be classified namely as technical, commercial and regulatory [180,181] and these include:

- UDN capacity
- UDN reliability
- CHP system connection cost
- CHP system penetration

The issues that arise with the connection of the CHP plant mainly focus on UDN operational concerns. Furthermore, as CHP system installation in urban area become more numerous, the UDNO must be aware of the influence of the total number of CHP system installations and this can suggest UDN hardware adjustment prior to the (n+1)th installation which raises the question of the distribution of the costs of adaptation. At present, evaluation of the CHP system connection scheme regarding the siting restriction is focused mainly on technical constraints (voltage profile, equipment thermal capacity and switchgear short-circuit capacity) on the UDN capacity and it is evaluated by the UDNO during the preliminary studies described in Chapter 3. Resolution of such issues depends on interconnection standards and CHP plant connection application processing regulations. Though connection standards mainly address technical issues associated with the UDN operation, they are constructed upon explicit policy decisions that include [181]:

- The maximum size of a qualified CHP plant;
- Whether the UDNO is allowed to control the CHP plant operation;
- Whether the CHP plant developer is responsible for the stranded UDN costs;

At present these policies have as much effect on the development of a CHP system in urban areas as the technical requirements. However, as the CHP generation penetration rises, changes in the operational practice of the network are needed in order to reduce the magnitude of some new problems regarding siting restriction. The operational changes that are needed are in the area of network protection, ancillary services and communication system operation.

### 5.1.4 CHP Generation Mode of Operational Access (UDN Connection Mode)

UDNs are normally designed and operated as the final phase in delivering electricity to the consumer and they change their role in order to allow penetration of DG primarily in CHP generation form. UDN deregulation, demand increase, shortage of UDN capacity and interest in CHP generation have led to increased studies on the connection of CHP system into the UDN [224]. The potential benefits or the negative impact caused by connection of CHP plant(s) are mainly dependent upon the size ( number of CHP systems), location and timing of the CHP system(s) operation. Moreover, one of the major changes that has a significant impact on UDN operational management is the number of traditional consumers in urban areas who are becoming prosumers. Prosumers are electricity consumers who have evolved into economically motivated subjects that not only consume but also produce and in some case store electricity. In addition, prosumers optimise the economic, and to some extent the technological and environmental decisions regarding energy utilisation.

The concept also suggests that prosumers are intimately involved in the value chain of commercial energy supplies. By coinciding with the supply and demand situation of the UDN supply, the energy prosumer gains a certain role as a co-player in energy supply in an urban area.

The constraints explained earlier have to be considered to allow the connection of CHP plants with specific capacity to a particular point of connection in the UDN. While some operational UDN conditions are static and do not significantly vary over time, other conditions in the UDN are more time dependent [184]. Equally some of the constraints are static while others are more flexible. The minimum and maximum voltage levels are normally fixed by the UDNO for any point in the UDN and should lie constantly within these limits. The voltage profile of the UDN changes depending on the load fluctuation supply by the network and the voltage profile in the HV-feeding transmission system. Therefore the voltage range that is available for change caused by injection of active/reactive power from CHP plants may vary. However the maximum capacity due to thermal line capacity is fairly constant over the year but is slightly different for overhead lines which are more exposed to the ambient temperature. Therefore, the thermal capacity of an overhead line may vary over time. In addition, connected loads change and hence the thermal capacity in a line that is available for power injection from a CHP plant changes as well.

With the present connection procedure for CHP systems, it is usually assumed by the UDNO and CHP system developers (prosumers) that the network should admit active power according to the nominal output of the CHP plant at any time without violating any of the stated constraints. Operational access where CHP plant power output can be injected into the CHP plant connection point without any operational restriction from the CHP system at each time is called an integrated operational access mode.

On the contrary if operational access where the nominal power output of the CHP plant is greater than the capacity at the CHP plant connection point that is guaranteed at any time, it is referred to as non-integrated access mode. In non-integrated operational access mode, the CHP plant will experience some restrictions over limited periods of time. A usual example of these limitations would include voltage limitations and line congestion.

To ensure the correct operation of the UDN in a case of a non-integrated CHP plant connection, it has to be ensured that the CHP plant restrict its impact on the UDN according to the network operational constraints defined by the UDNO [183]. A fixed time CHP plant operational scheme or a continuous control of CHP plant operation can be applied to follow the power infeed from the CHP plant into the network. Nevertheless, a fixed time operational scheme is more simple and it relies on the worst case operational scenario and therefore it is more strict than continuous control which takes the current UDN operational situation into account.

Due to the reasons mentioned above, these important efforts have been made in the energy sector in order to develop the appropriate mode of operational access for the reliable, environmental and economic exploration of the CHP generation sources and its integration into the UDN. Still, utility companies play a critical role in developing new planning strategies for maintaining the adequate operation and efficiency of the UDN. From the proper UDNP/UDNO planning of CHP plant(s), access to the UDN is important for obtaining its maximum potential benefit with LCTA principles. In order to achieve this, a number of operational access modes were developed and a method used to determine the most appropriate one by UDNP/UDNO is shown in Fig 5.2 and explained later in this chapter.

Hence, a major objective of this methodology is to establish which operational access of a CHP plant would be most suitable to facilitate maximum penetration of CHP generation and at the same time provide the service quality to be within technical, economical and environmental constraints established by UDNO and CHP system developers (prosumers) at different time/scenarios of the UDN and CHP system operation.

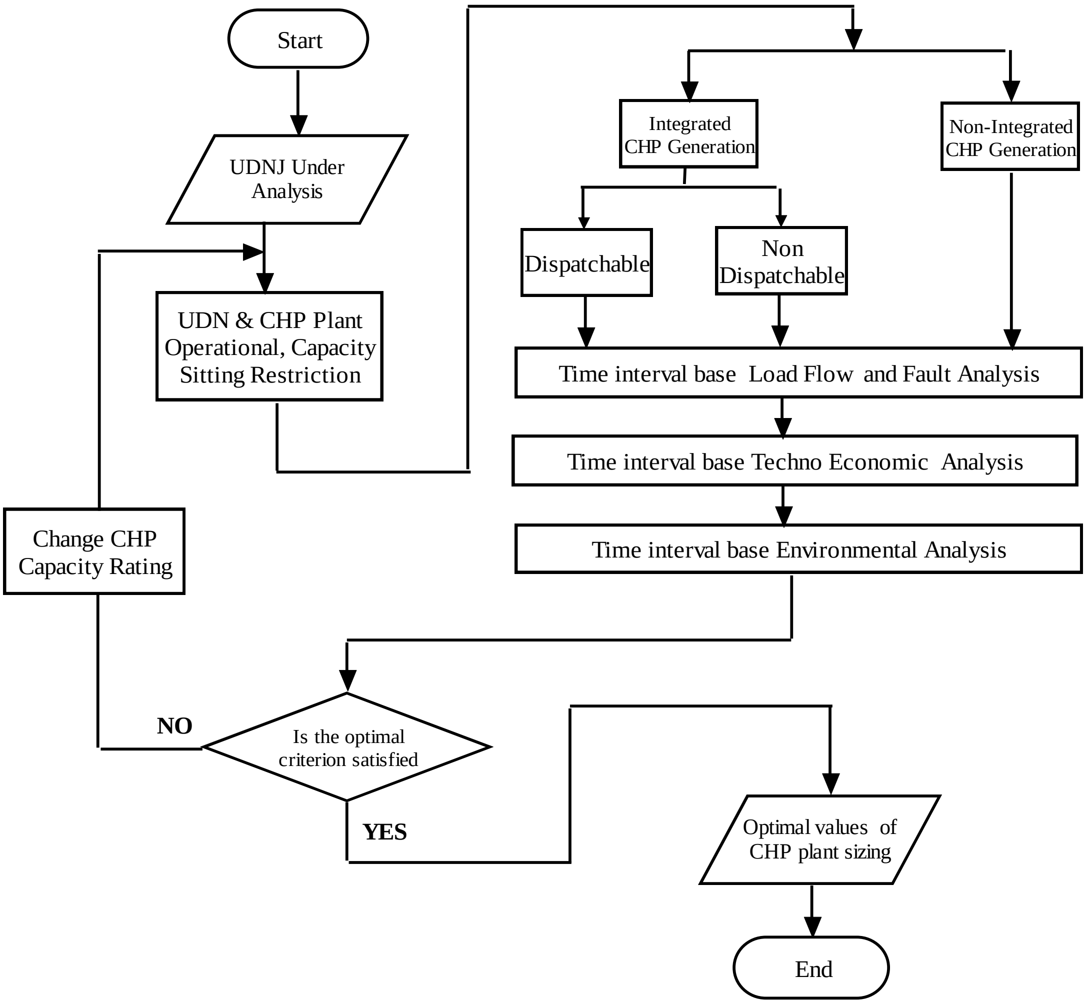


Fig 5.2 UDN and CHP plant Operational Settings Analysis Methodology

#### 5.1.4.1 Non-Integrated CHP Generation

Non-Integrated, also known as a non-firm, access refers to the connection that allows cheaper and quicker connection of a CHP system into the UDN by sacrificing the full electrical export of the CHP system capacity into the UDN at any time. Under the non-firm access the UDNO does not guarantee the full export of the CHP system electrical capacity to the UDN. This means that in the presence of the UDN, constraints, e.g voltage, short circuit current level and thermal constraints, the UDNO reserves the right to reduce the system electrical output based on the terms and conditions set in the connection contract agreement. In other words, under a non-integrated access mode the CHP system may be asked to curtail generation during periods of constraint on the UDN. The rules which dictate the order and frequency of these curtailments are known as Principle of Access. In determining the terms and conditions of the non-firm connection mode of CHP plant in UDN, one of the most significant technical constraints is voltage rise. The assessment of the voltage constraints in the UDN can introduce a substantial barrier to further development of CHP generation in the area and in addition to a limited size of CHP plant that can be connected at particular busbar. Even though voltage profile violation is occasional, occurrence in the UDN requires that the voltage profile stay within the statutory limits and therefore a number of techniques are employed by the UDNO to mitigate any voltage profile violation [182,183]. The short circuit level and thermal constraints are often dominant constraints for some part of the UDN and using active management to limit these constraints can be very expensive [184,163].

### 5.1.4.2 Integrated CHP Generation

Integrated, also known as a firm, access refers to a connection that allows the export of full CHP system electrical generation capacity into the UDN but at the same time is also subject to a higher connection cost in comparison with the non-firm access mode. The amount of integrated access arranged under the connection agreement given to CHP systems is the level of output at which they can always operate without violating any of the technical constraints of the UDN. The effect of these technical constraints on the penetration of CHP generation in UDN is described in detail in [132, 185] along with the consequences if CHP plant electrical capacity is not sized with full account of these limitations. The provision of this kind of connection may be required from the UDNO in order to guarantee CHP plant export capacity. The option of access is more reasonable for non-variable energy sources due to the sustainability of the maximum output for the extended period.

### 5.1.4.3 Dispatchable Operational Mode of CHP Generation in a UDN

Dispatchable operational access mode by definition is the mode where, at the request of the UDNO, the CHP plant can be turned ON or OFF or can be asked to adjust the power output on demand. The fact that CHP generation has increasingly been getting interconnected in urban areas due to its positive impact on the energy supply [186]. The integration of CHP systems into the UDN under dispatchable operational mode has been seen as a cost-effective options for meeting increasing load demand. Dispatchable operational access mode give the CHP plant owner a possibility of participating in the wholesale electricity market for added value beyond the value from the net-metering protocol. At present, in most cases, the individual CHP system connected into the UDN enjoys the credit at the utility's electricity retail cost by revolving the electricity meter backwards.

Dispatchable operational access mode can provide flexible generation capacity by exploiting fast acting generation through the use of existing CHP generation located at the consumers site [187, 190].

By effective usage of installed CHP generation capacity, dispatchable operational access mode has the potential to reduce the need for the construction of additional centrally controlled peaking plants (spinning reserve) and as a result lowering the cost of electricity for network consumers. The principal purpose of the operational access mode is to ensure high power quality supply and cost effective energy supply for the consumers (prosumers). The dispatchable operational access mode addresses many of the UDN operational constraints explained in Chapter 4 and should be a critical pillar in the policy to facilitate maximum penetration of CHP generation into existing UDN corresponding to the LCTA principle.

#### 5.1.4.4 Non-dispatchable Operational Mode of CHP Generation in a UDN

In contrast to dispatchable operational access mode, non-dispatchable operational access mode UDNO has no operational control over the CHP system. Its operational timing is predefined by the CHP plant owner and it is normally based on the site thermal energy demand. CHP systems operating in non-dispatchable operational mode are normally connected behind the customer's meter and are essentially seen as a negative load to the UDN. The challenge will be to know how much CHP generation capacity is installed in the area and how big the impact will be on reduction of loads in the area. Another challenge is to predict the real-time volatility. The volatility of CHP generation could be attributed to the change of the site thermal energy demand that was not known or factored in during the planning process. Unfortunately, the attribute of being non-dispatchable lowers the value of CHP generation capacity in terms of UDN reliability and security of supply compared to dispatchable CHP plants. Since there is no significant correlation between the thermal energy demand at CHP plant installation site and the hour of the peak electrical demand, it is not guaranteed that CHP plant electrical output will be available when needed. Non-dispatchable generating resources are also characterised with a substantial level of availability uncertainty. The combination of non-dispatchability and uncertainty creates unique challenges regarding UDN operational reliability planning. Non-dispatchable CHP generation is not worthless but is not nearly as valuable to a UDNO as dispatchable power generation mainly in a small isolated weak part of the UDN [186].

### 5.2.1 Techno-Economical Impact on UDN Operation

At present, most UDNPs/UDNOs have very little practice with large number of CHP generation interconnection and a few effective procedures are in place to understand the effects of CHP generation in urban areas to process an interconnection request efficiently and completely. It is reasonable to believe that after the installation of CHP plant consumers will not change their conventional energy demands and will continue to consume the same amount of energy for their daily activities. However, the fact that they change from traditional consumer behaviour to prosumers of energy will most probably create considerable changes in the load profile in the network. The issue that arises with the use of CHP systems focuses mainly on the technical and economic concerns related to the operation of the network with a CHP system interconnected. A CHP plant inappropriately connected to the network, and with the changed behaviour in place, could compromise the viability of operational and economic reliability of the network. Additionally, as connection of CHP generation become more numerous, the UDNO must be aware of the effect of the total number of CHP system installations as this can impact on UDN adaptation both technically and economically.

While interconnection standards mainly address technical issues they are built upon explicit decision making policy stated in section 5.1.2.

As with all system studies, there are some specific issues which cannot be extrapolated to all operational scenarios. However, a number of major results weighing the situation with typical CHP plant interconnection can be derived from the studies listed below [181]:

- In a case where the cumulative CHP plant output within the area of the UDN is less than the consumed power in the UDN, the variations in the voltage profile are acceptable.
- If the cumulative CHP plants' output is larger during the time of low load demand in the UDN will normally violate the voltage profile constrain. This may need a network reconfiguration or CHP system electrical output limitation .
- In some cases, even if cumulative CHP plant output is low, a single CHP unit may cause violation of the voltage profile and the short circuit level at point of the connection.
- As one consequence of CHP generation connection in the UDN is a violation of the network protection selectivity, this has to be evaluated during the CHP plant connection planning process and in many cases it needs additional protective devices in order to insure protection system reliability.
- By connecting the CHP plant into the network it can adversely impact UDN reliability. It can be compromised if the network is very reliable but it can also

decrease overall network reliability by adding internal failure. In a case when the UDN is not very reliable, connecting CHP plants can improve reliability in ways such as: in times of short supply, supporting the network and preventing blackouts and it may also facilitate islanding when the UDN fails and hence increase reliability of the local supply.

Planning a UDN is a mainly technical, economic and environmental optimisation task. In order to facilitate maximum penetration of CHP generation into the existing UDN, UDNP/UDNO examine the operational adequacy of the UDN via indicators used to analyse the result from one operating strategy to another that includes:

- Technical focus on operating variables such as load profile characteristics, power losses and CHP system dispatch.
- Economic data focus on data regarding the operational and capital investment of the UDN and CHP system cost, energy consumption locational marginal costs and spot market price. [21,191,192]

### 5.2.2 Environmental Impact of CHP generation on Urban area

The latest survey shows that urban areas account for approximately two – thirds of global primary energy consumption through large electrical and thermal energy demand [167] and according to [188] they will consume 73% of the world’s energy and will be responsible for 76% of the world’s greenhouse gas emission. As a result, there is a growing interest in improving the urban energy supply system so that adverse environmental impacts are reduced while at the same time maintaining economic prosperity and quality of life. One of the most obvious area of improvement is the integration of electrical and thermal energy services. Energy supply analysis of a number of European cities indicate that only about 20% of fuel’s available energy is recovered, with substantial amounts of energy wasted in the conversion of fossil fuels to low-temperature thermal and electrical energy [167,188]. CHP generation installation in urban areas provides the opportunity to reduce these losses by converting more of the fuel energy into useful thermal and electrical energy. In addition, installing CHP systems in urban areas reduces losses significantly produced by transmission and distribution of electrical energy usually generated in places far from the urban area. The installation/operation of CHP generation within an urban area can be limited by several factors. Planning restrictions related to noise or air quality might require restriction in CHP plants about to be installed. Limits on the size of the CHP plant can therefore restrict the overall efficiency of the energy supply system making it difficult to reach desired energy efficiency and greenhouse gas reduction targets. In general, at present, in urban areas, air quality standards are stringent because of high population density the overall pollution levels usually set by local regulatory authority can be quite narrow. This situation brings new important issue regarding the development of CHP generation in urban area for both policy makers and energy system planners. In order to quantitatively determine the effect of CHP system on greenhouse gas emissions, local and global emissions can be modelled using the emission balance approach [159].

Global: $\Delta m_{GHG} = (m_{GHG})_{CHP} - \left(m_{GHG}^{W} + m_{GHG}^{Wlosses} + m_{GHG}^{Q}\right)_{SPH}$

Local: $\Delta m_{GHG} = (m_{GHG})_{CHP} - \left(m_{GHG}^{Q}\right)_{SHP}$

where:

SHP - separate power and heat generation

$(m_{GHG})_{CHP}$ – mass of green-house gas emitted by CHP system

$(m_{GHG}^{W})$ – mass of green-house gas emitted from electricity generation

$(m_{GHG}^{Wlosses})$ – mass of green-house gas emitted by generation of the electricity that is lost during transmission & distribution

$(m_{GHG}^{Q})$ – mass of green-house gas emitted from thermal energy generation

The justification of this approach is based on comparison between CHP systems and SHP (separate heat and power) generation for the same quantities of heat and electricity generated from the point of view of greenhouse gas emissions. From a general perspective, greenhouse gas emission balances can be effectively estimated after drawing break- even emission maps for relevant greenhouse pollutants through which is possible to access the incremental environmental pressure due to CHP generation system with respect to the classical solution of separate electrical and thermal energy generation. The comparison between CHP generation and SHP generation may be strongly conditioned by the reference value adopted for SHP generation entries. In general adopting average values, the modern CHP systems can be competitive to a good extent in terms of greenhouse gas emission while emission from the state of-the-art SHP generation is often low for the current CHP system normally installed in urban area. Normally it is up to the local energy planners to establish which references are most suitable for the estimation on a case by case basis. In addition, the urban energy planners must define the greenhouse gas emission assessment techniques which must in turn provide important indications to the planners and decision-makers, for evaluating the trade-off between the local air pollution impact due to the connection of CHP generation. In general adopting CHP generation technology as a means of energy supply can save in absolute terms, the primary energy consumption with respect to the SHP [115, 219]. In addition on a small-scale CHP generation level, these savings occur due to the fact that the energy generation by the CHP system can be managed more effectively when privately owned. The lower primary fuel consumption brings about a reduction in the overall emission of $CO_2$, and could also reduce the absolute emission of hazardous air pollutants regulated by national environmental protection agency (EPA) shown in APPENDIX 1. The EU emissions trading directive (Directive 2003/87/EC), implemented in the Republic of Ireland by the EU (GHG emission trading) Regulations (SI No, 437 of 2004), which establishes an allowance-trading scheme for emissions to promote reductions of GHG, in particular $CO_2$, is being implemented by the EPA to achieve this target. Thresholds set in the directive are based on the capacity of the CHP system rather than the actual output of the total capacity of all directly associated and technically connected facilities on site. A CHP system operating in accordance with this scheme will have ratings that exceed 20MW of thermal output. In the case of the CHP system installed in Rochestawn Park Hotel with a thermal output of 385kW, which is considerable less that threshold introduced by the EU emission trading (Directive 2003/87/EC) this means that the CHP system is outside the EPA limit.

In order to demonstrate the impact of CHP generation on local emissions grade, data were collected over one year (2013) on monthly basis covering all seasonal weather conditions provided by the hotel authority.

Type of data presented in table 5.1 consists of data representing the natural gas input and electrical/thermal energy output expressed in kWh. This data was used to assess the different aspects of GHG emission and estimate the GHG emission savings made by utilisation of CHP generation vs SHP generation for the same amount of energy consumed by the hotel [115]. The CHP system installed at a four star hotel located in the Cork city area consists of dual fuel reciprocating spark ignition (SI) 6-cylinder 4-stroke engine with a normal synchronous speed of 1500rpm, generator capable of producing 306 kW of electrical power together with associated exhaust waste heat recovery system capable of producing 384kW of thermal output normally operating from 5:30 am to 19:30 pm.

The operational characteristics of CHP system installed at Rochestown Park Hotel are specified as follows [personal communication Robert Brockert, Temp Technology Ltd, August 2015]:

- From cold start to full online CHP system operational mode within the UDN is achieved normally with rump up time of less than 5 minutes.
- Process heat delivery from the CHP system to meet customer (hotel) thermal load demands normally takes between 15 – 20 minutes from cold start.
- In a case where customer heat load requirements is less than 50% of rated operational CHP system thermal output, the CHP system is switched off due to operational inefficiency.

From the results shown in Table 5.1 and Fig 5.3 it can be seen that CHP system used as a means of energy supply have positive impact on global GHG emission savings which is in this case 129.888 tonnes annually. However, looking at the emission level locally it can be seen from the results that the amount of GHG emission is increased significantly by using CHP generation as a means of energy supply and in this case it is 1544.79 tonnes annually.

**Table 5.1 Operational data for CHP system at Rochestown Park Hotel for the year 2013**

| | CHP Plant Operational Data | | | | | Separate Heat & Power Generation Data | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Months Year 2013 | Hours Run | Gas Input kWh | Electrical Output kWh | Thermal Output kWh | CHP Plant GHG Emissions tonnes | STG GHG Emissions tones | SEG GHG Emissions tones | T&D Losses Emissions tones | Total SHPG GHG Emissions tones | GHG Emissions Savings tones | CHP - STG GHG Emission tones |
| Jan | 436 | 388621 | 131354 | 154998 | 226.838 | 98.338 | 133.58454 | 4.956 | 236.878 | 10.040 | 128.500 |
| Feb | 347 | 224275 | 75805 | 89450 | 130.909 | 56.751 | 77.0922547 | 2.860 | 136.704 | 5.794 | 74.158 |
| Mar | 440 | 315030 | 106480 | 125646 | 183.883 | 79.716 | 108.288151 | 4.017 | 192.021 | 8.138 | 104.167 |
| Apr | 464 | 414370 | 140057 | 165267 | 241.868 | 104.853 | 142.435326 | 5.284 | 252.573 | 10.705 | 137.015 |
| May | 493 | 441021 | 149065 | 175897 | 257.424 | 111.597 | 151.596292 | 5.624 | 268.818 | 11.394 | 145.827 |
| June | 476 | 425707 | 143889 | 169789 | 248.485 | 107.722 | 146.332398 | 5.429 | 259.483 | 10.998 | 140.763 |
| July | 499 | 446796 | 151017 | 178200 | 260.795 | 113.058 | 153.58144 | 5.698 | 272.338 | 11.543 | 147.737 |
| Aug | 425 | 378044 | 127779 | 150779 | 220.664 | 95.661 | 129.948832 | 4.821 | 230.431 | 9.767 | 125.003 |
| Sep | 483 | 432189 | 151017 | 178200 | 252.269 | 113.058 | 153.58144 | 5.698 | 272.338 | 20.069 | 139.211 |
| Oct | 394 | 350379 | 118428 | 139745 | 204.516 | 88.661 | 120.439042 | 4.468 | 213.568 | 9.052 | 115.856 |
| Nov | 475 | 424757 | 143568 | 169410 | 247.931 | 107.481 | 146.005947 | 5.417 | 258.904 | 10.974 | 140.449 |
| Dec | 495 | 441858 | 149348 | 176231 | 257.913 | 111.809 | 151.884098 | 5.635 | 269.328 | 11.415 | 146.104 |
| Total | 5427 | 4683047 | 1587807 | 1873612 | 2733.495 | 1188.705 | 1614.76976 | 59.908 | 2863.383 | 129.888 | 1544.790 |

where:

STG – Separate Thermal Generation .

SEG – Separate Electrical Generation.

T&D – Transmission and Distribution Losses that need to be accounted for emission ranking evaluation.

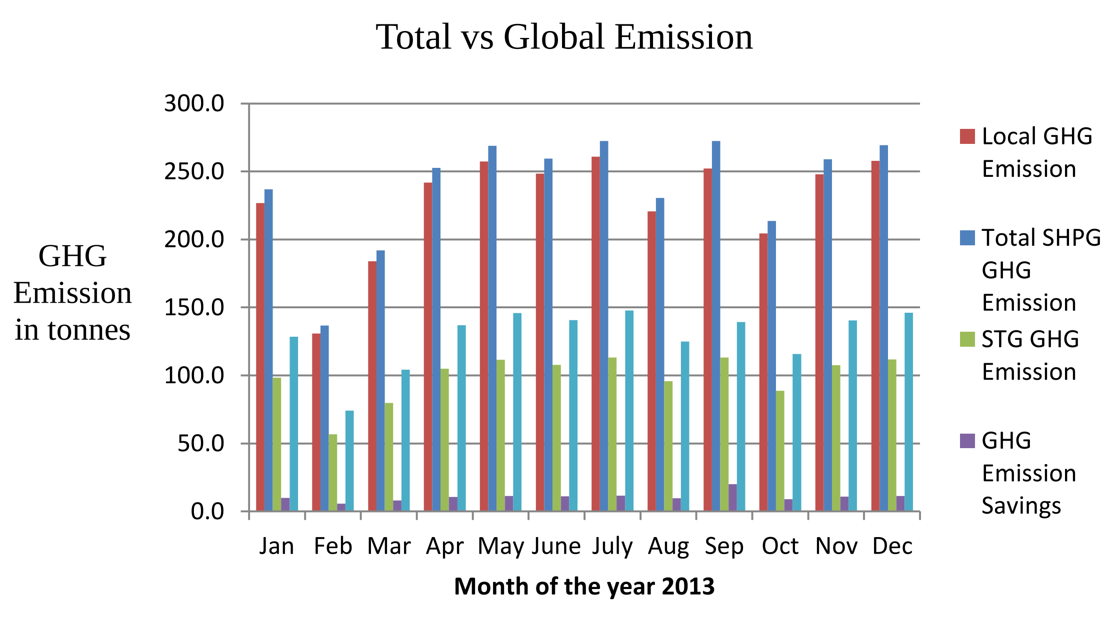


**Fig 5.3 CHP versus SHP generation emission**

This amount of GHG emission combined with other source of GHG emission could exceed overall pollution level set by the local regulatory authority. In the case when the local pollution level is exceeded and the CHP system developer has a desire to keep the proposed electrical and thermal output from the system, two obvious solutions to that problem exist and these are:

a) Change of CHP generation technology (type of prime mover)

b) Adopt adequate CHP system operational settings.

Implementing of one or both solutions could bring the pollution level below the level set by the local authority. However, these changes could bring difficulties with UDN technical/operational constraints explained earlier for which CHP developer is financially responsible.

Note: the additional data used for the purpose of this demonstration are as follows:
GHG emission for reciprocating spark engine used in CHP system is ≈ 0.58369 kg/kWh
GHG emission for gas turbine normally used in Large Power Station is ≈ 0.5392 kg/kWh
Local boiler efficiency ≈ 92%
Source: EPA US Environmental Protection Agency

Electricity efficiency of large power station is ≈ 53%
T&D electrical losses ≈ 7%
Source: ESB Ireland

From the results above it can be seen that CHP generation having fuel efficiency of greater than 75%. This can be compared with other method of generating electricity such as by Combined Cycle Gas Turbine technologies which have an efficiency in the region of 48% to 55% or single cycle technologies which generally have an efficiency in the region 33% to 38%.

It is clear that utilisation of CHP generation as a means of energy supply in urban area has overall environmental benefits. This benefit is increased if the primary fuel for CHP system is natural gas, as the carbon content and hence $CO_2$ emission is considerably reduced when compared with other fossil fuels.

The typical CHP system installation example presented above fully addresses the evaluation of $CO_2$ emission reduction by implementing CHP generation as a means of energy supply. However, it fails to correctly assess the impact on local urban air pollution due to the fact that SEG is partly generated far from the urban area, and hence impacts slightly on urban areas. In addition the air quality standard shown (Appendix 1) and road traffic pollution margins before reaching the allowed overall air pollution level (normally set by the local authority) can be quite low. Therefore any $CO_2$ emission from CHP system may cause this threshold to be exceeded.

## 5.3 Discussion

The optimal location and sizing of the CHP systems with appropriate operational settings is essential to maximise the amount of CHP generation connected and at the same time maximise the benefits of the CHP generation as a means of energy generation. The convergence of competition policy in the electricity market with the influx of highly efficient CHP generation technology could profoundly transform the urban electricity supply system as we know today. Interconnection process of CHP generation into the UDN is formulated as two stage single objective problem from the UDNP/UDNO point of view. It aims to obtain the optimal long-term network reinforcement and expansion

plan considering new CHP generation plants for all scenarios of production and load. It is assumed that the regulators send out incentives for UDNOs to minimise costs while guaranteeing operational technical requirements and that UDNOs do not own CHP units but are obliged to integrate them into the UDN. More CHP plants are expected to be connected to the UDN and are considered to have the potential of improving UDN integrity, reliability and efficiency. How to maximise the connection of CHP generation into the existing UDN is a common challenge for the UDNPs/UDNOs. At present the UDNP usually plans and designs the UDN with a number of critical factors in mind that include load, security and quality/efficiency. It aims to obtain the optimal long-term network expansion and reinforcement plan while considering new CHP plants connection in all scenarios of generation and load. In this process it is assumed that incentives sent by the regulator to UDNPs to minimise the connection and network utilisation costs while guaranteeing technical requirements that UDNOs do not own CHP units but are obliged to integrate them into the network.

As growing numbers of energy consumers in urban areas are becoming both consumers and CHP energy producers, a multitude of complexities is introduced which fundamentally changes the relationship between the consumers and the UDNOs. Because of the large scale integration of prosumer CHP units, the UDN will undoubtedly require significant change in the current operational settings structure in accordance with a high degree of flexibility and uncertainty that will characterise future consumption and generation. Basically, the benefit that prosumers can get from electricity consumption/generation can be quantified in terms of economic benefit and security. Prosumers' individual behaviour will determine the power injected or withdrawn to/from the network as prosumers will not necessarily struggle for the entire UDN welfare state, e.g. non-cooperative prosumers could be driven by their own energy demand and influenced by their social/business environment. From above, clearly besides the size of the prosumers CHP units associated with a particular location in the network, the integration of prosumers into the UDN will require the proper interaction of various roles and models.

The current EU regulatory framework provides a priority and guaranteed network access for electricity generated by CHP generation ( Art. 14 of new Energy efficiency Directive 2012/27/EC). CHP systems are connected on an integrated access basis but in order to maximise penetration of CHP generation connection can not be considered as integrated access for this purpose in most cases.

The lead time required to comprehend CHP generation investment is normally shorter than that for UDN reinforcement. Directive 2009/72/EC Art. 25.7 requires UDNPs/UDNOs to take into account DG/CHP energy generation facilities and conventional assets when planning their networks. This may be highly complicated when a connection application for a CHP plant is submitted at short notice and UDNPs have received no information regarding the CHP developer (prosumers) nature of the energy management. The situation will escalate in a case when UDNPs have large amounts of CHP generation connected to their networks and the resulting net demand seen further up the system hierarchy is lowered. CHP generation connection into the UDN poses a challenge not only for network balancing but also for UDN operation. The operational security and hosting of existing network capacity facilitating maximum penetration of CHP generation into the network is determined primarily by the voltage (ensuring that voltage in the network is kept within the proper margins and is never close to the technical limits of the network) and the physical current limits of the network (thermal rates of the network assets that determine the possible power flow).

In a UDN with a high penetration of CHP generation insecure situations already occur at present. As a result, UDNOs with high shares of CHP generation in their networks already face challenges in meeting some of their operational responsibilities. These challenges are expected to appear more often depending on the connected size of CHP units, their geographic location and the voltage level of the CHP plant connection. In order to maximise penetration of CHP generation, UDNPs/UDNOs should be able to plan well in advance to prevent congestion in the most cost-effective way. In addition, every connection request should be analysed and considered in the planning in order to make the best of the existing UDN. According to the traditional planning approach, CHP plant connection demands analysis are currently applied in most EU countries and the UDNPs/UDNOs performs a distinct analysis and provide a distinct solution to each CHP plant connection. The first connection may make use of the available capacity of the existing UDN but once there is an increased demand for new CHP generation connections in the same network area and the existing UDN capacity is limited then this approach is not always be optimal from the overall cost and UDN development perspective.

One way to tackle this issue is to allow for coordination of all relevant stakeholders including UDNO, CHP system developers and local authorities in the analysis of the connection request. UDN capacity management will normally incorporate optimisation of the network capacity via improved consideration of CHP generation operational access in the UDN planning process. The UDNO ability to identify network areas with possible operational critical problems well in advance as described in Chapter 3 is a precondition for this. The options that should be investigated further include:

- New network operational access modes such as those explained in Fig 5.2
- Alternative involving real-time operational access solutions such as UDNO flexible tendering [193].

To achieve maximum penetration of CHP generation into the UDN, corresponding LCTA sensitivity analysis needs to be performed in each connection case. These analyses are primarily of a technical nature explained in detail in Chapter 6 and they include: Voltage, Protection, Capacity and Losses sensitivity analysis

## 5.4 Conclusion

This chapter provides an introduction to the concepts associated with the operational setting of CHP plants connected into existing UDN. These concepts are discussed to create an understanding of how operational access mode of CHP plants installed by the prosumers will impact the penetration level of CHP systems into the UDN and also on the number of constraints described in 5.1.1. and 5.1.2. Prior to connection of the CHP plant UDNO only had to consider the effect of the supply from the main HV/MV substation on the UDN operational settings. CHP plants connection introduces on energy source in to the UDN where they had not existed before. As the UDN provides the main conduit for the distribution of electricity, the UDNP/UDNO main challenge is to be able to estimate the network operational settings in order to ensure that the principle objectives of electricity supply to the area customers are achieved. The ability of CHP plant to allow the UDN upgrade/expansion to be deferred is strongly correlated with the nature of the demand on the network feeder in question. Schedulable CHP plant may be able to follow a load subject to ramping limits and other operational constraints described in Chapter 4. Non-schedulable CHP plant operation depends on the correlation between the CHP plant output and the network feeder demand.

UDNs are currently experiencing a rapid increase in the number of energy consumers that are qualified as prosumers. In some cases, power feed-in from prosumers will surpass local network demand. However, the UDN still has to be designed to supply maximum demand for situations when there is no power generation from CHP or any other type of DG connected into the network. Once the share of prosumer generation capacity passes a certain point, it overstrains the local UDN. Therefore, the UDN in that situation is increasingly facing problems related to voltage profile and network congestion. UDNOs are responsible for operating their networks efficiently and at the same time providing high power quality supply for the end customers but in order to fulfil these responsibilities in the framework of UDNO/prosumers relationship the UDNO needs an adequate method of the for achieving UDN and CHP plant operational settings. The key operational setting described above will clarify the participation role of prosumers' CHP systems in network voltage, capacity and congestion management.

Operational settings of a CHP plant to be connected into the UDN must be assessed on an individual basis because of the variation in CHP plant size and time of plant operation and must also take into account that the impact on the UDN can be location specific.

In order to maximise the benefit of the CHP generation as a means of energy supply in an urban area, and at the same time facilitate maximum penetration of CHP generation in the UDN, connecting according to LCTA principles is absolutely vital. To determine the adequate operational settings of the CHP plant, UDNOs should apply the methodology shown in Fig. 5.2 accompanied with the sensitivity analysis described in Chapter 6 in section 6.2.

# Chapter 6 Least Cost Technically Acceptable (LCTA) Principle

## 6.1 Introduction

There is no general agreement regarding the practice concerning the optimal allocation of financial responsibility for the CHP system connection cost in the UDN. The differences in policies for the connection charges are substantial. They reflect the fact that different connection principles and policies considerations, each reasonable and valid, lead to different conclusions. The aim of planning is to ensure that the UDN is developed in an orderly and cost effective manner; UDNP/UDNO must ensure that there is sufficient UDN capacity available to meet new loads and DG/CHP system connection as they arise, and to meet ongoing growth and requirements. They also need to ensure that new connections are completed:

- as technically and economically acceptable
- able to meet the possible future needs of the customers/prosumers

For CHP plant connection into the UDN, the task for the UDNP and UDNO is to perform network studies in order to determine an appropriate connection method. Due to network complexity, a number of analyses such as equipment rating, protection sensitivity, voltage profile sensitivity and losses sensitivity analysis are carried out as a part of the operational/technical analysis. When considering the method of connection for a CHP plant or group of CHP plants the UDNP/UDNO will consider more than one connection option. Based on the results obtained from the above studies, the UDNP/UDNO will determine a connection method which complies with the UDN relevant standards and planning criteria. To determine the most appropriate connection method, the UDNP/UDNO will apply the LCTA principle which evaluates the connection according to the operational/technical standards against which the UDN is planned and operated. By definition the connection charge methodology is based on recovery of the appropriate proportion of the cost directly or indirectly incurred (or to be incurred) in carrying out the necessary modifications on the UDN such as extension or reinforcement of network equipment in question or providing, installing, maintaining and repairing the electrical lines, electrical plants, meters, data processing equipment or other items in question from the CHP system developer. In the case where connection of a number of CHP plants is processed at the same time, the LCTA principle is applied to the entire group of CHP plants and not on an individual basis [2,24,178]. Normally, UDNP/UDNO will provide customer connections which deliver the required capacity to an acceptable standard as outlined in the UDN code [183]. If a higher standard of connection arrangement is requested by customers then it can be provided by UDNO but at full cost to the customer.

## 6.2 LCTA Principle for Connection of CHP System into a UDN

Getting a CHP system connected to the existing UDN involves considerable interaction between the CHP system developer and UDNP/UDNO responsible for the planning, operation and maintenance of the UDN. In order to maximise the penetration of CHP generation in an existing UDN, UDNP/UDNO must give a signal to potential CHP system developers that connection into the UDN will be performed under the LCTA principle and based on a number of basic ideas including: simplicity, economic efficiency and equality of treatment [194,195,196].

Every connection of a CHP scheme has a unique set of technical, commercial and environmental characteristics. Therefore it is absolutely necessary to treat every CHP system connection on a case by case basis according to the key charging methodology shown in Table 6.1 [197].

**Table 6. 1 Charging Methodology (adapted from [197])**

| Charging Method | Summary | Advantages | Disadvantages |
|---|---|---|---|
| Shallow | CHP system developer pays only for the cost of equipment needed to make the physical connection to the grid. Costs of reinforcement are borne by UDNOs. | Lowest cost for CHP system developer<br>Transparency & consistency<br>Reinforcement costs can be recovered via tariff system | Poor locational signals<br>UDNO reinforcements can add project delays |
| Deep | CHP system developer pays all costs associated with its connection. Includes the cost of physical connection to the grid and any upstream grid reinforcement costs. | CHP system developers generally don’t pay utilisation of the UDN charges<br>Provides a degree of locational signal | Cost uncertainty, often prohibitively high for CHP system developers<br>Significant UDNO power<br>One CHP system developer can pay for reinforcements caused by others |
| Mixed | CHP system developer pays for the physical connection to the grid, plus a proportion of any upstream grid reinforcement costs based on its proportional use of new grid assets | Reinforcement costs paid by CHP system developer relate to his use of the new connection assets<br>Provides some locational signals to generators | Clear rules needed to determine proportional costs<br>Reliant on UDNO to perform upstream reinforcements<br>Costs can still be high for CHP system developer |
| True | CHP system pays a cost equivalent to the cost of connecting to the nearest point on the grid with sufficient capacity to accommodate the generator without reinforcement | Provides some locational signals to CHP system developer | Connection costs potentially very high |

Selection of a proper methodology to calculate connection cost is important for four main reasons [198, 199]:

- It is essential for rational planning by an UDNP/UDNO of its UDN expansion and reinforcement
- It provides the basis for the CHP system connection according to the LCTA principle.
- To preserve the safety, reliability and service quality of the UDN
- To provide transparent and uniform technical requirements, procedures and agreements to make interconnection reasonably timely and predictable.

In addition to above mentioned particulars regarding connection of a CHP system to the UDN, there are number of key stages that a CHP system developer and the UDNP/UDNO must go through a high degree of interaction which will mainly focus on information exchange that is typically needed to take place and the essential steps that must be taken by each party to ensure the efficient completion of the connection according to the LCTA principle. For the size of CHP system normally installed in an urban area the connection process includes a number of stages described below [200]:

- CHP system planning phase during which the CHP developer formulates the operational plans for the CHP system and consults already published relevant UDNO information, such as the long term development plan, in order to identify the opportunities for the connection of the CHP system into the existing UDN.
- Information phase during which the CHP system developer submits a plan about the proposed CHP plant to the UDNP/UDNO. Based on this information the UDNO analyses and explains the configuration of the UDN and the potential technical issues and costs involved in connecting the CHP plant at a proposed point.

- Design phase in which the CHP developer submits formal documents in accordance with the UDNO's specific procedures. This needs to be accompanied by all technical and operational CHP system details that are required by the UDNP/UDNO to develop a detailed design for the CHP system connection and any associated UDN reinforcement that may be required.
- Construction phase is a stage in which the CHP developer enters into a contract with the UDNO or third party contractor for the construction of the CHP system connection or any reinforcement in the UDN. During this stage it is important that works carried out are in accordance with the required standards and that the interface between each party's construction works is properly managed
- The fourth stage described above indicate the key stages required to get to the point where there is a physical connection in place between the CHP system and UDN. At this stage, the connection needs to be tested and commissioned by the UDNO to confirm its integrity and safety and to allow the CHP system to be energised.

Stages described above are subdivided into a number of more detailed stages as shown in Fig. 6.1.

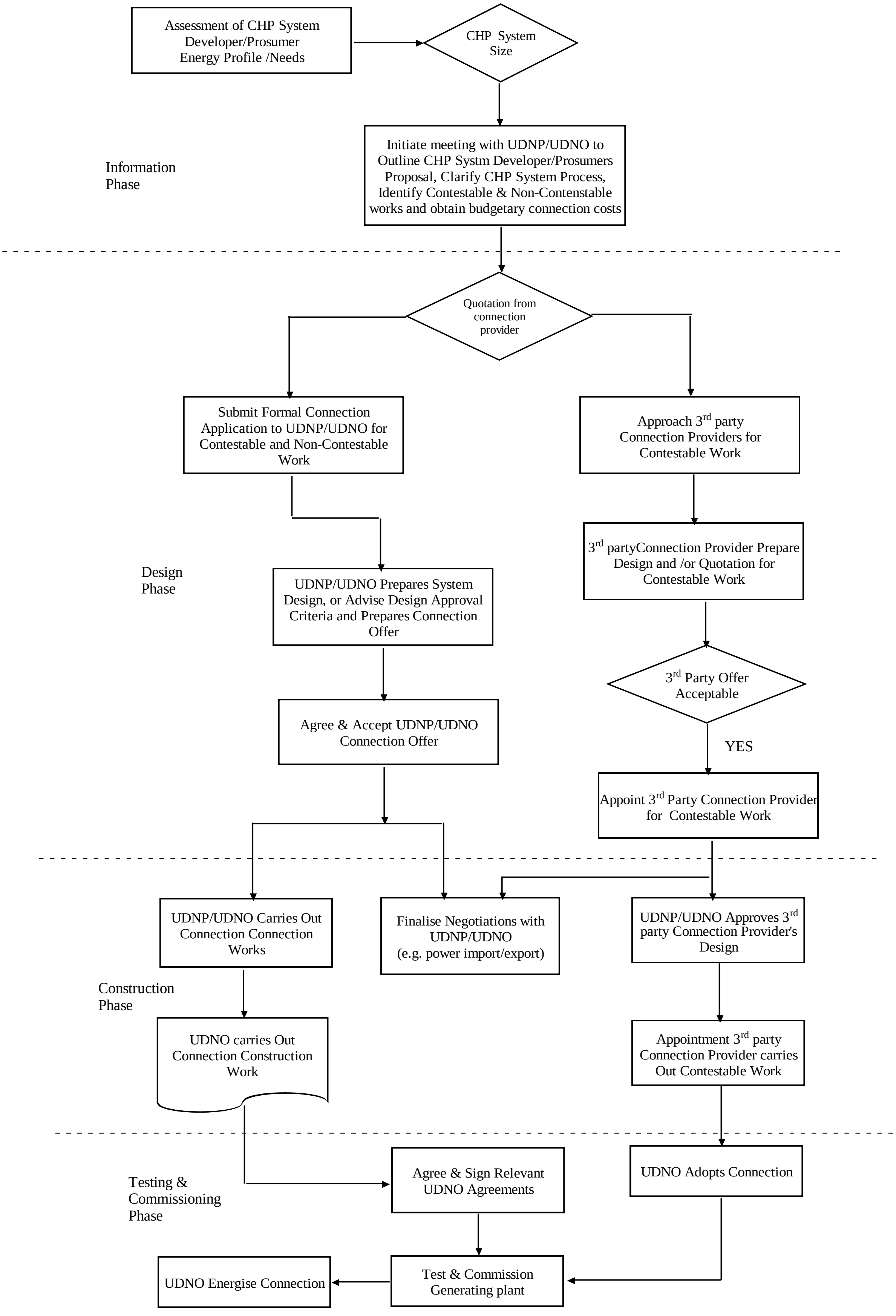


**Fig. 6.1 CHP System Connection Process**

At present, most UDNPs/UNDOs have or no little practice or none to deal with significant numbers of CHP system connections and with few effective procedures in place, to understand the effects of the CHP system on the UDN, to process a connection request efficiently and to complete the connection in accordance with the LCTA principle. The typical issues confronting the CHP developer when requesting connection to the network involves both technical and financial and in order to overcome these issues the following analysis need to be performed as shown in Fig. 6.2.

Overcoming such issues relies on information from interconnection standards and the connection application process regulations. At present, the situation with respect to standards and regulations in EU countries is such that there is no well-defined universal standard to manage the CHP generation connection into the UDN. In fact, these standards and regulations are seen in most cases as recommendations and responsibility is left to the local UDNP/UDNO to provide the adequate connection conditions. In some EU countries there are national guidelines which are used as a framework and are only slightly modified to conform to needs of the local UDN.

In most cases, it is normal practice for the UDNO to charge all the connection costs to the CHP developer. However, there are some cases in which the works carried out to provide a connection can provide benefits to the UDNO or to other users of the network. UDN reinforcement is often beneficial from the UDNO’s viewpoint and new network infrastructure installed to provide a connection for one CHP system may be used subsequently to provide connection for other network users. Under the provisions of the Electricity Connection Charges regulation, UDNOs are required to reimburse to CHP system developer an appropriate proportion of the amount they have paid for their connection in the event that the connection infrastructure is utilised by another party.

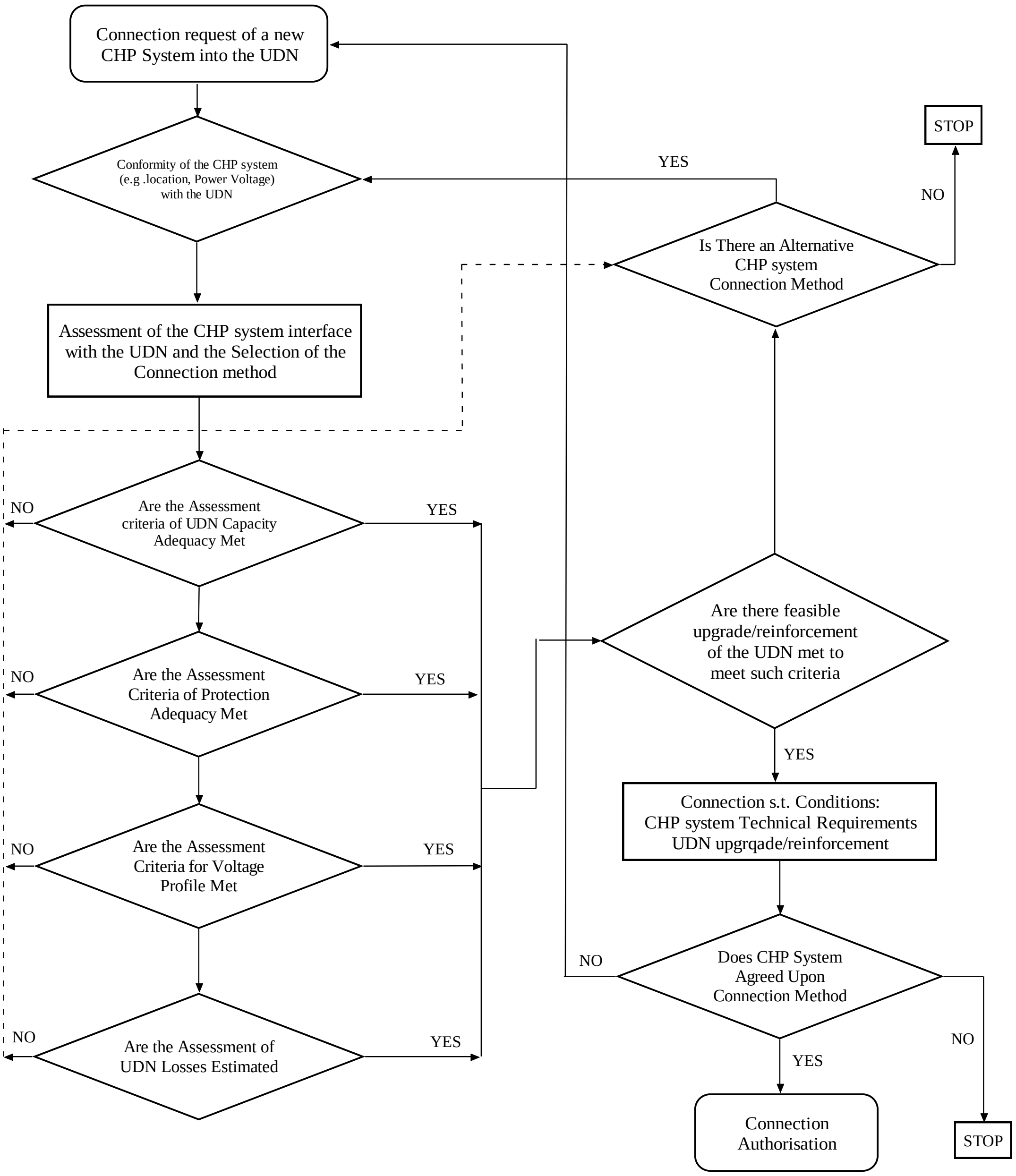


Fig 6.2  CHP System Connection & Integration Planning Process

In order to complete the CHP system connection to the UDN according to the above planning process based on the LCTA principle, the following sensitivity analyses are necessary and these are described under the headings below.

### 6.2.1 Equipment Rating

Each component of the UDN, e.q. lines, cables, transformers, have limited current carrying capacity usually described via thermal capacity. The thermal capacity rating of the UDN electrical equipment should be sufficient to facilitate the electrical power flow for which it is designed without a reduction in the mechanical properties to a level at which it could provide safe operational performance. Connection of CHP generation to the UDN has the effect of changing the current flow in the UDN and changing the shape of the load cycle seen by each component of the UDN. Connecting CHP generation into the UDN where the local load requirement is surpassed and exporting power back to the network beyond the point where the lines become congested and UDN equipment thermal ratings pose a failure risk, limits the amount of CHP generation that can be connected. In addition there is the possibility that some parts of the UDN could become overloaded in the event of an outage [201].

The maximum allowable apparent power, $S_{max}$ that can be fed through the UDN components is a function of the current and voltage and can be described by:

$$S_{max} = |P + jQ|_{max} = \sqrt{3}EI_{max} \qquad (6.1)$$

Where P(W) and Q(VAr) are the real and reactive components of the maximum allowable power flow, E(V) is the voltage level on the network where a particular component is installed and $I_{max}$(A) is the steady-state current carrying capacity of the component.

In order to connect an increasing level of CHP generation according to the LCTA principle it is necessary to apply a deterministic planning approach to upgrade the network components. One such methodology described in [202], is a desktop exercise by the UDNP/UDNO during the planning process relating to the connection of new CHP system into the UDN. The process incorporates results obtained from analysis as described in earlier chapters and is performed on a case by case basis. A method for UDN power flow management using sensitivity factors that account for thermally exposed network components limiting the CHP system connection capacity and at the same time identifying the CHP system with a power output that requires additional investment is described in [203]. At present, the capacity rating of switchgear, transformers and cables are used to determine the size of the CHP system that can be installed in the UDN at a particular location. UDN equipment short-circuit capacity ratings are also used as standards for determining the size of CHP system connection. The short-circuit level of the UDN with the additional short-circuit power added by the CHP plant must not exceed the switchgear tripping capacity. In addition, the network voltage level is used as a standard for determining the maximum size of CHP system permitted to be connected to the UDN. The connection of a CHP system must not lead the network voltages out of the UDN operating limits. The connection of CHP system may need re-enforcement of the UDN components such as switchgears, transformers, cables or other UDN operating devices. Detailed analysis must be done to define the correlation between the costs of upgrading the network assets and the costs of connecting a CHP system at a particular busbar in the UDN. In current practice, the CHP system developer is liable for the cost relating to network equipment upgrading.

### 6.2.2 Protection Sensitivities

Both the increased number and the electrical power output of CHP plants connected to UDNs changes the characteristics of these networks. As a consequence, UDN and CHP plant generator protection must fit new requirements, both on economic and technical grounds. Currently UDNs are subjected to a variety of events leading to disturbances of their proper operational behaviour. Most of these disturbances are small and include unforeseen imbalances in generations and loads along with accepted overload and voltage deviation.

Large disturbances are generally related to faults and they are accompanied by large current and voltage deviations that can lead to serious network equipment damage. A significant contribution to the fault-current by CHP plant affect the protection system of the UDN. Because fault currents are affected by the CHP plant connection, measured currents used for protection purposes are affected as well. This can lead to incorrect operation of the network protective system and is manifest in detection, sensitivity and selectivity problems [204,205 ].

The fact that the presence of CHP generation provides an additional contribution to the fault level and also that the embedded nature of the CHP generation makes fault current calculation more complex, the UDNP/UDNO should take into account the effect of all this on the UDN protection system operation to a degree not required when all power supply in the UDN originally were supplied via HV/MV substation.

The fault current level contribution from CHP system connection is determined by a number of factors that include [109]:

- The size and location of the CHP plant
- The operational access mode of the plant
- The distance of the CHP plant from the fault point
- Whether or not transformers are present between the fault location and the contributing CHP plant as transformer short circuit impedance may assist in limiting the fault current
- The configuration of the network between the CHP plant and the fault as different paths for the flow of the fault current will alter the magnitude of the fault current level (due to cable impedance and other installed equipment).

- The method of coupling of the CHP plant to the UDN. Directly connected CHP plant will contribute significantly higher towards fault current than a CHP plant connected via a power electronics interface.

In order to achieve the main objective of a protective relay system, which is the detection of a typical UDN operational fault condition as quickly as possible, it is necessary to take action to bring the network to a normal operational condition as outlined in diagram shown in Fig. 6.3 below.

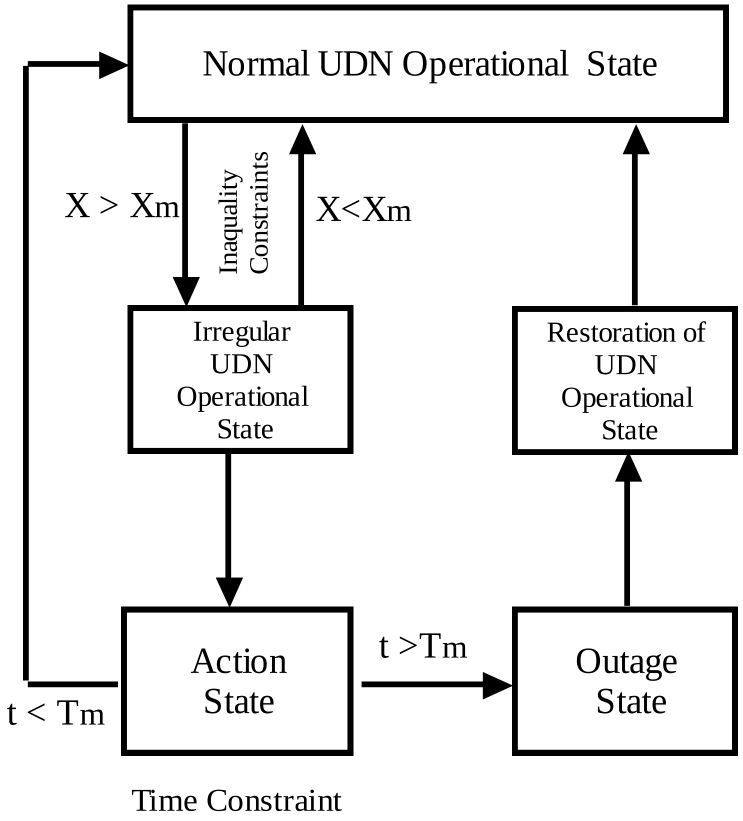


**Fig 6.3 Operational Process of UDN Protection System (adapted from [205, 206])**

In Fig 6.3 X is an observed UDN fault quantity, t is the time elapsed from the beginning of the disturbance and $X_m$, $T_m$ are certain thresholds of protection relay settings.

Traditionally, requirements for network protection system applied in the UDN are based on the requirements outline in ESB Document (Ref: DTIS-250701-BDW Issued October 2012) listed in Appendix 4 and IEEE 1547 standard which provides limited real guidance and highlights only the essential requirements. Newer imposed standards are gradually being developed towards more detailed requirements for network integration of CHP generation in the UDNs. Requirements demanded by the currently employed standards include:

- No over-voltage or loss of UDN relay operational coordination
- Disconnection of the CHP plant when no longer operating in parallel with the UDN
- No activation of the UDN when the network is in the de-energised state
- No creation of unintentional islands
- Use UDN graded relays

To fully comply with established operational procedures for UDN system protection subjected to the requirements listed above, the CHP connection process must also coincide with the general concepts of protection system normally employed in UDNs and explained in [206, 207, 208]:

- Reliability of a protection system: the ability of the protection system to operate correctly.
- Security of a protective system: the ability of a system or device to refrain from unnecessary operation.
- Sensitivity of a protective system: the ability of the system to identify an irregular operational condition that exceeds a certain operational UDN threshold.

- Selectivity of a protective system: the ability to maintain continuity of supply by disconnecting the minimum sized section of the network necessary to isolate a fault condition.

The protection system needs to satisfy both UDN and CHP system requirements to balance complexity and the cost of the protection system installation/modification in order to facilitate connection of CHP generation plant into in the UDN. In addition, the protection system design strategy regarding the connection of CHP generation must achieve the lowest possible cost with minimal impact on the existing protection system. Determining the protection system settings involves selecting the parameters that define the required time, tripping current, voltage and frequency characteristics. These parameters have to be selected in such a way that the protective system operates reliably and that selectivity is guaranteed, see Fig 6.4. Normally the CHP system interface protection is designed to disconnect the system from the UDN during abnormal network conditions by tripping a dedicated circuit breaker or recloser located as close as is practically possible to the interface between the IPP equipment and the network. The main objective of the CHP system interface protection is to preserve the safety of the network personnel, the general public and avoid damage to the UDN [209]. Once the protection system configuration has been established from the correct protection requirements in combination with appropriate grading/settings, required protection devices can lead to an effective simple and economically feasible UDN/CHP system protective system.

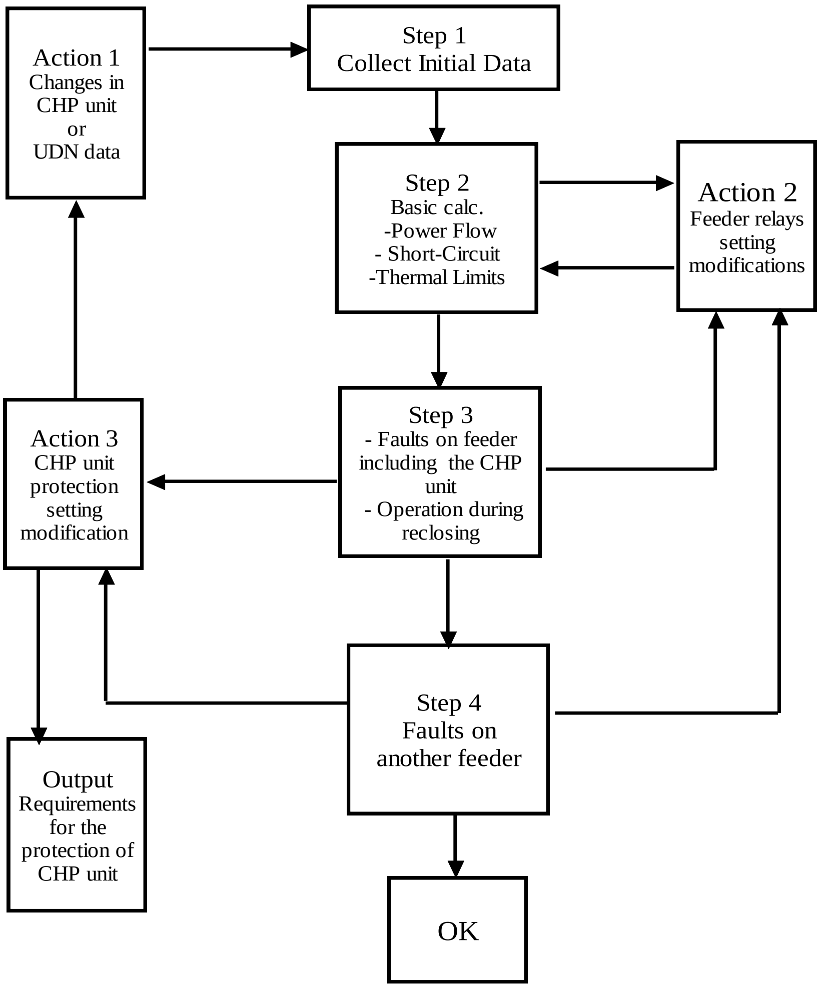


**Fig 6.4 Procedure for CHP Generation Protection Interconnection Studies (adapted from [204])**

In the Irish context, CHP systems are normally connected into the UDN according the method shown in Fig 6.5. In this process it is absolutely vital to determine what CHP generation plant interface protection (CHPIP) if is required to install as well as the settings which should be applied to each protection function outlined in Appendix 4.

Once the protection hardware has been established from the correct protection requirements, the relevant settings for the required CHPIP relays can be obtained as Table 4L in Appendix 4.

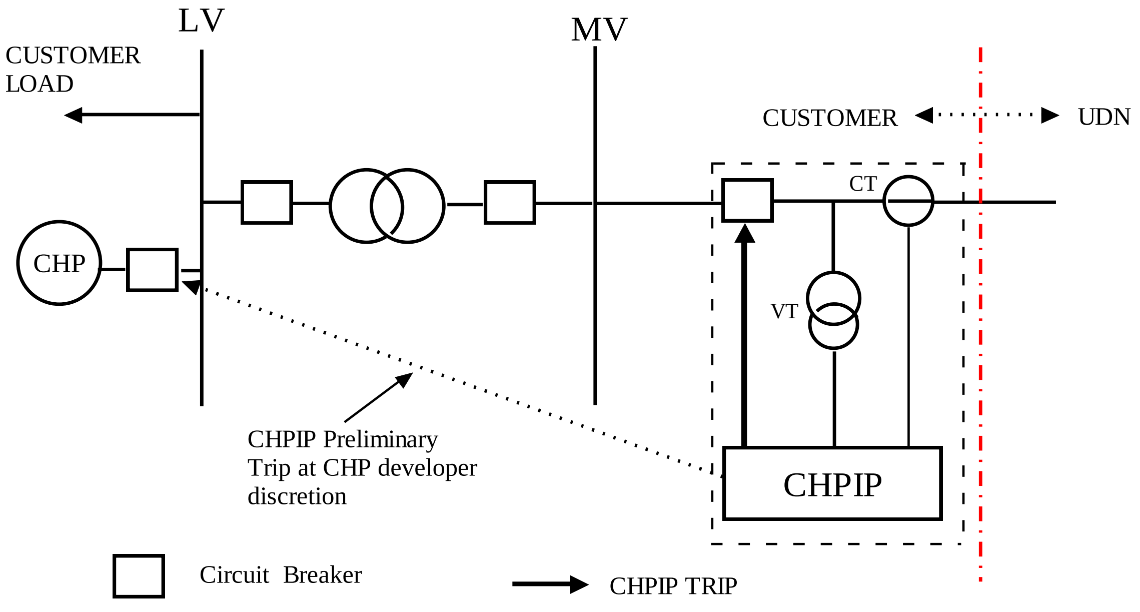


**Fig. 6.5: MV connected CHP System ≤ 2MVA installed capacity (adapted from [209])**

In all operational cases, CHPIP must measure system quantities and be wired to trip a circuit breaker or recloser, located as close as is practically possible to the interface point, between the CHP system developer site and the UDN. The quantities measured must facilitate protection requirements provided by CHPIP system and these include: frequency protection, voltage protection, overcurrent protection, earth fault protection, and loss of mains protection. In the case where the CHP generation is one part of a customer installation an additional approach may be considered by the customer whereby the CHPIP is configured for two stage tripping of circuit breakers with downstream customer generator breaker tripping faster than the main incoming circuit breaker. In such instances, the UDNO will, at its discretion, specify alternative CHPIP trip times to be applied to the main incoming circuit breaker and the generator circuit breaker to allow for time tripping coordination. Where a CHP developer is concerned about the potential impact of rate of change of frequency (ROCOF) protection on the non-generation part of the CHP system , the required loss-of-mains protection can instead be implemented by means of an inter-tripping scheme designed by the UDNO.

According to the current ESB network regulations ( listed in Appendix 3), the CHPIP can either be incorporated within the CHP system or provided by separated devices. In either case the CHPIP shall meet the relevant standards and the manufacturer/developer of the CHP system shall declare that the combined devices fulfil these requirements. The CHPIP shall cease energise/disconnect ESB's network when any parameter exceeds the applied operational setting and in addition disconnection is required in case of any hardware malfunctioning. However, it is recognised by the network operator that CHP system installed in urban area are special case by virtue of their type of operation and potentially large numbers, therefore it is acceptable to dispense with the isolator to be accessible at all times, subject to the provision of two means of automatic disconnection with a single control. Under current conditions governing connection and operation of CHP system in Ireland, at least one of the means of disconnection must be provided by the separation of mechanical contacts. The CHPIP settings may only be altered, from those in place at the time of commissioning, with the written agreement of ESB Networks and then only in accordance with the CHP system manufacturer instruction. Any change of the CHPIP setting may cause a breach making re-testing/re-setting of CHPIP necessary unless the CHP system and CHPIP are type tested on the full setting range of the interface protection.

It is possible that a part of the UDN to which the CHP system is connected can during emergency conditions, becomes detached from the rest of the network as an island network section. The UDNO may decide, based on local network conditions, if it is feasible for the CHP system to continue to supply the islanded part of the UDN, see Fig. 6.6.

Island operational modes are not essentially harmful to UDNs although most UDNOs require some form of anti-islanding operation due to the associated network operational problems associated with islanding which include:

- Complying with UDN regulatory limits frequency and voltage control during island operation and reconnection of CHP system while achieving acceptable power quality.
- Arranging adequate earthing including provision for earthing of the neutral of the island network.
- Managing the large increase in loads a CHP system may not be capable of supporting the island operation and this may result in damage to the CHP system generator as it speeds up in attempt to meet the load demand.
- Requirement of significant level of ancillary equipment to permit island mode of operation.
- Difficulties in ensuring that all relevant UDN operational/maintenance staff can react in a coordinated manner with each other during island operation.

Under present design/operational practice of UDNs, islanding operation is not allowed in most cases due to the problems listed above. Due to the fact that a large number of CHP units is expected to be connected to the UDN, as a consequence, demand for island operational mode will increase. In the event of an incoming supply failure to an area of the UDN in which CHP generation is installed, the protection system can be set to operate (on the basis of the rate of frequency change) to island the CHP generation plant and part of the affected UDN in order to ensure that at least part of the network remains supplied. To facilitate island mode operation of the network, the UDNO will be required to install more complex interface protection equipment to satisfy safety and supply quality criteria.

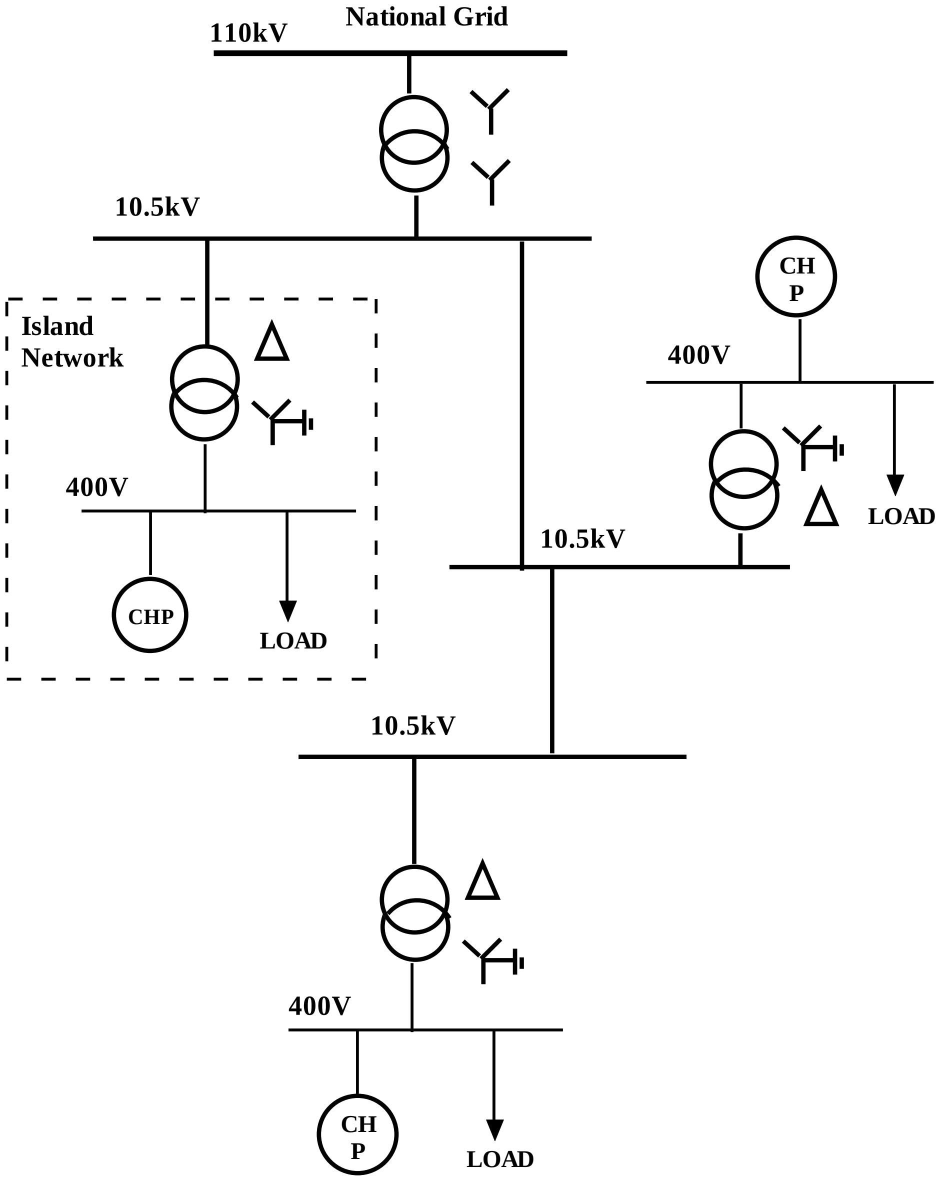


Fig 6.6 Typical UDN arrangement with an Island network using CHP system support

An additional cost that also has to be accounted for is a secure communications channel from the CHP system to the UDNO control centres. By having the ability to operate in island mode, the UDNO will benefit from reductions in Customer Supply Time Lost (CSTL) and Customer Supply Interruption (CSI) that are used to measure quality of the supply availability. The economics are dependent on the value of lost load, the outage duration and avoided penalties that could be imposed in the event that the islanding scheme does  not meet the quality of the supply. Such benefits could be outweighed by the cost of implementing an island scheme that addresses these safety and quality concerns.

### 6.2.3 Voltage profile deviation

It is the responsibility of the UDNO to ensure that its network  operats within the limits defined  by the Electricity Supply Regulations. At present, the general practice applied by UDNPs/UDNOs is to limit the capacity of the connected CHP system based on the extreme conditions of minimum load and maximum generation. In this context, evaluation of voltage profiles under critical conditions is a part of  network design. In order to keep voltage fluctuations within permissible limits defined by the local UDNO, voltage control in UDNs is carried out automatically by OLTC on HV/MV transformers and reactive power compensation is normally installed at the consumer's site. In addition, the UDNO will adjust the turns ratio of the MV/LV transformer windings  so that at times of maximum load the most remote customer will receive an acceptable voltage level, just above the minimum value. On the other hand, during minimum load conditions the voltage received by all customers is just below the maximum allowed.

The robust specification of passive UDN effectively minimises voltage variations across a wide range of the network operating conditions. Therefore, voltage considerations may drive the design capacity of the UDN mainly due to the fact that the ratio of resistance over reactance of UDN circuits is usually significant and therefore distribution of active power through these circuits makes a substantial impact on the voltage profile. This is the opposite to that in transmission system where reactive power flow determines voltage profile. In the context of CHP system connection pricing, the UDNP/UDNO can treat network loading as the primary cost driver and to facilitate the voltage profile within the operational limits set by the local UDNO, actual network power flow capacity must be greater than the maximum power flow in order to keep the volt drop within the network operational limits. With CHP system connection at the consumer site and with an output that causes reduction of the power flow in the upstream circuit, the CHP system will reduce demand for increased network capacity and will postpone the demand for network reinforcement [211].

In order to determine the impact of the CHP system connection on the network voltage deviation and on network losses and at the same time assess the network operational efficiency, the proposed methodology is shown Fig 6.7. It indicates existence of a correlation between the voltage level and the magnitude of the current flow through the branches with network losses. The outcome of any analysis performed according to the strategy suggested in Fig 6.7, besides the determination of voltage profile deviation, and network power loss sensitivity indexes can be used to assess the network equipment ratings and to some degree network protection settings. In the case where the size of the CHP system connection is to be evaluated, the UDNP/UDNO must consider a number of operational cases to determine the relationship between the voltage variation, network losses, magnitude of the network currents and size of the CHP system installed. The nature of this relationship will determine the need for the network modifications. These modifications will have a substantial impact on the CHP system connection cost imposed by UDNO on the CHP system developer. Furthermore, results from this analysis can be used to identify the part of the network that is significantly affected and also provide remedies for mitigation of the adverse impact on the UDN caused by CHP system connection.

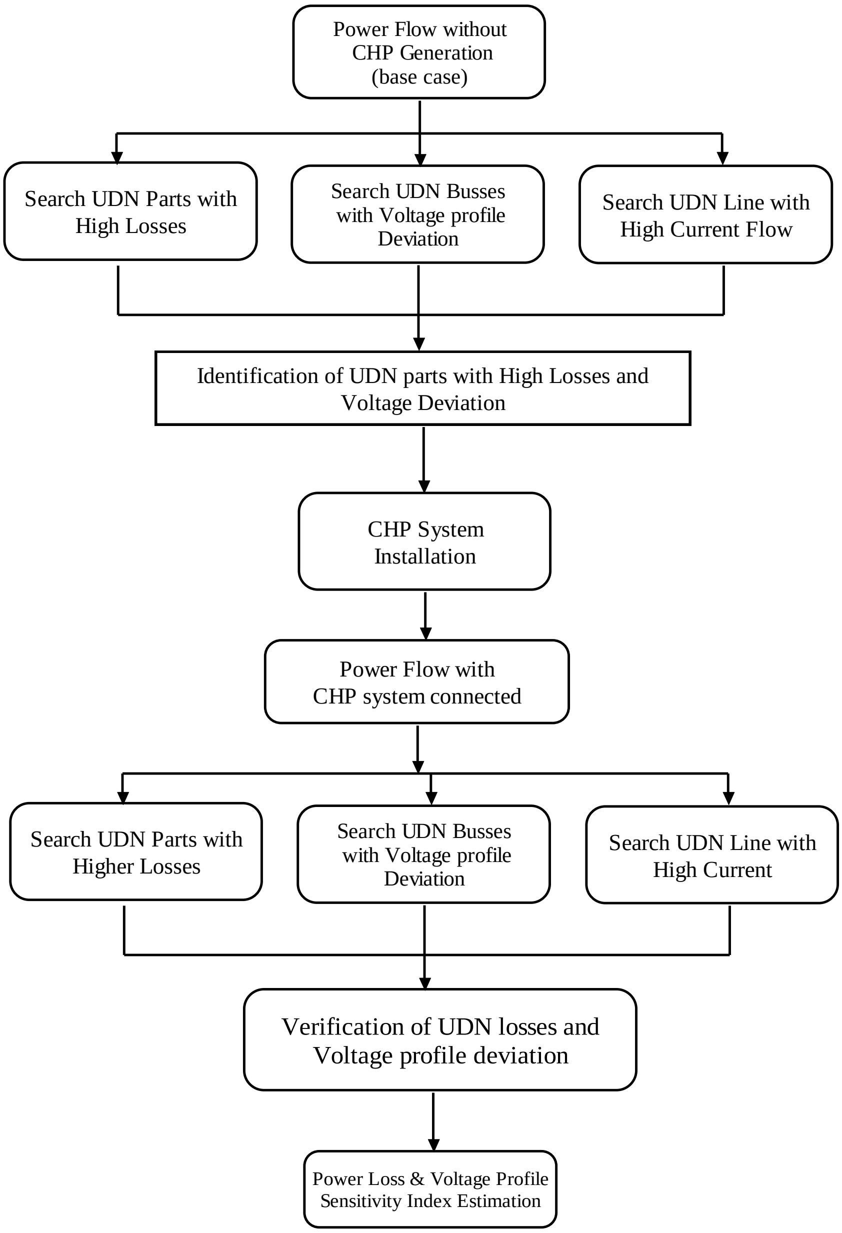


**Fig. 6.7 Methodology for establishing impact of CHP system connection concerning UDN technical operational issues.**

The acceptable range of voltage deviation depends on the regulation compliance of different network operators. In Republic of Ireland, the limits of voltage variations in UDNs are -10%/+10% in normal operating conditions. Using the results obtained by the methodology outlined in Fig 6.7 the voltage deviation at any particular busbar in the network caused by load deviation can be defined as the difference between the nominal voltage (voltage defined by the UDNO for any particular busbar) and the actual voltage level under different network load conditions.

In order to determine the overall impact of the load variation on the network voltage profile, the total voltage deviation (TVD) needs to be determined and it is defined as the sum of squared value of absolute voltage difference between the nominal voltage and the actual voltage for all busses in the network under investigation and can be written as [214]

$$\mathrm{TVD} = \sum_{i=1}^{N} \left|V_{nom,i} - V_i\right|^2 \qquad (6.2)$$

where:

N is the number of busses

$V_{nom,i}$ is the nominal voltage at bus i

$V_i$ is the actual voltage at bus i

Connecting the CHP system into the network, the voltage deviation can be written as

$$\mathrm{TVD}_{CHP} = \sum_{i=1}^{N} \left|V_{nom,i} - V_{CHPi}\right|^2 \qquad (6.3)$$

where

$V_{CHPi}$ is the actual voltage after CHP system is connected

The change in the voltage deviation of the network due to the CHP system connection can be calculated by subtracting eq. 6.2 from eq. 6.3.

$$\Delta TVD = \sum_{i=1}^{N} \left[ \left| V_{nom,i} - V_i \right|^2 - \left| V_{nom,i} - V_{CHP} \right|^2 \right] \qquad (6.4)$$

Finally, the total voltage profile deviation index (TVPDI) of the network can be defined as the ratio of (6.3) and (6.2) and is written as:

$$\text{TVPDI} = \frac{TVD_{CHP}}{TVD} \qquad (6.5)$$

In order to demonstrate the impact of CHP system connection on the network voltage profile, the TVPDI is calculated under different loading levels without and with CHP system connected.

This analysis will examine the impact of a newly connected CHP system on 0.4kV B14-1 busbar in the network shown in Fig 3.8 via the voltage deviation index through observation of voltage profile deviation on a number of critical busbars. This is determine under a number of loading scenarios of the feeder where the proposed CHP system is connected through selection by the UDNO based on preliminary network operational analysis described in earlier chapters. The operational setting of the CHP system can be described as integrated and non-dispatchable with electrical; capacity of 520kW and 171kVAr. In order to determine the voltage profile deviation on the busbar under investigation, ERAC load flow simulation analysis is performed under different loading scenarios with the CHP system ON and OFF. Results obtained from load flow analysis show the voltage profile deviation and total voltage profile deviation index and these are tabulated in Table 6. 3a, 6.3b, 6.3c, and 6.3d and also presented in graph form in Fig 6.8, Fig 6.9 and Fig 6.10. The reference voltage level for each network busbar is normally defined by the UDNO based on the network preliminary studies explained in earlier chapters. For this analysis the voltage profile for each busbar

,corresponding to the load of 50% of nominal feeder capacity, at following busbars: B11; B12; B13; B14 and B15 is used as a reference.

**Table 6.2 Load and CHPs output profile**

|  | Feeder Load |  |  | CHPs Output |  | CHPs + New CHP Output |  |
|---|---|---|---|---|---|---|---|
| No | Load % | P (kW) | Q (kVAr) | P (kW) | Q (kVAr) | P (kW) | Q (kVAr) |
| 1 | 10 | 843 | 269 | 1950 | 690 | 2470 | 861 |
| 2 | 20 | 1686 | 538 | 1950 | 690 | 2470 | 861 |
| 3 | 30 | 2529 | 807 | 1950 | 690 | 2470 | 861 |
| 4 | 40 | 3372 | 1076 | 1950 | 690 | 2470 | 861 |
| 5 | 50 | 4215 | 1345 | 1950 | 690 | 2470 | 861 |
| 6 | 60 | 5058 | 1614 | 1950 | 690 | 2470 | 861 |
| 7 | 70 | 5901 | 1883 | 1950 | 690 | 2470 | 861 |
| 8 | 80 | 6744 | 2152 | 1950 | 690 | 2470 | 861 |
| 9 | 90 | 7587 | 2421 | 1950 | 690 | 2470 | 861 |

**Table 6.3a Voltage profile without CHP system (V)**

| Voltage profile without CHP system (V) |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| B2 | B11 | B12 | B13 | B14 | B15 | B24 | B34 |
| 10820 | 10846 | 10867 | 10878 | 10879 | 10880 | 10675 | 10573 |
| 10769 | 10776 | 10780 | 10777 | 10773 | 10771 | 10622 | 10520 |
| 10709 | 10696 | 10683 | 10665 | 10656 | 10651 | 10562 | 10459 |
| 10643 | 10609 | 10578 | 10544 | 10530 | 10521 | 10494 | 10391 |
| 10568 | 10513 | 10463 | 10412 | 10393 | 10380 | 10419 | 10314 |
| 10485 | 10406 | 10336 | 10267 | 10242 | 10224 | 10334 | 10228 |
| 10389 | 10286 | 10194 | 10106 | 10074 | 10052 | 10236 | 10130 |
| 10280 | 10151 | 10035 | 9925 | 9887 | 9859 | 10125 | 10018 |
| 10153 | 9994 | 9852 | 9718 | 9673 | 9639 | 9996 | 9886 |

**Table 6.3b Voltage profile after proposed CHP system connection (V)**

| Voltage profile after CHP system connection (V) |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| B2 | B11 | B12 | B13 | B14 | B15 | B24 | B34 |
| 10851 | 10889 | 10942 | 10949 | 10955 | 10957 | 10706 | 10605 |
| 10803 | 10822 | 10841 | 10852 | 10855 | 10853 | 10657 | 10555 |
| 10747 | 10747 | 10749 | 10746 | 10744 | 10738 | 10600 | 10498 |
| 10685 | 10664 | 10650 | 10631 | 10624 | 10615 | 10537 | 10434 |
| 10615 | 10574 | 10541 | 10506 | 10494 | 10481 | 10467 | 10363 |
| 10538 | 10474 | 10421 | 10370 | 10353 | 10335 | 10387 | 10283 |
| 10449 | 10362 | 10289 | 10219 | 10196 | 10173 | 10297 | 10192 |
| 10349 | 10236 | 10141 | 10051 | 10022 | 9995 | 10195 | 10088 |
| 10233 | 10093 | 9974 | 9862 | 9826 | 9793 | 10078 | 9969 |

## Table 3c Voltage profile deviation without proposed CHP system connected (V)

| Voltage profile deviation without proposed CHP system connected (V) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Load % | B2 | B11 | B12 | B13 | B14 | B15 | B24 | B34 |
| 10 | 252.0 | 333.0 | 404.0 | 466.0 | 486.0 | 500.0 | 256.0 | 259.0 |
| 20 | 201.0 | 263.0 | 317.0 | 365.0 | 380.0 | 391.0 | 203.0 | 206.0 |
| 30 | 141.0 | 183.0 | 220.0 | 253.0 | 263.0 | 271.0 | 143.0 | 145.0 |
| 40 | 75.0 | 96.0 | 115.0 | 132.0 | 137.0 | 141.0 | 75.0 | 77.0 |
| 50 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 60 | -83.0 | -107.0 | -127.0 | -145.0 | -151.0 | -156.0 | -85.0 | -86.0 |
| 70 | -179.0 | -227.0 | -269.0 | -306.0 | -319.0 | -328.0 | -183.0 | -184.0 |
| 80 | -288.0 | -362.0 | -428.0 | -487.0 | -506.0 | -521.0 | -294.0 | -296.0 |
| 90 | -415.0 | -519.0 | -611.0 | -694.0 | -720.0 | -741.0 | -423.0 | -428.0 |

## Table 3d Voltage profile deviation with proposed CHP system connected (V)

| Voltage profile deviation with proposed CHP system connected (V) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Load % | B2 | B11 | B12 | B13 | B14 | B15 | B24 | B34 |
| 10 | 283.0 | 376.0 | 479.0 | 537.0 | 562.0 | 577.0 | 287.0 | 291.0 |
| 20 | 235.0 | 309.0 | 378.0 | 440.0 | 462.0 | 473.0 | 238.0 | 241.0 |
| 30 | 179.0 | 234.0 | 286.0 | 334.0 | 351.0 | 358.0 | 181.0 | 184.0 |
| 40 | 117.0 | 151.0 | 187.0 | 219.0 | 231.0 | 235.0 | 118.0 | 120.0 |
| 50 | 47.0 | 61.0 | 78.0 | 94.0 | 101.0 | 101.0 | 48.0 | 49.0 |
| 60 | -30.0 | -39.0 | -42.0 | -42.0 | -40.0 | -45.0 | -32.0 | -31.0 |
| 70 | -119.0 | -151.0 | -174.0 | -193.0 | -197.0 | -207.0 | -122.0 | -122.0 |
| 80 | -219.0 | -277.0 | -322.0 | -361.0 | -371.0 | -385.0 | -224.0 | -226.0 |
| 90 | -335.0 | -420.0 | -489.0 | -550.0 | -567.0 | -587.0 | -341.0 | -345.0 |

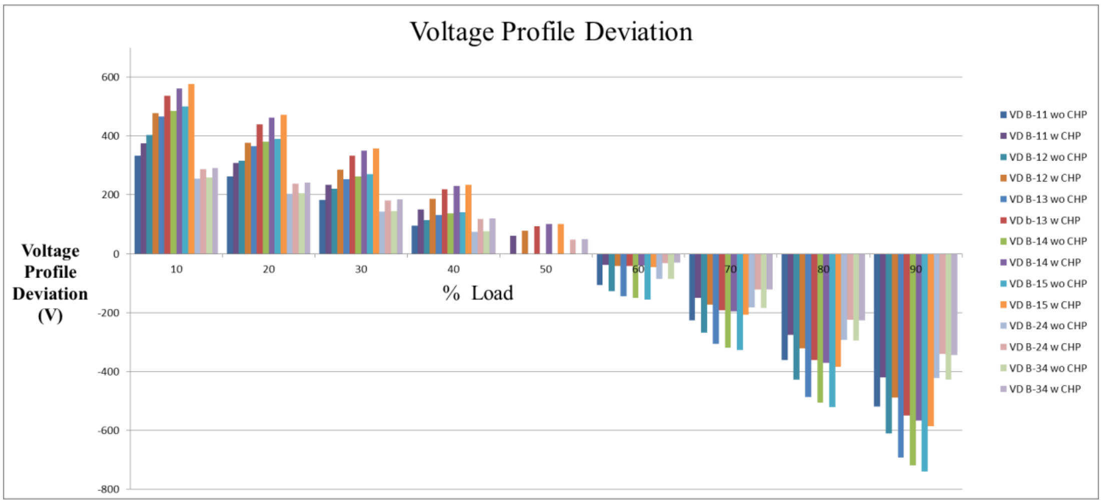


**Fig 6.8 Voltage Profile Deviation**

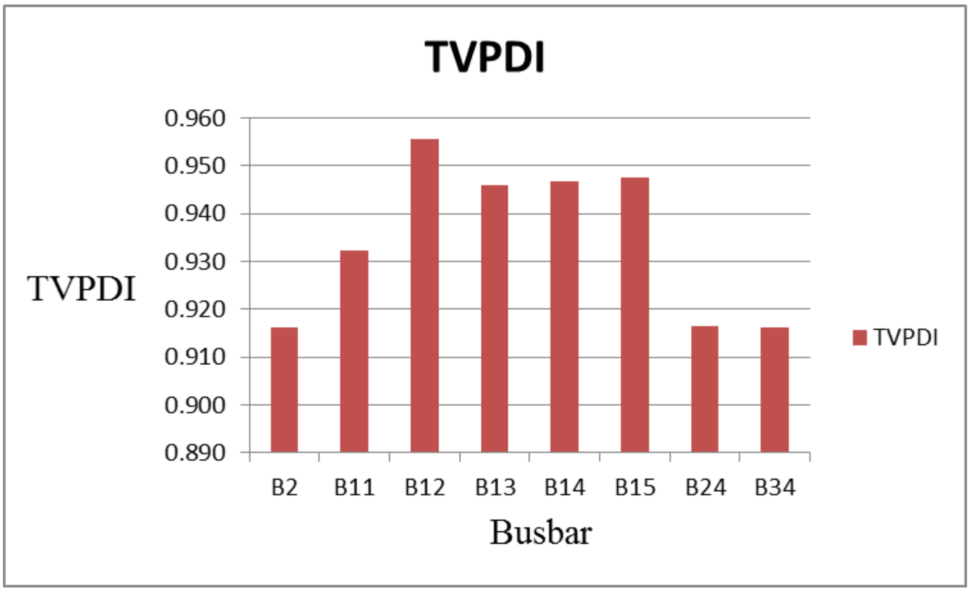


**Fig 6.9 TVPDI with respect to network busbars of interest under different load profile**

TVPDI is dimensionless value obtained from equation (6.5) and it is used to indicate the most critical points (in this case busbars) in the network regarding the voltage profile deviations caused by connection of the CHP system Fig 6.9. In Fig 6.10, it also indicates the voltage profile deviation in the network (or part of the network) of interest under different network load profiles with the CHP system connected.

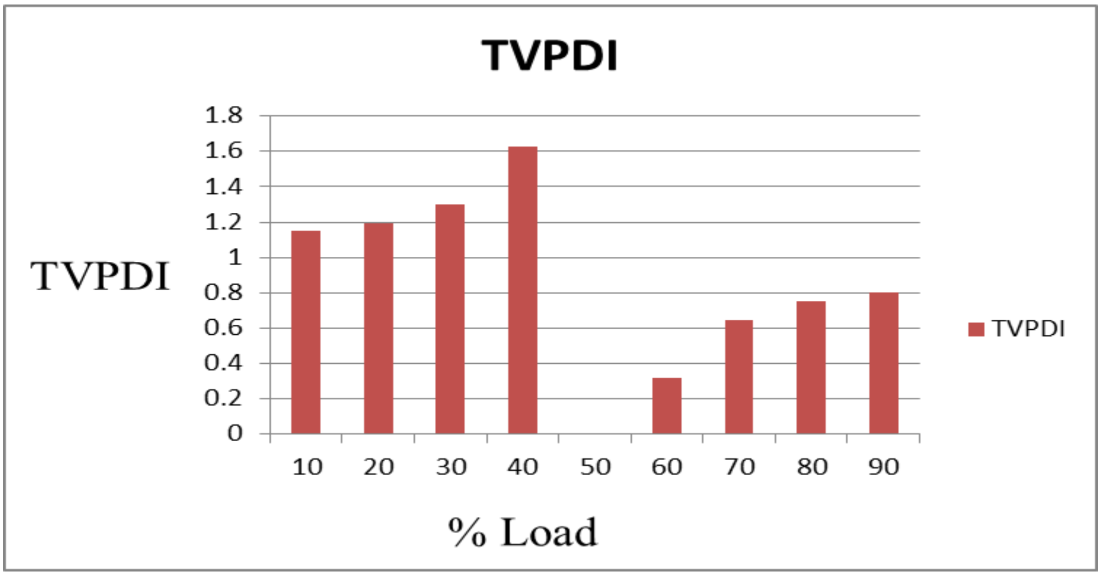


**Fig 6.10 TVPDI with respect to the network of interest (consists of B2, B11, B12, B13, B14, B15, B24, B34) under different load profile**

[Note: In order to determine TVPDI with respect to the network of interest Fig 6.10, UDNO normally defines the 50% load as a reference with respect to the voltage level across the network of interest. As can be seen in Table 3c, voltage profile deviation is zero and therefore, TVPDI for load of 50% can not be estimated using equation (6.5). However, the state of voltage profile deviation at 50% loading can be estimated from data presented in Table 3d regarding 50% loading.]

In general a CHP system connection into the UDN improves the voltage profile and reduces the voltage deviation. However, this analysis will give an indication to the UDNO, what action needs to be taken in order to facilitate connection of the proposed CHP system into the network regarding the voltage profile deviation. In addition it will also provide an indication as to which part of the network needs to be upgraded and to what level that upgrade should be carried.

From the above results it can be seen that busbars B15; B14 and B13 are experiencing considerable voltage deviation that require action by the UDNO in order to reduce the VPD to the acceptable network operational level. In addition to this information regarding the voltage deviation of any particular busbar, the voltage deviation index will also indicate to the UDNP/UDNO what action needs to be taken in order to mitigate voltage deviation caused by CHP system connection. There are number of methods to improve voltage profile and minimise the voltage deviation and at present the most applicable methods used in existing UDNs include [215]:.

- Application of voltage-regulation equipment in the UDN substations (MV/LV)
- Application of capacitors in the UDN MV/LV substations
- Balancing the load on the network primary feeder
- Increasing feeder conductor size

- Transferring the loads to new feeders
- Increasing of primary voltage level
- Application of shunt/series capacitors on the primary feeders.

The selection of the method or methods will depend on the particular network requirements needed to accommodate the new CHP system corresponding to the LCTA connection principle.

### 6.2.4 Impact of Proposed CHP system Connection on the UDN Losses

Appropriate and fair allocation of losses is very important for efficient operation of the network which can affects future sitings of CHP systems and UDNs development. Electrical loss allocation is mainly an economic consideration and can represent a considerable UDN operational cost. However, similar to any other cost they must be balanced against other costs and objectives and therefore their absolute minimisation may not be always desirable. Power losses in networks vary due to a number of factors depending on the network configuration, such as the level of losses through network lines, transformers etc. Normally, power losses are divided into two categories real/reactive power losses and technical/non-technical losses. Technical losses are due to the transport of electrical power energy, related to the characteristics of the UDN, through supply demand and the types of equipment in use. They are inherent to the transport of electricity and cannot be eliminated but they can be computed and controlled, provided the network in question consists of known quantities of loads and the output/operational settings of DG/CHP systems connected into the network are also known to the UDNO. On the other hand non-technical losses are caused by actions external to the UDN. They are more difficult to evaluate because these losses are often uncounted for by UDNO and thus have no recorded information. These losses occur mainly as a result of metering inaccuracy and unmetered energy. The CHP generation connection may contribute to the reduction or increase of UDN losses, and this issue primarily depends on the CHP system location, size and the network structure and configuration. In addition, it is necessary that those elements are thoroughly considered while assessing the CHP impact on the UDN losses.

To estimate the effects of network loss reduction/increase on the network operational efficiency, it is necessary to calculate the changes of losses caused by connection of the CHP generation.

In order to determine the impact of the CHP system connection on network losses and at a same time assess the network operational efficiency the following methodology is suggested and it is presented in algorithm on Fig 6.7.

The amount of active and reactive power losses without the proposed CHP system connected for the network shown in Fig. 6.11 can be written as [213]:

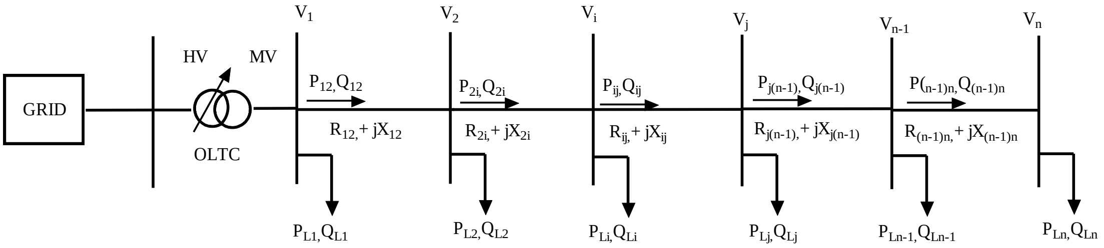


**Fig.6.11 Typical UDN feeder without CHP system connected**

$$P_L = \sum_{i=1}^{n} \frac{P_i^2 + Q_i^2}{|V_i|^2} R_i \qquad (6.6)$$

$$Q_L = \sum_{i=1}^{n} \frac{P_i^2 + Q_i^2}{|V_i|^2} X_i \qquad (6.7)$$

where:

$R_i$ is the resistance of branch i

$X_i$ is the reactance of branch i

$|V_i|$ is the voltage magnitude at bus i

As show in Fig 6.12 due to the active and reactive power injected at bus m, the active and reactive powers flowing from the HV/MV substation to bus m is reduce, but the active and reactive power flow in the rest of the feeder stay the same. Using the same analogy used the equation (6.6) power losses for the network feeder shown in Fig. 6.12 can be written [213].

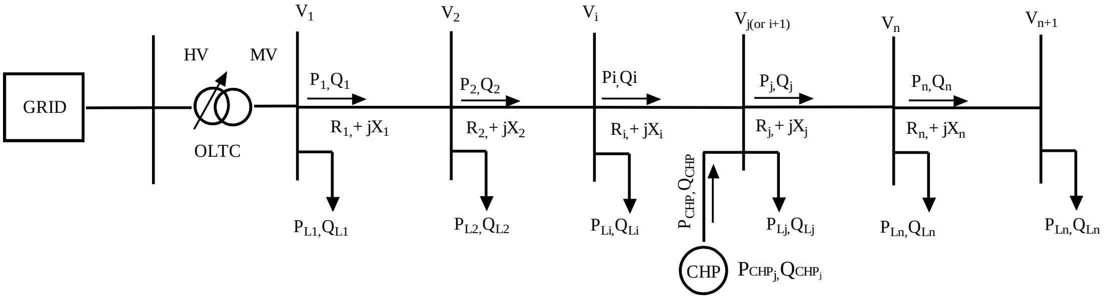


**Fig 6.12 Typical UDN feeder with CHP system connected**

$$\mathrm{P_{LCHP}} = \sum_{\mathrm{i=1}}^{\mathrm{m}} \frac{(\mathrm{P_i} - \mathrm{P_{mCHP}})^2}{|\mathrm{V_i}|^2}\mathrm{R_i} + \sum_{\mathrm{i=m+1}}^{\mathrm{n}} \frac{\mathrm{P_i^2}}{|\mathrm{V_i}|^2}\mathrm{R_i} +$$

$$+ \sum_{\mathrm{i=1}}^{\mathrm{m}} \frac{(\mathrm{Q_i} - \mathrm{Q_{mCHP}})^2}{|\mathrm{V_i}|^2}\mathrm{R_i} + \sum_{\mathrm{i=m+1}}^{\mathrm{n}} \frac{\mathrm{Q_i^2}}{|\mathrm{V_i}|^2}\mathrm{R_i} \qquad (6.8)$$

$$Q_{LCHP} = \sum_{i=1}^{m} \frac{(P_i - P_{mCHP})^2}{|V_i|^2}X_i + \sum_{i=m+1}^{n} \frac{P_i^2}{|V_i|^2}X_i +$$

$$+\sum_{i=1}^{m}\frac{(Q_i - Q_{mCHP})^2}{|V_i|^2}X_i + \sum_{i=m+1}^{n}\frac{Q_i^2}{|V_i|^2}X_i \qquad (6.9)$$

To estimate the impact of the proposed CHP system connection on the UDN losses the UDN loss index (LI) can be written as [216]

$$LI = \frac{Losses_{With\ CHP}}{Losses_{Without\ CHP}} \qquad (6.10)$$

There are number of significant factors that influence the actual UDN power losses, the complexity of these factors is often a problem in practical applications.

The estimated total energy losses in a UDN for one year with a time duration usually (Δt) of 1 hour can be written as:

$$E_{loss} = 365\sum_{t=1}^{24} P_{loss}\,\Delta t \qquad (6.11)$$

At present, the approach used in computing annual losses in a UDN where a CHP system has been connected, is based on equation (6.11). Therefore, UDN losses should be calculated for every hour of the year and this will require a load flow analysis for each hour, taking into account load levels and CHP system production at that hour.

To analyse the overall impact of the CHP system connection on the network losses, for this analysis, several scenarios with different load levels were created. CHP system impact on losses was measured for the scenarios considered and compared with the losses for the case without CHP system connection. An additional calculation that helps to better understand the network losses is the evaluation of the percentage of power losses reduction (PLR) that is achieved by connecting the CHP system into the existing UDN which is written as follows:

$$PLR = \frac{P_{loss} - P_{loss}^{CHP}}{P_{loss}} * 100\% \qquad (6.12)$$

where:

$P_{loss}$ - Power loss of the network before connecting CHP system

$P_{loss}^{CHP}$ – Power loss of the network after in the network after CHP system connection

In order to demonstrate the impact of CHP system connection on the network loss profile, the load flow calculation is performed under different loading levels without and with CHP system connected.

This analysis will examine the impact of a newly connected CHP system on 0.4kV B14-1 busbar in the network shown in Fig 3.8 in terms of the network losses under a number of loading scenarios of the feeder where the proposed CHP system is to be connected. These scenarios are selected by UDNO based on preliminary network operational analysis described in earlier chapters. The operational setting of the CHP system can be described as integrated and non-dispatchable with electrical; capacity of 520kW and 171kVAr. [Note: Network feeder of interest under analysis incorporate the following MV busbars: B2, B11, B12, B13, B14, B15 and two MV lines on different feeders between B21-B22 and B32-B33]

Results obtained from power flow analysis performed, by using ERAC power analysis software, are tabulated in Table 6.4a and presented through different graphs in Fig 6.13, Fig 6.14, Fig 6.15. The results presented illustrate the influence of each parameter/factor that affects the several loss variation such as: load profile variation, penetration of CHP generation and load, and CHP system location in the network. In addition, it can be said that in all situations, power loss variation in an existing UDN can be seen as a function of load level and penetration level of CHP generation.

**Table 6.4a Network losses in the feeder under analysis**

| No | Load % | Losses Without Proposed CHP (kW) | Losses With Proposed CHP (kW) | Loss Index (LI) | Power Loss Reduction (PLR) |
|---|---|---|---|---|---|
| 1 | 10 | 13 | 22 | 1.769 | -69.231 |
| 2 | 20 | 10 | 12 | 1.100 | -20.000 |
| 3 | 30 | 10 | 10 | 0.727 | 0.000 |
| 4 | 40 | 26 | 12 | 0.560 | 53.846 |
| 5 | 50 | 49 | 30 | 0.608 | 38.776 |
| 6 | 60 | 90 | 60 | 0.667 | 33.333 |
| 7 | 70 | 143 | 103 | 0.715 | 27.972 |
| 8 | 80 | 218 | 163 | 0.748 | 25.229 |
| 9 | 90 | 317 | 243 | 0.767 | 23.344 |

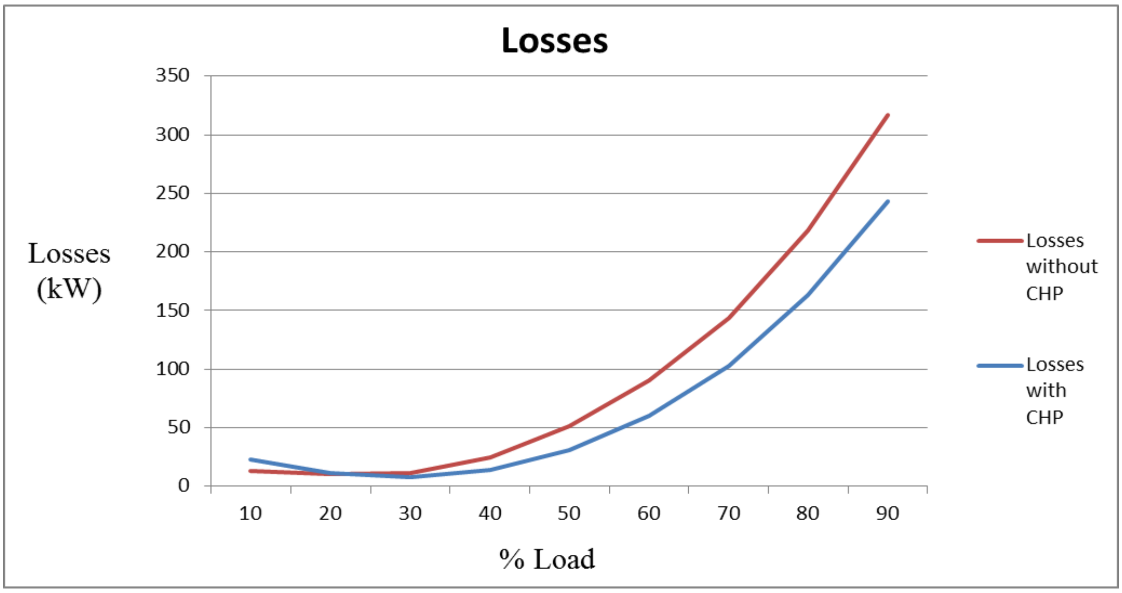


**Fig 6.13 Losses in the network feeder under analysis**

**Fig 6.14 Loss index of the network feeder under analysis**

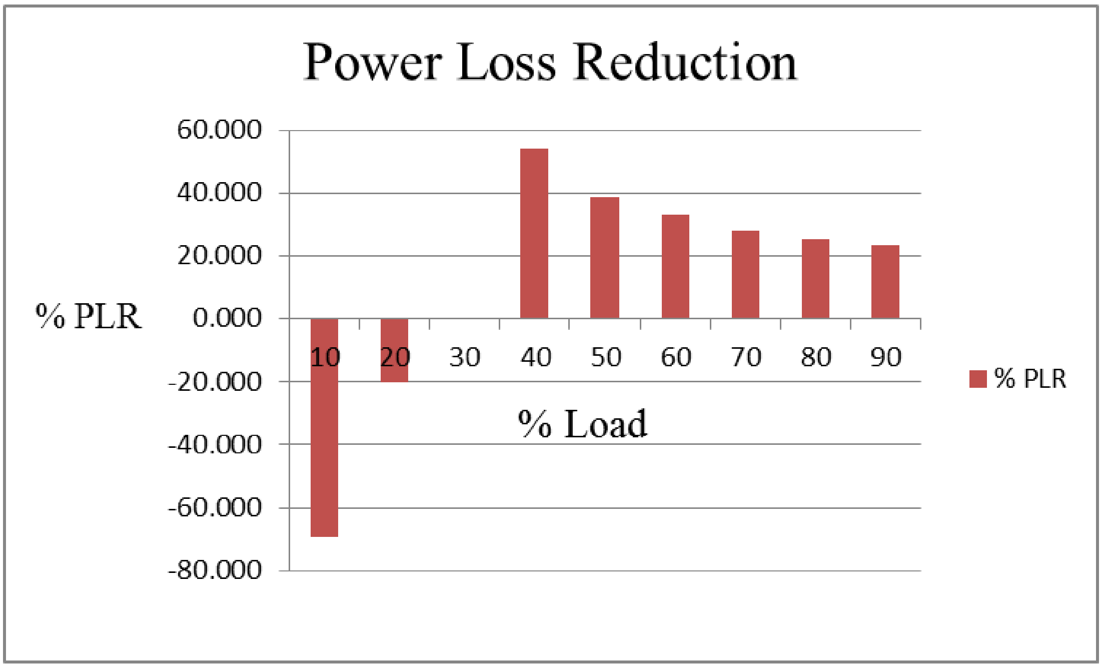


**Fig 6.15 Power loss reduction in the network feeder under analysis**

From the results above it can be seen that CHP system connection into an existing UDN in most cases will reduce the network losses. The negative impact of CHP system connection on the network losses from the results above, can be seen during the light loads where network losses increases.

In addition to the loss profile, UDNOs will be very interested in knowing which network component is causing a significant level of the losses. This information is obtained from the load flow analysis and is presented in Table 6.4b and Fig 6.16.

**Table 6.4b Network component losses under analysis (kW)**

| No | Load % | MV/LV Transformers | | MV Line | | MV Line B21-B22 | | MV Line B32-B33 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Without CHP | With CHP | Without CHP | With CHP | Without CHP | With CHP | Without CHP | With CHP |
| 1 | 10 | 9 | 12 | 4 | 11 | 9 | 9 | 9 | 9 |
| 2 | 20 | 10 | 10 | 0 | 2 | 9 | 10 | 9 | 10 |
| 3 | 30 | 8 | 9 | 2 | 1 | 10 | 9 | 10 | 9 |
| 4 | 40 | 14 | 10 | 12 | 2 | 10 | 9 | 9 | 10 |
| 5 | 50 | 23 | 16 | 26 | 14 | 10 | 10 | 9 | 9 |
| 6 | 60 | 38 | 28 | 52 | 32 | 10 | 10 | 10 | 10 |
| 7 | 70 | 58 | 45 | 85 | 58 | 10 | 10 | 11 | 10 |
| 8 | 80 | 85 | 67 | 133 | 95 | 9 | 11 | 10 | 10 |
| 9 | 90 | 122 | 99 | 196 | 146 | 11 | 10 | 11 | 11 |

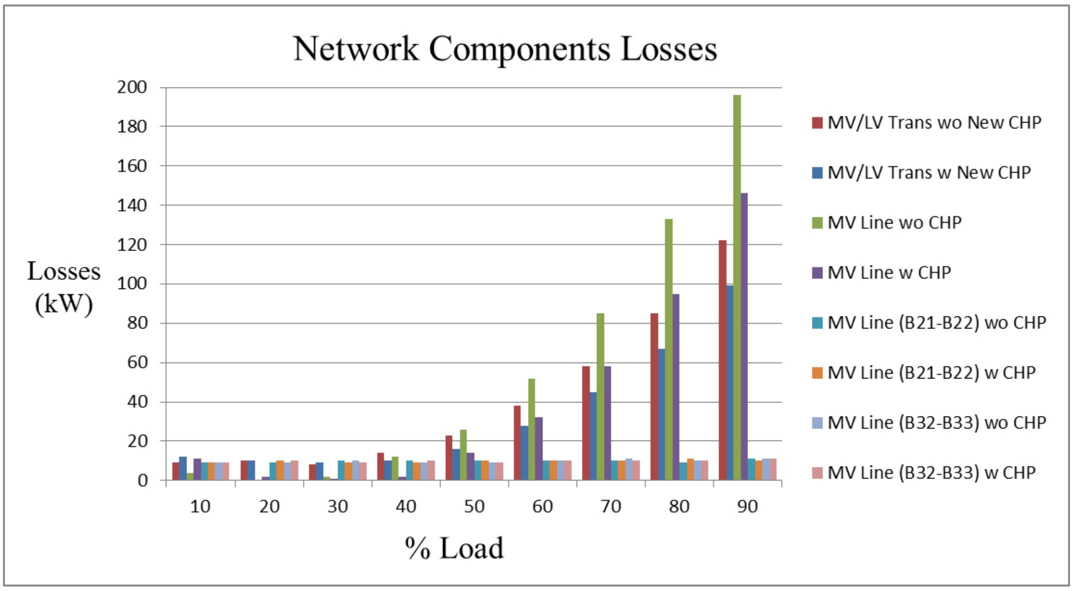


**Fig 6.16 Losses of network components of interest under different load profile**

From the results presented in Table 6.4b and Fig 6.16 it can be seen that highest losses occurring in the network feeder under analysis are in the MV lines while losses in the MV busbar links ( B21-B22 and B32-B33), lines located on different feeders experience a negligible change in the power losses.

UDN losses are a reality due to the inherent dissipative elements associated with various network components. Techniques for analysing losses are not new but have primarily focused on evaluating network losses during specific periods because of the limitations of available data. Current methods employed to evaluate energy losses rely heavily on assumptions that usually focus on average and peak demand on major network components. Other difficulties associated with traditional network loss analysis is the level of network detail evaluated.

The disadvantage is that the relative contribution of various network components to the overall network loss budget may not be defined to the detailed level required to truly evaluate network loss alleviation techniques, especially when time periods other than peak demand times are being evaluated.

Given all the challenges associated with the collection of network load data for a large number of meters, the collection of this data may not be practical or even practically useful.

In order to overcome difficulties regarding the power loss evaluation and allocation due to a number of factor stated earlier, most UDNOs introduce a time differentiate loss adjustment factor (DLAF) for each voltage level in the network. The loss adjustment factor would apply to the customer load consumption metered at the customer premises so as to gross it up to the HV/MV substation. The current loss level assessment procedure employed by the UDNOs to determine the distributed loss adjustment factor in Ireland is outlined in [2, 217, 218] and current DLAF is tabulated in Table 6.5:

**Table 6.5 Distributed Loss Adjusted Factor (DLAF) [217]**

| Voltage Level | Time period | | |
|---|---|---|---|
| | Composite | Day | Night |
| 38kV | 1.015 | 1.016 | 1.013 |
| MV | 1.035 | 1.038 | 1.030 |
| LV | 1.085 | 1.091 | 1.073 |
| Aggregate | 1.070 | 1.074 | 1.060 |

In general DLAFs are calculate on a site specific basis and are defined in the relevant DG/CHP system connection agreement. DG/CHP systems installed in the UDN will generally have a positive impact on overall UDN losses and will naturally be subject to a DLAF greater than 1. For the site with the DG/CHP system connected, a specific DLAF value is dependent on the connection voltage and the type of connection assets installed. Table 6.5 displays typical DLAF values update annually, but normally only change by small amounts year on year basis.

Rather than collecting load data for selected network voltage levels states of interest, and applying the loss evaluation method, introduction of a DLAF will give an opportunity to the UDNO to recover the cost of the losses caused by network components in a fair and transparent fashion.

## 6.3 CHP Generation System Connection Charging Method

Connection costs can make up a significant proportion of CHP generation development cost and may therefore have a significant impact on the financial feasibility of a CHP generation scheme. These costs are project specific and will be driven by the CHP system characteristics and the local part of the UDN into which the CHP system is applying for connection. Specifically, factors such as the location of the CHP system, connection voltage, rated capacity of the network, the electricity demand of that local part of the network, export capacity of the CHP system and operational access of CHP system in the UDN will all have a major impact on the connection cost. The CHP system developer should be aware of operation & maintenance and network charges that will be levied by the UDNO when the CHP system is operational [2]. The modalities adopted for settling the connection charges are an issue of risk allocation between the UDNO and CHP system developer. Allocating the connection costs to the CHP system developer can help to ensure that the connection cost corresponds to the LCTA principle as CHP system developers are in a better position to influence their connection cost by virtue of CHP system size, location and operational access mode. Connection of CHP systems into the UDN normally has to be established by UDNPs/UDNOs who are seeking to minimise their operational and investment risk against uncertain CHP generation operation and development. A risk-balance between CHP system developer and UDNP/UDNO has to be established. The connection process should determine and try to minimise all relevant technical, environmental and social impacts by making use of local knowledge through obligations on all parties involved. Discussing each party's requirements is a necessity in the connection process and open and transparent discussions should take place during the infrastructure planning phase. A consultative planning framework merged with the connection process can thus create a high level of consistency, transparency and interactivity.

The connection costs of the CHP system in the UDN is obtained by calculating the cost of the network reinforcement needed to mitigate technical and environmental problems that are caused by its connection. On the other hand, the benefit that the CHP system can provide for the UDN is determined by calculating the reduction in some of the network operational costs (network losses) and the ability of CHP generation to release network capacity which can be used to accommodate future loads/CHP generation. The CHP system integration costs, either positive or negative, are mainly related to new reinforcement in the network and to matching different CHP systems' operational characteristics and UDN characteristics.

The cost evaluation framework shown in Fig 6.17 presents the general cost evaluation process used in order to predict the CHP system connection cost. This process is designed to be applicable for assessment of CHP system integration impact for every scenario and can be consistently applied to different network feeders which are considered critical by the UDNO. There are two cost components associated with CHP system connection into the UDN. The first is the cost of connection, which includes new lines and equipment needed to connect the CHP system to the network. The second is the network upgrade which includes enhancement of the existing network or applicable mitigation measures designed to remedy network deficiencies or constraints violations. The primary evaluation criteria are based on the premise that any CHP system connection should not unreasonably degrade or comprise network performance, safety, operating flexibility or network assets use. Evaluation criteria include performance standards for the UDN components based on specification for the network feeder loading, voltage regulation, protection system and power quality. Violations of network performance standards and loading limits are identified using commercially available software. Other network impacts not detected by software simulation alone also can be identified by the supplemental analysis of data acquired**.**

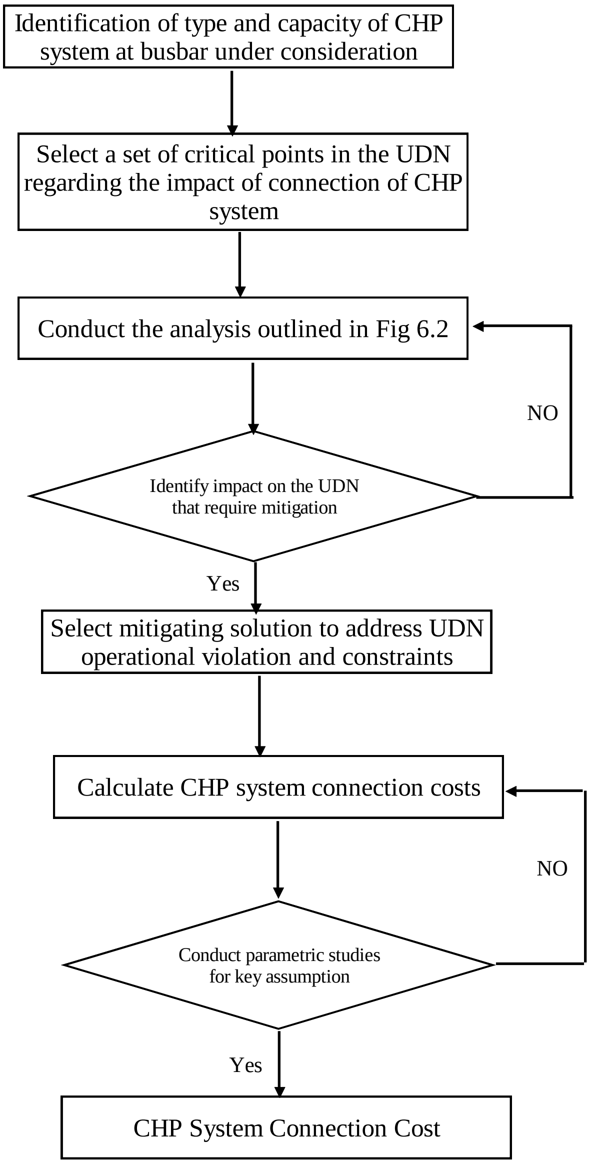


**Fig 6.17 CHP system Cost Evaluation Framework**

In the Irish context, ESB Networks is the monopoly owner of the high voltage transmission system and is the monopoly owner and operator of the MV and LV of the UDN. ESB Networks is the authority to which a new CHP generation developer must apply in order to obtain a connection to the UDN. In addition, there are number of approvals that may need to be obtained in order to construct and operate a new CHP system installation in a urban area, each of which is required under specific legislation listed in Appendix 2**.**

Most new CHP system connections into a UDN are completed according to the layout shown in Fig 6.5 and every connection must comply with EN 50438 with specific Irish protection settings. The method of CHP system connection charging in Ireland is implemented through a mixture of legislation and specific ESB policies described in documents listed in Appendix 3.

In most cases, the site for a proposed CHP generation system installation does not require the installation of new ESB connection infrastructure. However, in some cases the network assets may have to be reinforced or adjusted in order to accommodate the new CHP generation capacity. Whether new CHP generation capacity connection requires approval or not, the CHP system developer must still apply to the UDNO to connect a new CHP generation unit.

For reasons of economic connection efficiency, the UDNO chooses a design for a new CHP system connection into the network that will provide the required capacity and technical performance as defined in the ESB Network System Security Planning Standards according to the LCTA principle. Whilst there is a relatively high level of transparency in the connection process in Ireland, the charging cost methodology that can be implemented may have a negative impact on CHP generation development. This is due to the fact that CHP developers are exposed to potentially significant and often uncertain network reinforcement costs. These are risks that many potential CHP generation developers are not prepared to take. It is not surprising, therefore, that the penetration of CHP generation into the UDN is relatively low by comparison with other EU countries.

At present, CHP system developers applying to connect a CHP system to the UDN are required to pay an application fee to cover ESB Networks in processing CHP system developer application documents and in designing the CHP system connection method. The level of fee depends on the size of Maximum Export Capacity (MEC) and or whether shallow connection works are required in order to connect the proposed CHP system capacity. All developers are liable to an application fee prior to commencement of the connection process. The application fees shown in Table 6. 6 are for 2014 and these costs are updated yearly by the Consumer Price Index (CPI).

**Table 6.6a Application Fees**

| Application Fees ( excluding VAT) | | |
|---|---|---|
| MEC (Maximum Export Capacity) | Shallow Works Required | No Shallow Works Required |
| 0 ≤ 11kW | €0 | €0 |
| > 11kW ≤ 50kW | €764 | €764 |
| > 50 kW ≤ 500kW | €1,559 | €1,559 |
| > 500kW ≤ 4MW | €8,850 | €8,522 |
| > 4MW ≤ 10MW | €27,303 | €22,881 |
| > 10MW ≤ 30MW | €52,884 | €32,671 |
| > 30MW ≤ 50MW | €61,627 | €36,628 |
| > 50MW ≤ 100MW | €73,910 | €39,493 |
| > 100MW | €86,512 | €42,921 |

Note: On initial receipt of an application the fee requested will be on the assumption that shallow works are required. Should no shallow works be required the difference will be refunded.

**Table 6.6b Modification Application Fees**

| | Modification Fees ( excluding VAT) | | |
|---|---|---|---|
| Level | Initial non-refundable deposit (excl. VAT) | Balance of Fee ( excl. VAT) | Total Fee(excl. VAT) |
| Level 1 | €866 | €0 | €866 |
| Level 1.5 | €866 | €4,355 | €5,220 |
| Level 2 | €866 | €8,710 | €9,576 |
| Level 2.5 | €866 | €13,216 | €14,082 |
| Level 3 | €866 | €17,722 | €18,588 |
| Level 3.5 | €866 | €21,383 | €22,249 |
| Level 4 | €866 | €25,044 | €25,910 |

Source: ESB Networks, Schedule of generator Application and Modification Charges, Revision No 1, Document No: DOC-170913-BPL, Approved by CER, Effective Date: 01/10/2014 to 30/09/2015

In a case where the CHP system developer request a modification or the connection process after initial connection has been presented the following practice is applied:

- For minor modifications the fee imposed by UDNO will be evaluated on an individual basis.
- For a considerable modification that requires a complete reprocessing of a new connection offer need to be issued

In both cases the methodology shown in Fig 6.18 will give satisfactorily results [212].

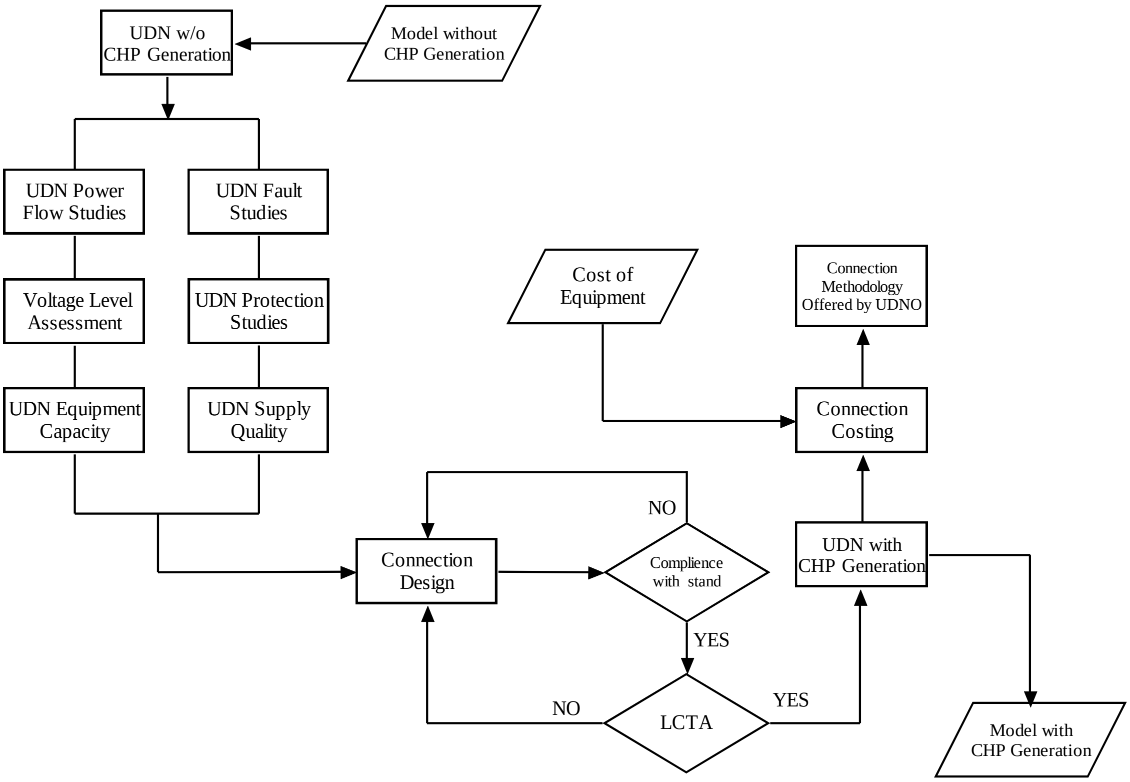


**Fig 6.18 Costing methodology for CHP system connection into the UDN**

Based on the studies indicated in Fig 6.18, the UDNP/UDNO will arrive at a connection method which complies with the relevant standards, practices and network planning criteria. The UDNP/UDNO may arrive at several feasible connection methods but will only make a connection offer based on one of these methods and based on this connection fee will be determined.

At present, connection method used for typical size of CHP system normally employed in urban area offered by UDNP/UDNO is shallow connection method. It is the method where CHP system developer will be financially responsible for the cost of equipment needed to make the connection to the network. Connection equipment depends on the connection scheme determined by UDNP/UDNO generated during the connection offer process. It could include items such as upgrades of existing network equipment and new equipment in an existing substation, a length of overhead lines or cables and onsite metering. Typical connection cost break down for the size of CHP system normally installed in urban area is shown in Appendix 8.

## 6.4 Discussion

With an increasing amount of CHP generation connected, UDNs can no longer be seen as passive radial systems. In light of this fact, UDNOs should review and update their technical, environmental standard procedures agreements and align them with best connection practices corresponding to the LCTA principle, emerging issues, and revised EN, IEEE standards and recommended procedures. A UDNO will also need to consider revising its methods within the rules and guidelines for assessing networks and CHP systems operational settings. This revision should lead to easier interconnection and allow additional CHP generation capacity to be connected and expedited without having to perform detailed technical and environmental impact studies and yet comply with the LCTA principle. However, a potential CHP generation system developer needs to realise that just because the CHP system connection complies with standards outline in ESB Document (Ref: DTIS-250701-BDW Issued October 2012) listed in Appendix 4 and IEEE1547 it does not mean that a CHP system can be connected anywhere in the network without causing a significant technical impact. In some cases, even a small deviation from the standards will cause an impact requiring detailed impact studies, as explained earlier, and could require additional network upgrades or changes in network operational practices in order to accommodate the new CHP generation capacity.

The primary objectives of UDNPs/UDNOs regarding the connection of CHP generation into the UDN is to ensure the following [211]:

- To maintain the safety and service quality of the UDN
- To provide transparent and uniform technical requirements and procedures with agreements to make interconnection as timely as possible which is predictable and priced according to the LCTA principle.
- Economic efficiency in the context of UDN operation by sending advanced price signals to CHP developers regarding the cost a developer has to bear in terms of network operation and development.
- Provide stable and predictable CHP system connection pricing which is an important factor in the investment decision making process. The right balance must, however, be struck between price stability and flexibility by allowing pricing to respond to changing situations and increased supply demand.
- Determination of CHP system connection cost must be transparent, consistent and auditable by allowing CHP developer and other interested parties to easily understand the cost implications involved in CHP system connection to a UDN .
- Send clear connection cost information regarding the location of new CHP generation facilities in order to encourage efficient network investment and discourage over-investment.

In many cases the choice of connection charge methodology relating to CHP generation connection into UDNs is a subject of considerable discussion as it can profoundly affect the financial viability of a new CHP generation scheme. The main focus of discussion concerns how the costs of connection of a CHP system should be allocated fairly between the parties involved. At present, it appears that there is no general consensus by virtue of the fact that the UDNO and CHP system developer are the main parties involved and also the fact that the costs of connection for a CHP system connection is highly dependent on the point of connection and on the characteristics of the UDN at the connection point concerned.

Connecting a CHP system to an existing UDN implies a direct investment cost in the system connection. The increased number of CHP generation systems in the UDN can generate an additional need for investment in the network elsewhere, especially in a situation where the network operates under a passive management mode and where the network is designed using deterministic rules for minimum and maximum generation and consumption.

## 6.5 Conclusion

This chapter outlined and discussed the main objectives and procedures of CHP generation system connection into the UDN and presented a detailed account of the connection process drivers. A costing methodology based on the LCTA principle was discussed. A set of key questions introduced by UDNP/UDNO and the CHP developer in the context of developing a connection cost charging methodology was addressed. The primary objectives of connection cost charging methodology corresponding to the LCTA principle is to ensure economic efficiency (cost reflectivity). In the context of the UDN, regarding the CHP system connection, economic efficiency is concerned with sending price signals to CHP system developers with respect to the cost that the developer imposes on the network operation and /or development pattern thus ensuring that in the short-term, the network is efficiently operated and in the long term it follows the path of least cost technically acceptable development.

Economic efficiency of the CHP system in the UDN is achieved by sending price information to CHP developers so as to influence their decisions with regard to:

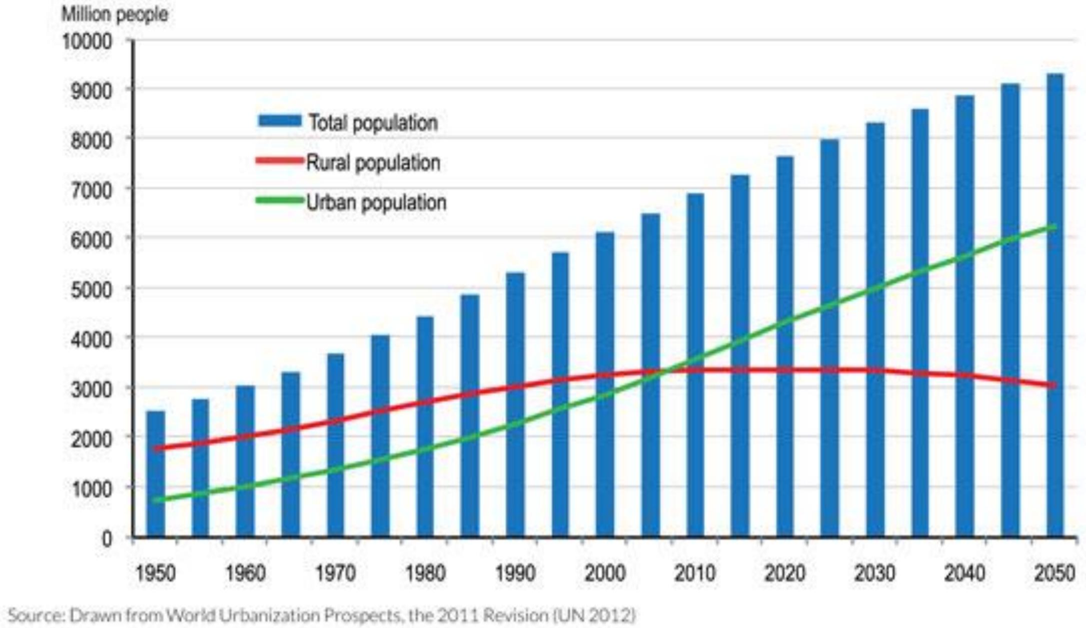
- CHP system location in the network
- Pattern of the network use
- Signal for the UDN investment needed to accommodate CHP generation.

In order to ensure that the costs of the network components required for upgraded/modification are correctly identified it is necessary to study the range of loading conditions covering periods of minimum demand – maximum generation and maximum demand – secure/minimum generation. These conditions may be influenced by the size of the CHP system connection and the operational patterns that drive investment to facilitate the CHP system connection which are found mainly by evaluating power flows and fault current analysis in all loading conditions.

# 7. Conclusion and Future Work

## 7.1 Conclusion

Diversification of the energy mix is one of the main challenges in the energy agenda of governments worldwide. Due to increase of urban population shown in Fig 7.1, with consequent increase in energy demand in urban areas the adoption of CHP generation as a means of energy supply becomes inevitable and it has made substantial strides in the last two decades in many countries worldwide.



Source: Drawn from World Urbanization Prospects, the 2011 Revision (UN 2012)

Fig 7.1 Distribution of World Population

Technology advances together with energy supply security and environmental concerns have paved the way for the increasing integration of CHP generation into urban areas as seen over recent years. Viewed on many levels, the adoption of CHP generation in most cases is a gain for all parties involved such as UNDOs, CHP generation system developers and the environment. Because of these expectations the capacity of CHP generation connection in UDNs will significantly increase in the near future in EU countries and elsewhere.

This scenarios presents UDNPs/UDNOs with a number of challenges in terms of technical and operational settings in order to properly accommodate CHP system integration.

In this thesis, the impact of CHP generation connection on UDN planning and operation has been analysed and the implications for UDNOs, incorporating CHP generation within the network planning process, are identified. These results will assist the UDNP/UDNO in assessing the possibilities and the effort that is required to accommodate privately owned CHP generation systems into UDNs while at a same time improve network efficiency and save investment. The values quantified from analysis would also act as a fundamental element in deriving an effective CHP system connection methodology with charging scheme based on the LCTA principle.

These new approaches not only analyse the technical impact of CHP generation on UDNs, but also translate the technical impacts into an economic cost assessment thereby offering UDNPs/UDNOs robust and transparent models to generate results that are sensitive to connection costs of different sizes of CHP systems at different locations in the UDN. It is critical and invaluable to know how a CHP generation capacity connection can affect capital expenditure on network planning. The analysis shows that CHP generation can be a powerful replacement option for network reinforcement which then can be utilised for different purposes such as: improvement voltage profile; security and power quality of the network supply; reduced the network losses and postponement of necessary network reinforcement through network component replacement.

In certain situations there are some conditions in which CHP generation capacity can trigger additional spending due to its adverse impact on the network operation. In this instance the cost quantified for the preferred connection methodology would assist UDNPs/UDNOs in judging the necessity of incentivising the CHP generation developer to limit the CHP system size or to alternatively change the operational system settings in order to mitigate the negative impact thereof. To meet the rising energy demand in urban areas it is essential for the UDNPs/UDNOs to incorporate CHP generation capacity into network planning. To achieve this the UDNPs/UDNOs must be able to determine the most cost-effective way to facilitate new CHP generation capacity which must comply with the network operational standards. Furthermore through comprehensive analysis the UDNP/UDNO must derive a comprehensive network planning strategy in order to maximise the penetration of CHP generation into the UDNs and at the same time to take advantage of the new CHP generation connection in order to save significant capital expenditure required for the network assets upgrade. All of the forgoing scenarios and solution strategies have been discussed and analysed in this thesis.

## 7.2 Future work

Up to the present the UDN operational control problem has been traditionally resolved at planning stage (passive operation) and hence the network configuration preferred provides an integrated/non-dispatchable mode of operational settings for a CHP generation system. Traditionally UDN design/operational practise is known to considerably limit the amount of CHP generation capacity that can be connected into an existing network due to the limitations explain earlier.

In order to maximise the connection of CHP generation into existing UDN under the LCTA principle, the determination of the optimum location and sizes of CHP systems to be installed subjected to electrical network operating constraints, CHP system operational constraints and financial constraints is an essential task to be undertaken as future ongoing network adaptation. The optimal CHP system placement is a complex mix of optimisation problems and this needs to be analysed and modelled to meet the needs of the UDNP/UDNO and CHP system developer to address the following key network issues.

- Coordinated planning

  UDN reconfiguration, CHP system placement and capacitor placement are three major methods for loss reduction in the network. It is important to investigate the network reconfiguration with simultaneous placement of CHP systems, protection devices and capacitors as they are interdependent on each other. Such coordinated planning can provide maximum benefits for the UDNO and CHP system developer and also in evaluating the feasibility of CHP system investment versus other traditional planning options.

  - Active network management

    The introduction of CHP system into the UDN enables active management of the UDN, which certainly require communication and control facilities. CHP generation systems can be used not only to control the network voltage profile, but also prevent the network from overloading. Furthermore, deployment of active network management could reduce significantly connection costs of CHP systems. Optimal placement of CHP systems with an active network management scheme in place can facilitate high power quality supply with high penetration of CHP generation.

  - Islanded operation

    Intentional islanding of part of a UDN in the form of microgrid a increases the economic competitiveness of the CHP generation and improves the reliability of the network. It is important to identify the network operational system that will facilitate CHP system operation in island mode. An active network management policy with overall UDN control allows CHP system operation in island mode. New models for optimal CHP system placement are needed to evaluate advanced methods for intentional islanding.

- Ancillary services

  CHP systems can provide an ancillary service in the provision of active power on demand by the UDNO. The ability of CHP systems to provide such ancillary services has to be taken into account within the integration process of CHP system into the UDN.

By utilising the analysis outlined above and combined with methodology explain in the thesis can result in vastly improved CHP generation penetration into local existing UDN.

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# APPENDIXS:

## Appendix 1

EPA has number of control greenhouse gas control points and in case if these limits are violated the agency will examine violation and identified the cause and take appropriate action. These limits are presented in table below:

**Limit values of CAFE Directive 2008/50/EC**

| Pollutant | Limit Value Objective | Averaging Period | Limit Value ug/m3 | Limit Value ppb | Basis of Application of the Limit Value | Limit Value Attainment Date |
|---|---|---|---|---|---|---|
| **SO2** | **Protection of human health** | **1 hour** | **350** | **132** | **Not to be exceeded more than 24 times in a calendar year** | **1 Jan 2005** |
| **SO2** | **Protection of human health** | **24 hours** | **125** | **47** | **Not to be exceeded more than 3 times in a calendar year** | **1 Jan 2005** |
| **SO2** | **Protection of vegetation** | **calendar year** | **20** | **7.5** | **Annual mean** | **19 July 2001** |
| **SO2** | **Protection of vegetation** | **1 Oct to 31 Mar** | **20** | **7.5** | **Winter mean** | **19 July 2001** |
| **NO2** | **Protection of human health** | **1 hour** | **200** | **105** | **Not to be exceeded more than 18 times in a calendar year** | **1 Jan 2010** |
| **NO2** | **Protection of human health** | **calendar year** | **40** | **21** | **Annual mean** | **1 Jan 2010** |
| **NO + NO 2** | **Protection of ecosystems** | **calendar year** | **30** | **16** | **Annual mean** | **19 July 2001** |
| **PM10** | **Protection of human health** | **24 hours** | **50** | | **Not to be exceeded more than 35 times in a calendar year** | **1 Jan 2005** |
| **PM10** | **Protection of human health** | **calendar year** | **40** | | **Annual mean** | **1 Jan 2005** |
| **PM2.5 -<br>Stage 1** | **Protection of human health** | **calendar year** | **25** | | **Annual mean** | **1 Jan 2015** |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **PM2.5 -<br><br>Stage 2** | **Protection of human health** | **calendar year** | **20** |  | **Annual mean** | **1 Jan 2020** |
| **Lead** | **Protection of human health** | **calendar year** | **0.5** |  | **Annual mean** | **1 Jan 2005** |
| **Carbon Monoxide** | **Protection of human health** | **8 hours** | **10,000** | **8620** | **Not to be exceeded** | **1 Jan 2005** |
| **Benzene** | **Protection of human health** | **calendar year** | **5** | **1.5** | **Annual mean** | **1 Jan 2010** |

# Appendix 2

There are a number of approvals that may need to be obtained in order to construct and operate a new CHP facility, each of which is required under a specific piece of legislation. These approvals are listed as:

| | | | |
|---|---|---|---|
| | **Activity** | **Licensing body** | **Required when:** |
| | **Construction of a CHP Facility** | | |
| 1 | Planning Permission (including EIS where required) | Local planning authority (LA) and An Bord Pleanála | Decision up to planning authority |
| 2 | Authorisation to construct or reconstruct a generating station | Commission for Energy Regulation (CER) | Mandatory (at present) |
| | **Operation of a CHP Facility** | | |
| 3 | Licence to generate electricity | Commission for Energy Regulation | Mandatory (at present) |
| 4 | Fire Safety Certification | Fire Authority (LA) | Mandatory |
| 5 | IPPC Licence | Environment Protection Agency (EPA) | Needed only if total rated thermal input of 50MW or more |
| 6 | Emissions Trading Licence | Environment Protection Agency | Need only if the site has a combined total rated thermal input greater than 20MW |
| 7 | Waste Licence | Environment Protection Agency | Needed where waste is to be burned |
| 8 | Gas shippers/suppliers Licence | Commission for Energy Regulation | Needed only if operator shipping gas to plant |
| 9 | Standard Transportation Agreement and Entry Point Agreement | Bord Gais Eireann | Needed only if operator shipping gas to plant |
| | **Connection to the Electricity Grid** | | |
| 10 | Electricity Connection Agreement with DSO | Distribution System Operator | Needed only if exporting or importing electricity to the distribution system |
| | **Electricity Supply and Trading Arrangements** | | |
| 11 | Electricity Supply Licence | Commission for Energy Regulation | Needed only if supplying electricity to final customers |
| 12 | Accede to the Trading and Settlement Code | Electricity Supply Board (ESB) | Needed only if hold a Supply Licence or if wish to trade electricity |

# Appendix 3

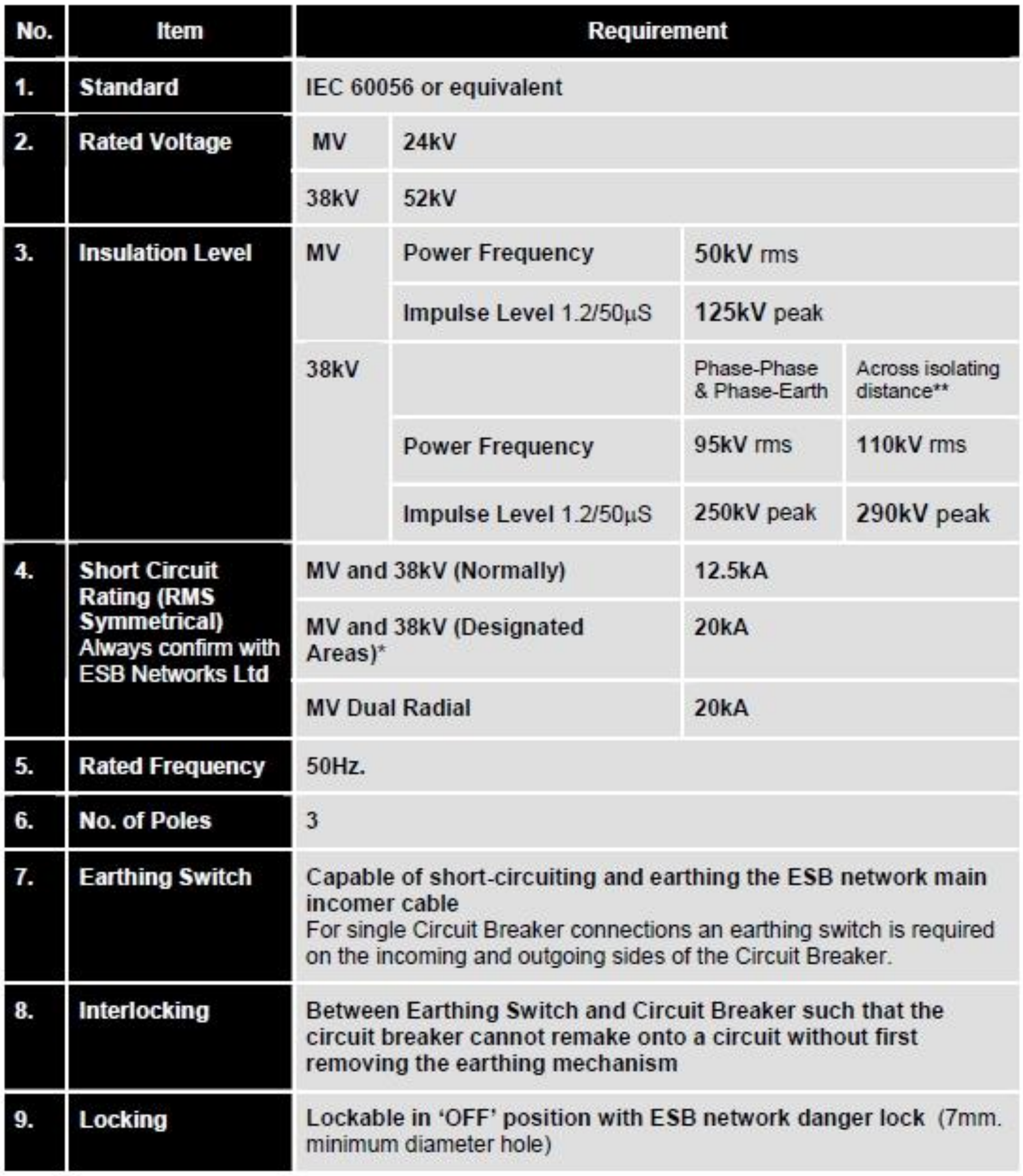
## ESB Networks regulations

| No | |
|---|---|
| | |
| 1 | I.S. EN – 50438 – 2013<br>Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks<br>Publish under the authority of the NSAI valid from 17/12/2013<br>ICS number : 29.160.20<br>Dublin 2013 |
| 2 | ESB Network<br>Distribution Code<br>Approved by CER; Version 4.0 ; Date: February 2015<br>Issued by Distribution System Operator, ESB Network Limited |
| 3 | ESB Network<br>Statement of Charges<br>Revision No 11<br>Document No: DOC – 101209 – AXR<br>Issued by ESB Network Ltd; Approved by CER<br>Effective Date 01/10/2014 |
| 4 | ESB Network<br>Standard Price for Generator Connection 2015<br>Revisions Date: November 2014<br>Issued by: ESB Networks Ltd; Document Number: DOC – 050110-AUX<br>Revision: 5; Approved by: CER<br>Effective Date: 01/01/2015/ - 31/12/2015 |
| 5 | ESB Network<br>Indicative Construction Timelines for Distribution Connection IPP’s<br>Revision date: 28/07/2011<br>Revision No: 0; Document No: DOC – 200711 – BIW<br>Issued by: ESB networks Ltd |
| 6 | ESB Networks<br>General Conditions for Connection of Industrial and Commercial Customers and generators to the Distribution System<br>Applied to:<br>• Import Customer Connection of Capacity of 100kVA or Greater<br>• Embedded Generators<br>• Auto-producer and CHP Producers<br>Document No: DTIS – 150200 – AXY<br>Issued by Distribution System Operator, Year: 2012 |
| 7 | ESB Network<br>Condition Governing Connection to the Distribution System:<br>• Connections at MV and 38kV<br>• Embedded generators at LV, MV and 38kV<br>Document ref. DTIS – 250701 – BDW<br>Issue date: October 2012 |
| 8 | ESB Networks, EIRGRID<br>Modification Fees for Connection offers |

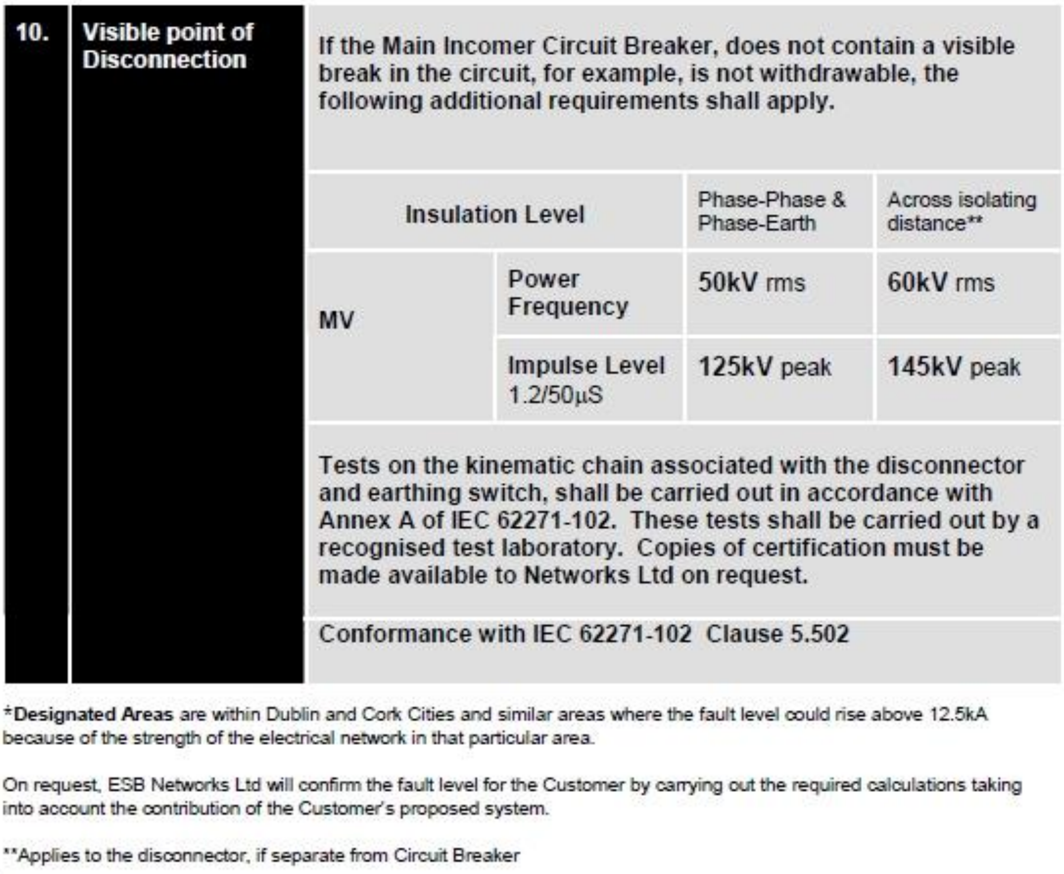
|  |  |
|---|---|
|  | Document Ref: DOC-310811 – BIX<br>March 2013 |
| 9 | ESB Network<br>Form NC%<br>Form NC6 – Micro Generation Notification |
| 10 | ESB Network<br>Schedule of Generator Application and Modification Charges<br>Revision date: September 2014; revision N0 1<br>Document No: DOC – 170913 –BPL<br>Issued by ESB Networks Ltd.; Approved by CER<br>Effective date: 01/10/2014 to 30/09/2015<br>Commercial and Renewable regulation Asset management<br>ESB Network Ltd. |
| 11 | ESB network<br>Standard Prices for generator Connections 2015<br>Revision date: November 2014<br>Document Number: DOC – 050110 – AXU; revision: 5<br>Approved by: CER<br>Effective date: 01/01/2015 – 31/12/2015<br>Commercial and renewable regulation Asset Management<br>Distribution System Operator<br>ESB networks Ltd |

# Appendix 4

Table 2A: Customer's MV/38 kV Main Incomer Circuit Breaker Requirements



| No. | Item | Requirement | | | |
|---|---|---|---|---|---|
| 1. | Standard | IEC 60056 or equivalent | | | |
| 2. | Rated Voltage | MV | 24kV | | |
| | | 38kV | 52kV | | |
| 3. | Insulation Level | MV | Power Frequency | 50kV rms | |
| | | | Impulse Level 1.2/50µS | 125kV peak | |
| | | 38kV | | Phase-Phase & Phase-Earth | Across isolating distance** |
| | | | Power Frequency | 95kV rms | 110kV rms |
| | | | Impulse Level 1.2/50µS | 250kV peak | 290kV peak |
| 4. | Short Circuit Rating (RMS Symmetrical) Always confirm with ESB Networks Ltd | MV and 38kV (Normally) | | 12.5kA | |
| | | MV and 38kV (Designated Areas)* | | 20kA | |
| | | MV Dual Radial | | 20kA | |
| 5. | Rated Frequency | 50Hz. | | | |
| 6. | No. of Poles | 3 | | | |
| 7. | Earthing Switch | Capable of short-circuiting and earthing the ESB network main incomer cable<br>For single Circuit Breaker connections an earthing switch is required on the incoming and outgoing sides of the Circuit Breaker. | | | |
| 8. | Interlocking | Between Earthing Switch and Circuit Breaker such that the circuit breaker cannot remake onto a circuit without first removing the earthing mechanism | | | |
| 9. | Locking | Lockable in 'OFF' position with ESB network danger lock (7mm. minimum diameter hole) | | | |



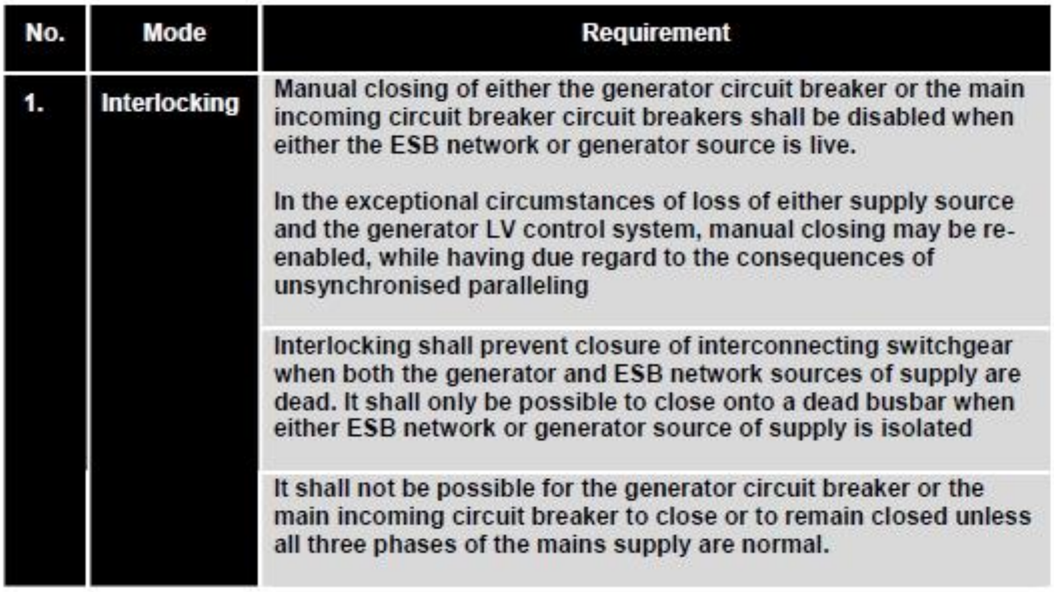
<table>
<tr><td rowspan="6"><b>10.</b></td><td rowspan="6"><b>Visible point of Disconnection</b></td><td colspan="4">If the Main Incomer Circuit Breaker, does not contain a visible break in the circuit, for example, is not withdrawable, the following additional requirements shall apply.</td></tr>
<tr><td colspan="2">Insulation Level</td><td>Phase-Phase & Phase-Earth</td><td>Across isolating distance**</td></tr>
<tr><td rowspan="2">MV</td><td>Power Frequency</td><td>50kV rms</td><td>60kV rms</td></tr>
<tr><td>Impulse Level 1.2/50μS</td><td>125kV peak</td><td>145kV peak</td></tr>
<tr><td colspan="4">Tests on the kinematic chain associated with the disconnector and earthing switch, shall be carried out in accordance with Annex A of IEC 62271-102. These tests shall be carried out by a recognised test laboratory. Copies of certification must be made available to Networks Ltd on request.</td></tr>
<tr><td colspan="4">Conformance with IEC 62271-102 Clause 5.502</td></tr>
</table>

***Designated Areas** are within Dublin and Cork Cities and similar areas where the fault level could rise above 12.5kA because of the strength of the electrical network in that particular area.

On request, ESB Networks Ltd will confirm the fault level for the Customer by carrying out the required calculations taking into account the contribution of the Customer's proposed system.

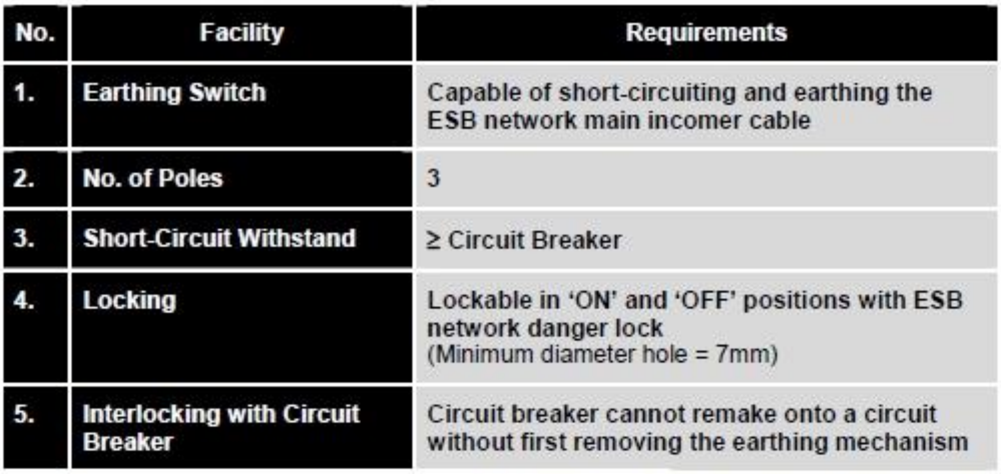
**Applies to the disconnector, if separate from Circuit Breaker

Table 2B: Additional Interlocking Requirements in Embedded Generator Installation



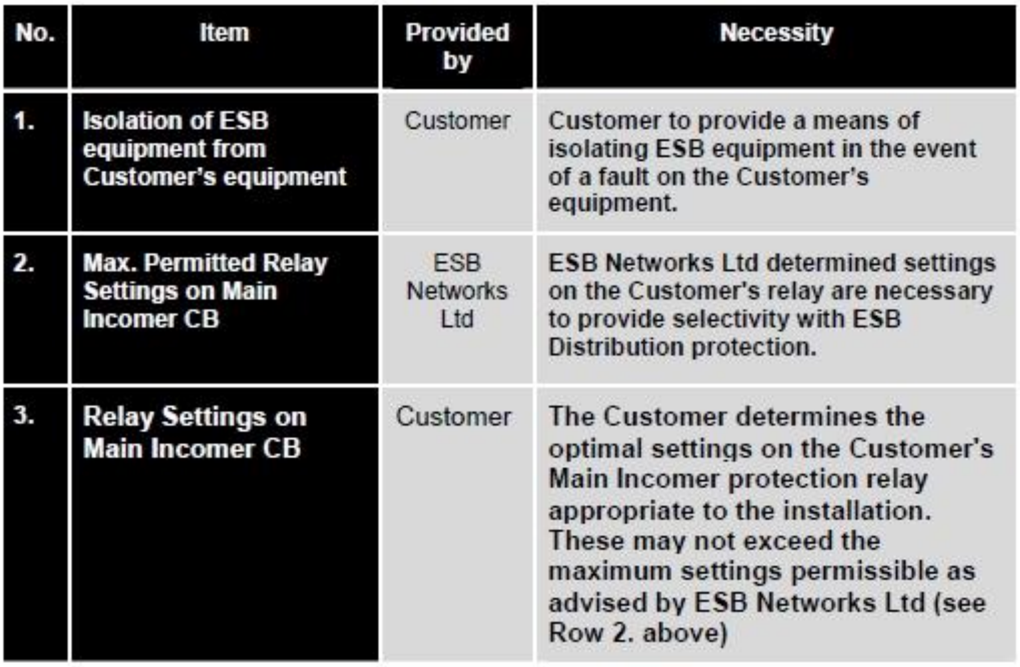
| No. | Mode | Requirement |
|---|---|---|
| 1. | Interlocking | Manual closing of either the generator circuit breaker or the main incoming circuit breaker circuit breakers shall be disabled when either the ESB network or generator source is live.<br>In the exceptional circumstances of loss of either supply source and the generator LV control system, manual closing may be re-enabled, while having due regard to the consequences of unsynchronised paralleling |
| | | Interlocking shall prevent closure of interconnecting switchgear when both the generator and ESB network sources of supply are dead. It shall only be possible to close onto a dead busbar when either ESB network or generator source of supply is isolated |
| | | It shall not be possible for the generator circuit breaker or the main incoming circuit breaker to close or to remain closed unless all three phases of the mains supply are normal. |

Table 3: Customer’s Main Incomer Circuit Breaker Earthing Facility Requirements



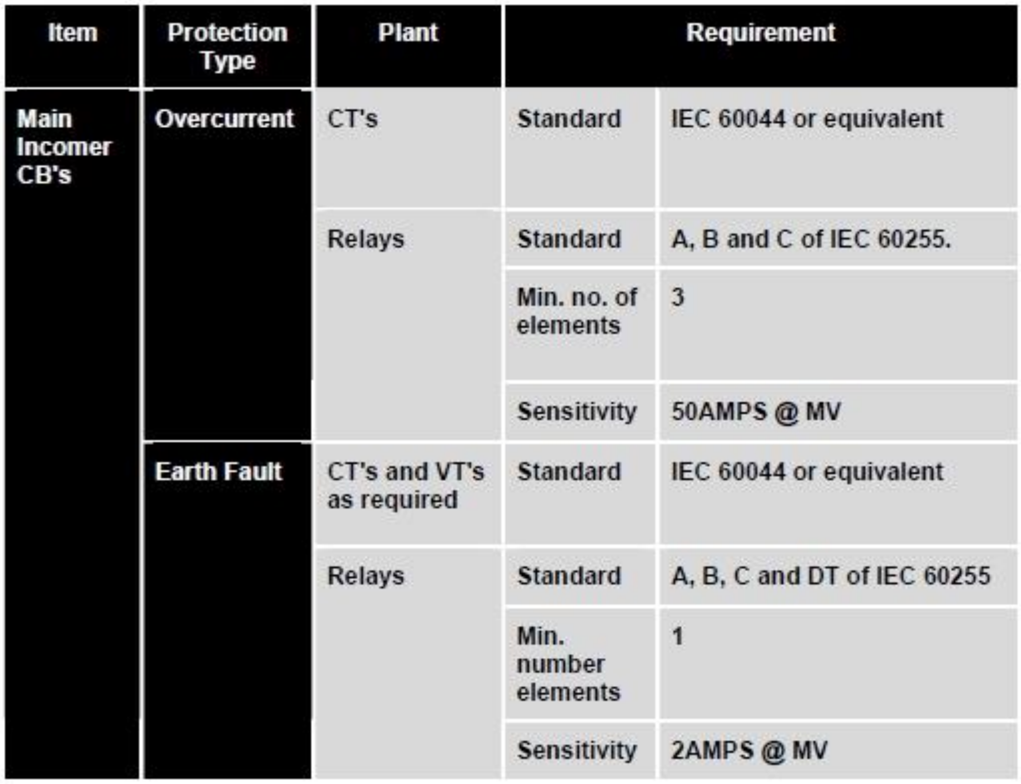
| No. | Facility | Requirements |
|---|---|---|
| 1. | Earthing Switch | Capable of short-circuiting and earthing the ESB network main incomer cable |
| 2. | No. of Poles | 3 |
| 3. | Short-Circuit Withstand | ≥ Circuit Breaker |
| 4. | Locking | Lockable in ‘ON’ and ‘OFF’ positions with ESB network danger lock<br>(Minimum diameter hole = 7mm) |
| 5. | Interlocking with Circuit Breaker | Circuit breaker cannot remake onto a circuit without first removing the earthing mechanism |

Table 4A: Isolator and Maximum Permitted Relay Settings



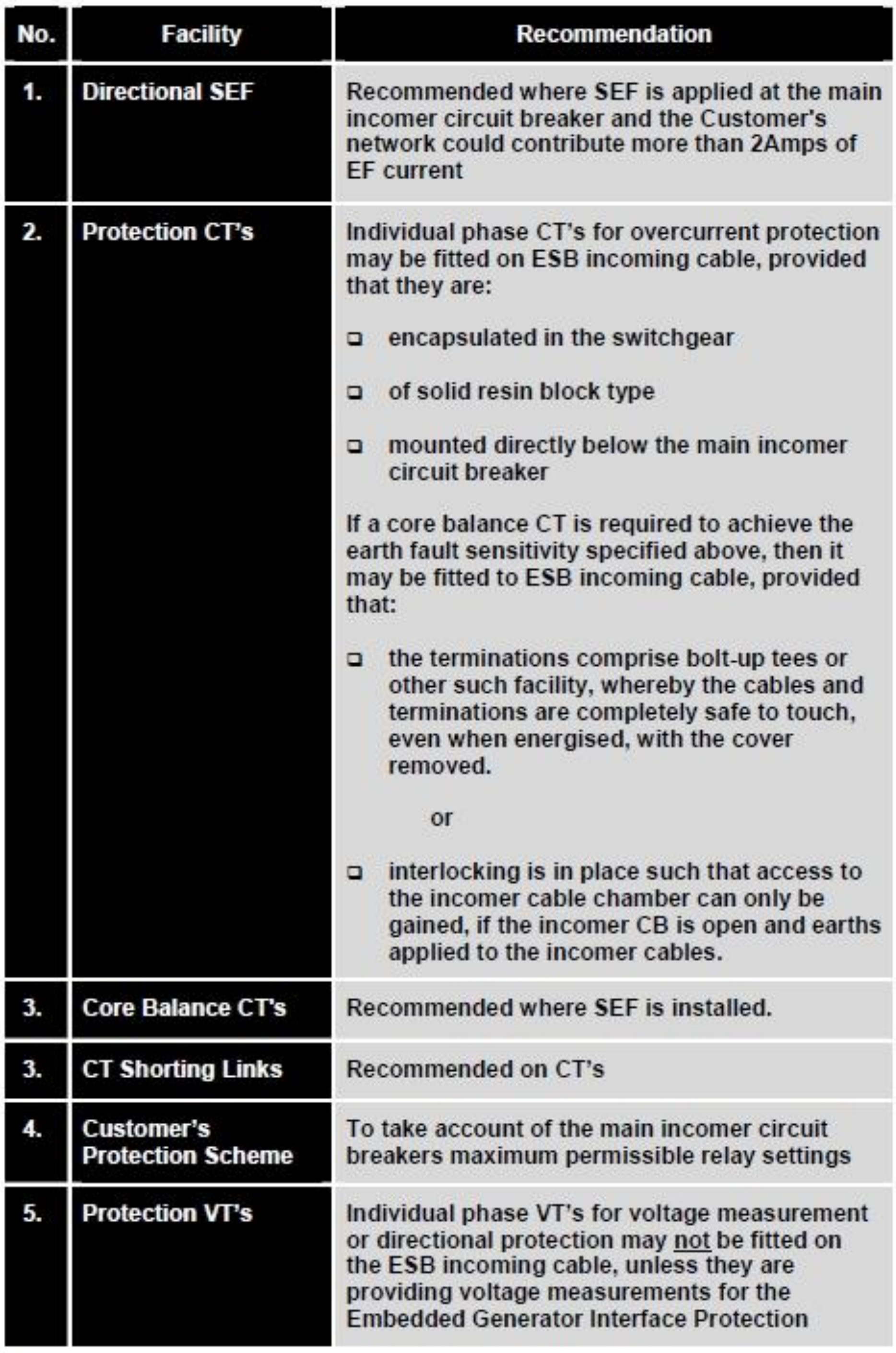
| No. | Item | Provided by | Necessity |
|---|---|---|---|
| 1. | Isolation of ESB equipment from Customer’s equipment | Customer | Customer to provide a means of isolating ESB equipment in the event of a fault on the Customer’s equipment. |
| 2. | Max. Permitted Relay Settings on Main Incomer CB | ESB Networks Ltd | ESB Networks Ltd determined settings on the Customer's relay are necessary to provide selectivity with ESB Distribution protection. |
| 3. | Relay Settings on Main Incomer CB | Customer | The Customer determines the optimal settings on the Customer's Main Incomer protection relay appropriate to the installation. These may not exceed the maximum settings permissible as advised by ESB Networks Ltd (see Row 2. above) |

Table 4B: Protection Requirements



| Item | Protection Type | Plant | Requirement | |
|---|---|---|---|---|
| **Main Incomer CB's** | **Overcurrent** | CT's | Standard | IEC 60044 or equivalent |
| | | Relays | Standard | A, B and C of IEC 60255. |
| | | | Min. no. of elements | 3 |
| | | | Sensitivity | 50AMPS @ MV |
| | **Earth Fault** | CT's and VT's as required | Standard | IEC 60044 or equivalent |
| | | Relays | Standard | A, B, C and DT of IEC 60255 |
| | | | Min. number elements | 1 |
| | | | Sensitivity | 2AMPS @ MV |

Table 4C: Protection Recommendation

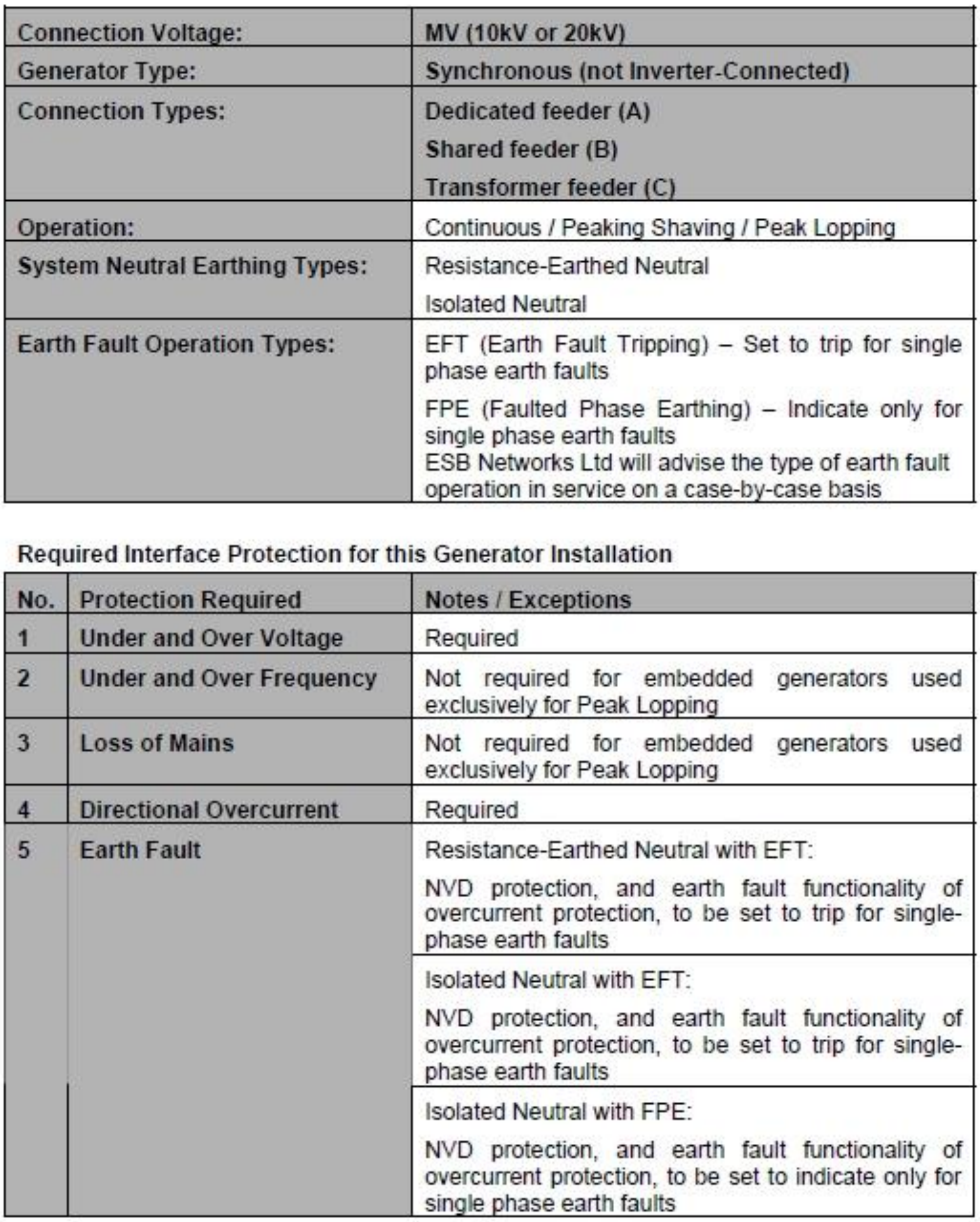


| No. | Facility | Recommendation |
|---|---|---|
| 1. | **Directional SEF** | Recommended where SEF is applied at the main incomer circuit breaker and the Customer's network could contribute more than 2Amps of EF current |
| 2. | **Protection CT's** | Individual phase CT's for overcurrent protection may be fitted on ESB incoming cable, provided that they are:<br>❑ encapsulated in the switchgear<br>❑ of solid resin block type<br>❑ mounted directly below the main incomer circuit breaker<br>If a core balance CT is required to achieve the earth fault sensitivity specified above, then it may be fitted to ESB incoming cable, provided that:<br>❑ the terminations comprise bolt-up tees or other such facility, whereby the cables and terminations are completely safe to touch, even when energised, with the cover removed.<br>or<br>❑ interlocking is in place such that access to the incomer cable chamber can only be gained, if the incomer CB is open and earths applied to the incomer cables. |
| 3. | **Core Balance CT's** | Recommended where SEF is installed. |
| 3. | **CT Shorting Links** | Recommended on CT's |
| 4. | **Customer's Protection Scheme** | To take account of the main incomer circuit breakers maximum permissible relay settings |
| 5. | **Protection VT's** | Individual phase VT's for voltage measurement or directional protection may not be fitted on the ESB incoming cable, unless they are providing voltage measurements for the Embedded Generator Interface Protection |

Table 4D : Additional Requirements for Embedded Generation Installations – Generator Interface Protection Devices

| No. | Device | Requirement |
|---|---|---|
| **1.** | **Protection Devices** | Independent of other equipment and protection |
| | | Located in a separate and secure compartment that can be sealed |
| | | |
| | | Comply with IEC Standard 60255 |
| | | Protection Relay types specified by ESB Networks Ltd |
| | | |
| | | Accessible from ground level |
| | | Clearly identified |
| | | Monitor installation at ESB Distribution Connection Voltage |
| | | Monitor Line Voltage for Under and Over Voltage protection |
| | | Fail safe operation<br>In the event that the LSC or watchdog contacts energise, indicating the failure of an EGIP relay or DC supply:<br>- Generator or main incomer CB should be tripped<br>- Alarm should be sent to the Distribution Control Centre (DCC) |
| | | Prevent reclosure of the CB that EGIP trips, until all EGIP relays have fully reset, and conditions on the ESB network system have returned within normal parameters for at least 5 minutes' |

Table 4E: Embedded Generation Interface Protection Requirements
MV Category

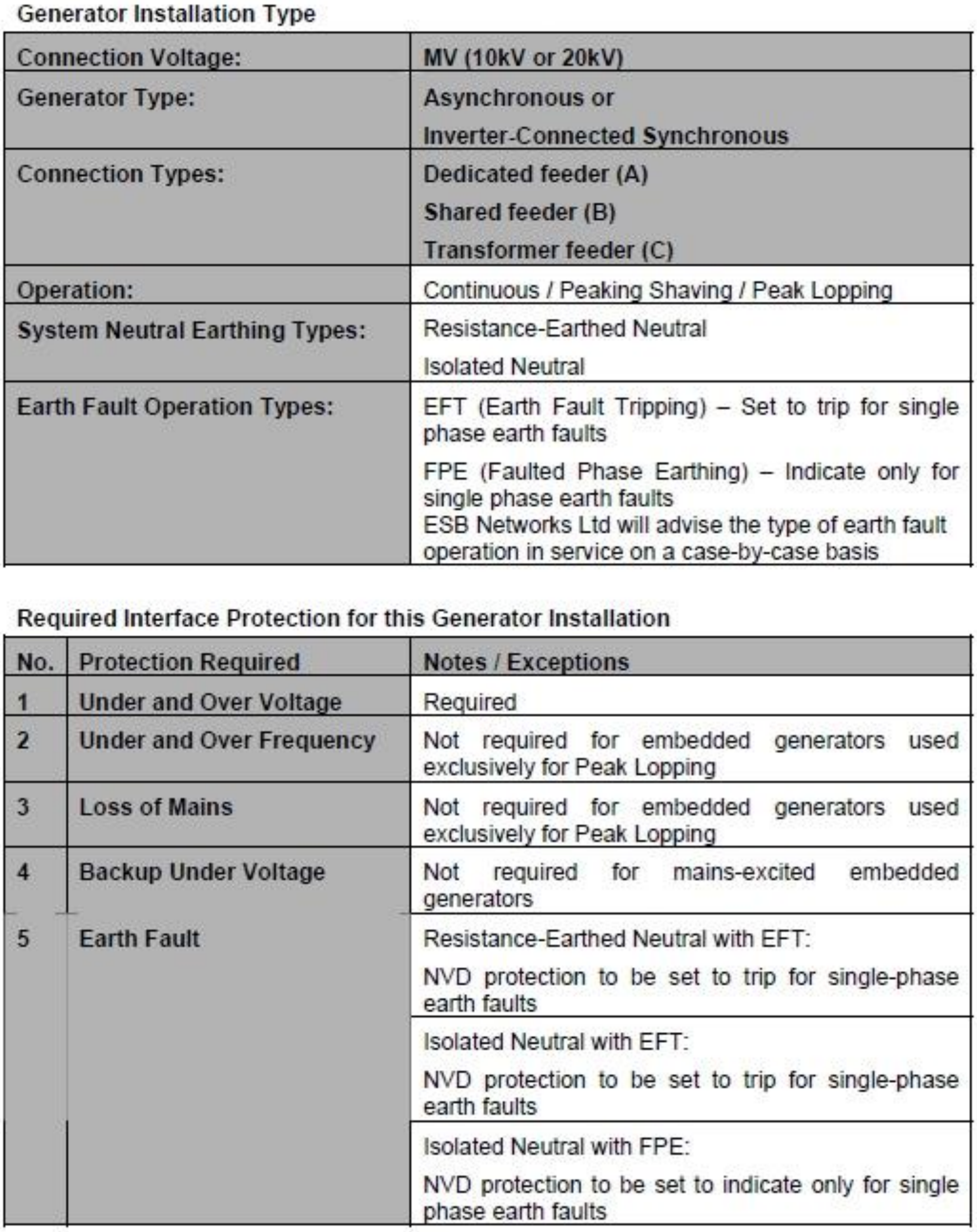


| | |
|---|---|
| **Connection Voltage:** | **MV (10kV or 20kV)** |
| **Generator Type:** | **Synchronous (not Inverter-Connected)** |
| **Connection Types:** | **Dedicated feeder (A)**<br>**Shared feeder (B)**<br>**Transformer feeder (C)** |
| **Operation:** | Continuous / Peaking Shaving / Peak Lopping |
| **System Neutral Earthing Types:** | Resistance-Earthed Neutral<br>Isolated Neutral |
| **Earth Fault Operation Types:** | EFT (Earth Fault Tripping) – Set to trip for single phase earth faults<br>FPE (Faulted Phase Earthing) – Indicate only for single phase earth faults<br>ESB Networks Ltd will advise the type of earth fault operation in service on a case-by-case basis |

**Required Interface Protection for this Generator Installation**

| No. | Protection Required | Notes / Exceptions |
|---|---|---|
| 1 | Under and Over Voltage | Required |
| 2 | Under and Over Frequency | Not required for embedded generators used exclusively for Peak Lopping |
| 3 | Loss of Mains | Not required for embedded generators used exclusively for Peak Lopping |
| 4 | Directional Overcurrent | Required |
| 5 | Earth Fault | Resistance-Earthed Neutral with EFT:<br>NVD protection, and earth fault functionality of overcurrent protection, to be set to trip for single-phase earth faults |
| | | Isolated Neutral with EFT:<br>NVD protection, and earth fault functionality of overcurrent protection, to be set to trip for single-phase earth faults |
| | | Isolated Neutral with FPE:<br>NVD protection, and earth fault functionality of overcurrent protection, to be set to indicate only for single phase earth faults |

Table 4F: Embedded generation Interface Protection Requirements
MV Category



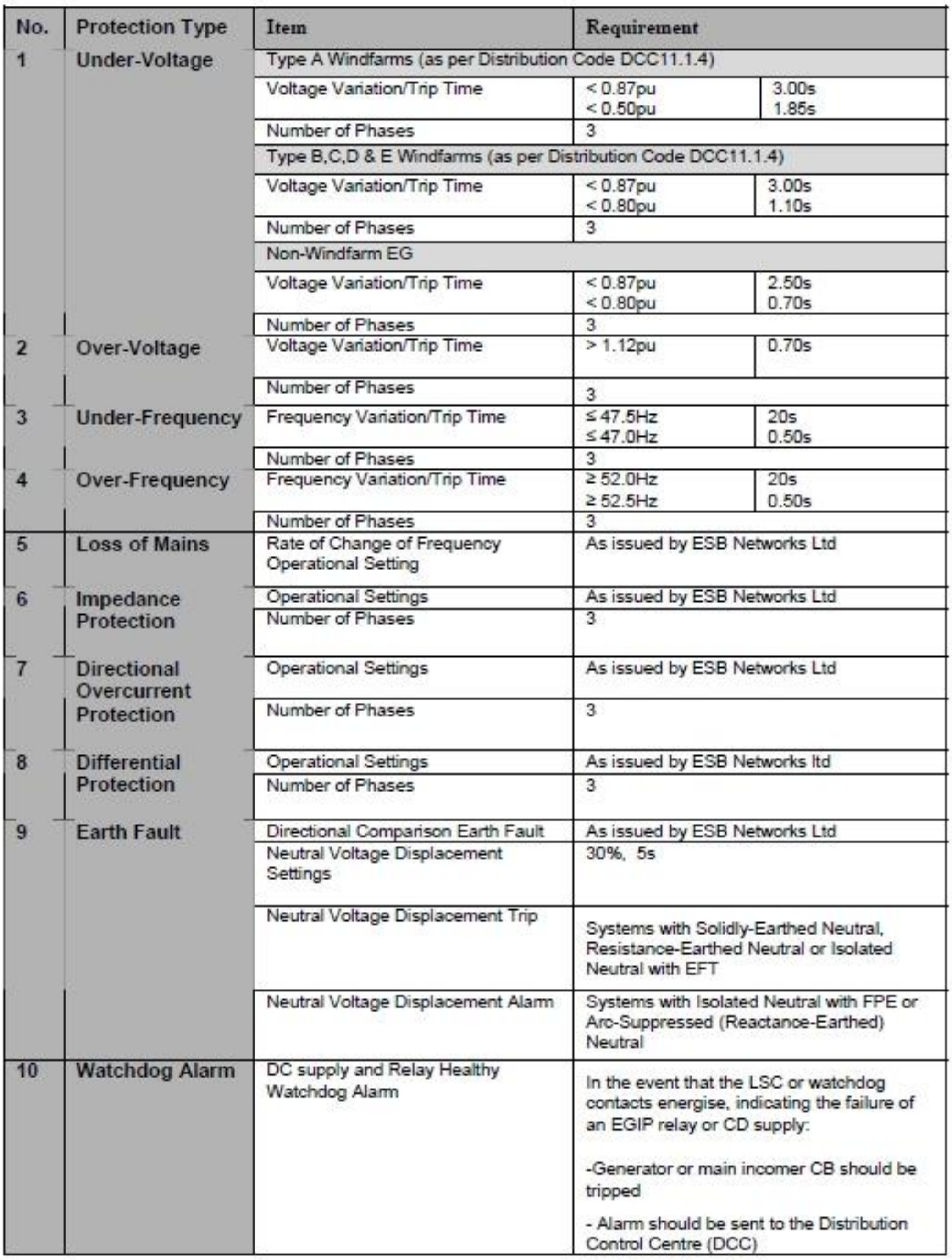
Generator Installation Type

| | |
|---|---|
| **Connection Voltage:** | **MV (10kV or 20kV)** |
| **Generator Type:** | **Asynchronous or**<br>**Inverter-Connected Synchronous** |
| **Connection Types:** | **Dedicated feeder (A)**<br>**Shared feeder (B)**<br>**Transformer feeder (C)** |
| **Operation:** | Continuous / Peaking Shaving / Peak Lopping |
| **System Neutral Earthing Types:** | Resistance-Earthed Neutral<br>Isolated Neutral |
| **Earth Fault Operation Types:** | EFT (Earth Fault Tripping) – Set to trip for single phase earth faults<br>FPE (Faulted Phase Earthing) – Indicate only for single phase earth faults<br>ESB Networks Ltd will advise the type of earth fault operation in service on a case-by-case basis |

Required Interface Protection for this Generator Installation

| **No.** | **Protection Required** | **Notes / Exceptions** |
|---|---|---|
| **1** | **Under and Over Voltage** | Required |
| **2** | **Under and Over Frequency** | Not required for embedded generators used exclusively for Peak Lopping |
| **3** | **Loss of Mains** | Not required for embedded generators used exclusively for Peak Lopping |
| **4** | **Backup Under Voltage** | Not required for mains-excited embedded generators |
| **5** | **Earth Fault** | Resistance-Earthed Neutral with EFT:<br>NVD protection to be set to trip for single-phase earth faults |
| | | Isolated Neutral with EFT:<br>NVD protection to be set to trip for single-phase earth faults |
| | | Isolated Neutral with FPE:<br>NVD protection to be set to indicate only for single phase earth faults |

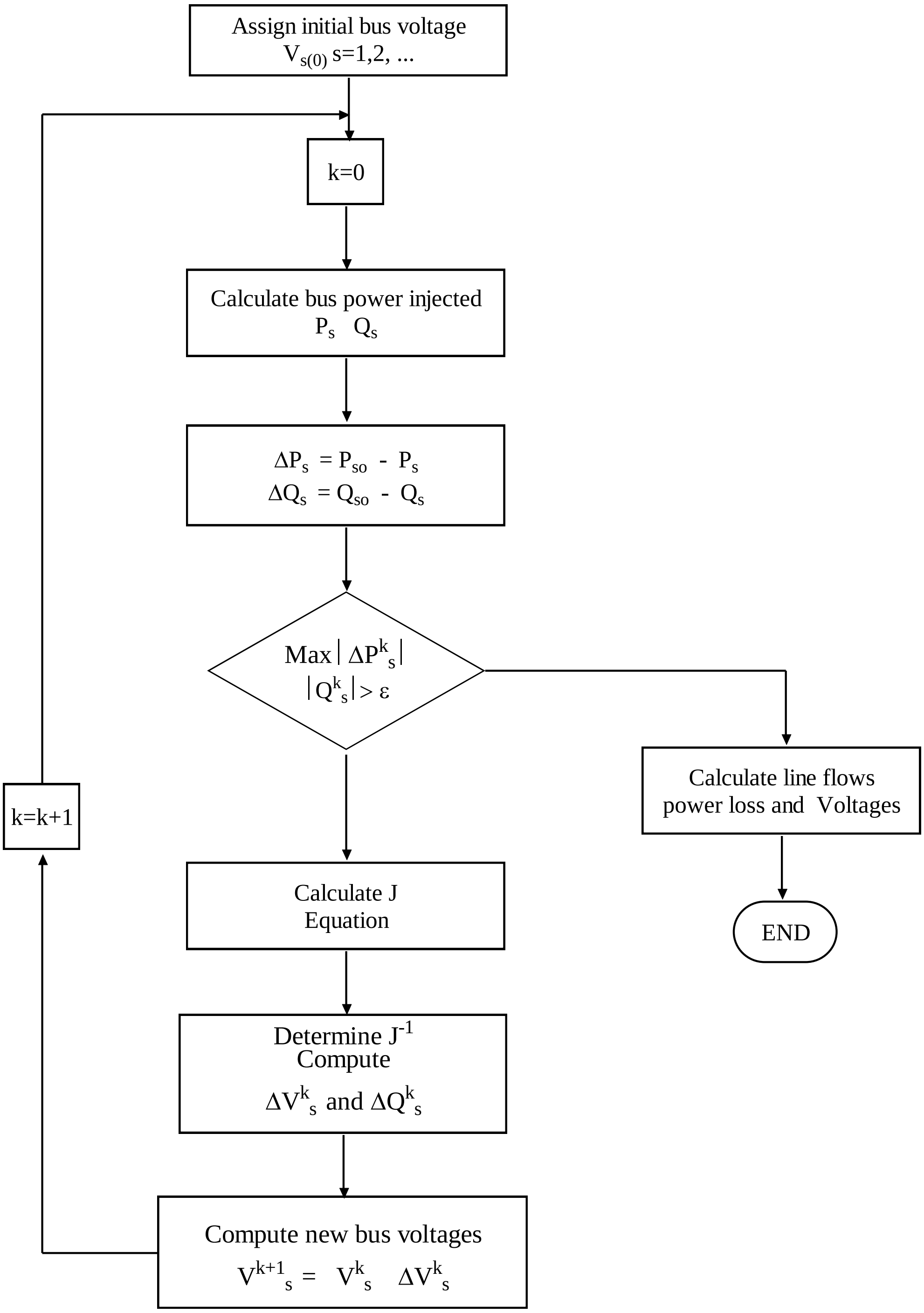
Table 4L: Additional Requirements for Embedded Generators – Protection Types and Summary of Protection Settings



| No. | Protection Type | Item | Requirement | |
|---|---|---|---|---|
| 1 | Under-Voltage | Type A Windfarms (as per Distribution Code DCC11.1.4) | | |
| | | Voltage Variation/Trip Time | < 0.87pu<br>< 0.50pu | 3.00s<br>1.85s |
| | | Number of Phases | 3 | |
| | | Type B,C,D & E Windfarms (as per Distribution Code DCC11.1.4) | | |
| | | Voltage Variation/Trip Time | < 0.87pu<br>< 0.80pu | 3.00s<br>1.10s |
| | | Number of Phases | 3 | |
| | | Non-Windfarm EG | | |
| | | Voltage Variation/Trip Time | < 0.87pu<br>< 0.80pu | 2.50s<br>0.70s |
| | | Number of Phases | 3 | |
| 2 | Over-Voltage | Voltage Variation/Trip Time | > 1.12pu | 0.70s |
| | | Number of Phases | 3 | |
| 3 | Under-Frequency | Frequency Variation/Trip Time | ≤ 47.5Hz<br>≤ 47.0Hz | 20s<br>0.50s |
| | | Number of Phases | 3 | |
| 4 | Over-Frequency | Frequency Variation/Trip Time | ≥ 52.0Hz<br>≥ 52.5Hz | 20s<br>0.50s |
| | | Number of Phases | 3 | |
| 5 | Loss of Mains | Rate of Change of Frequency Operational Setting | As issued by ESB Networks Ltd | |
| 6 | Impedance Protection | Operational Settings | As issued by ESB Networks Ltd | |
| | | Number of Phases | 3 | |
| 7 | Directional Overcurrent Protection | Operational Settings | As issued by ESB Networks Ltd | |
| | | Number of Phases | 3 | |
| 8 | Differential Protection | Operational Settings | As issued by ESB Networks ltd | |
| | | Number of Phases | 3 | |
| 9 | Earth Fault | Directional Comparison Earth Fault | As issued by ESB Networks Ltd | |
| | | Neutral Voltage Displacement Settings | 30%, 5s | |
| | | Neutral Voltage Displacement Trip | Systems with Solidly-Earthed Neutral, Resistance-Earthed Neutral or Isolated Neutral with EFT | |
| | | Neutral Voltage Displacement Alarm | Systems with Isolated Neutral with FPE or Arc-Suppressed (Reactance-Earthed) Neutral | |
| 10 | Watchdog Alarm | DC supply and Relay Healthy Watchdog Alarm | In the event that the LSC or watchdog contacts energise, indicating the failure of an EGIP relay or CD supply:<br>-Generator or main incomer CB should be tripped<br>- Alarm should be sent to the Distribution Control Centre (DCC) | |

# Appendix 5

Alternative method to the method explain in in section 6.1.3 regarding the network Voltage profile (deviation) is performed according the flow chart shown below.



Flow chart for Newton-Raphson method of load flow for PQ buses showing methodology to defined impact on active and reactive power injection on voltage profile (deviation), Method presented in the flow chart above is explain in detail in the following literature:

J.C.Das., Power System Analysis, Short-Circuit, Load Flow and Harmonics., Marcel Dekker. Inc. 2002, Chapter 12 Load Flow Methods Part II

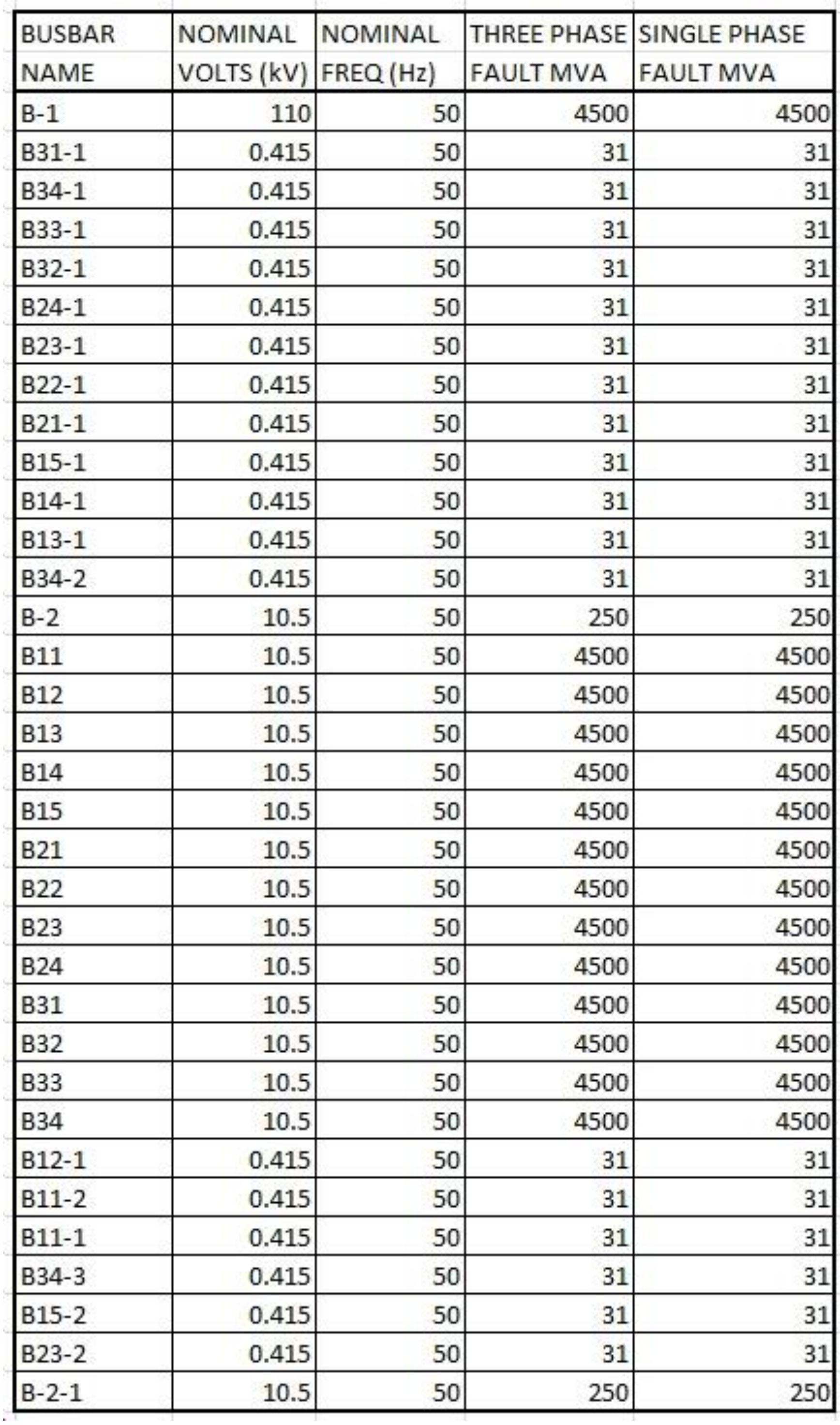
Hadi Sadat., Power System Analysis, Tata McGraw Hill, ISBN – 0-07-012235-0, 2002 edition, Chapter 6 Power Flow Analysis

John J. Grainger, William D. Stevenson, Jr. Power System Analysis, McGraw-Hill International Editions, ISBN 0-07-113338-0, 1994, Chapter 9 Power-Flow Solution

# Appendix 6

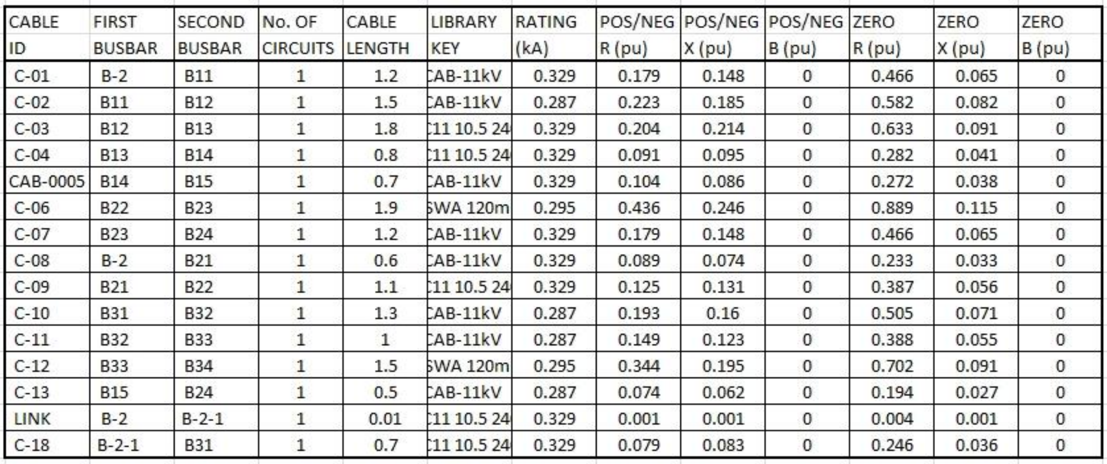
Study data for ERACS software Version 3.8.4 for the network under analysis.

Network Busbars



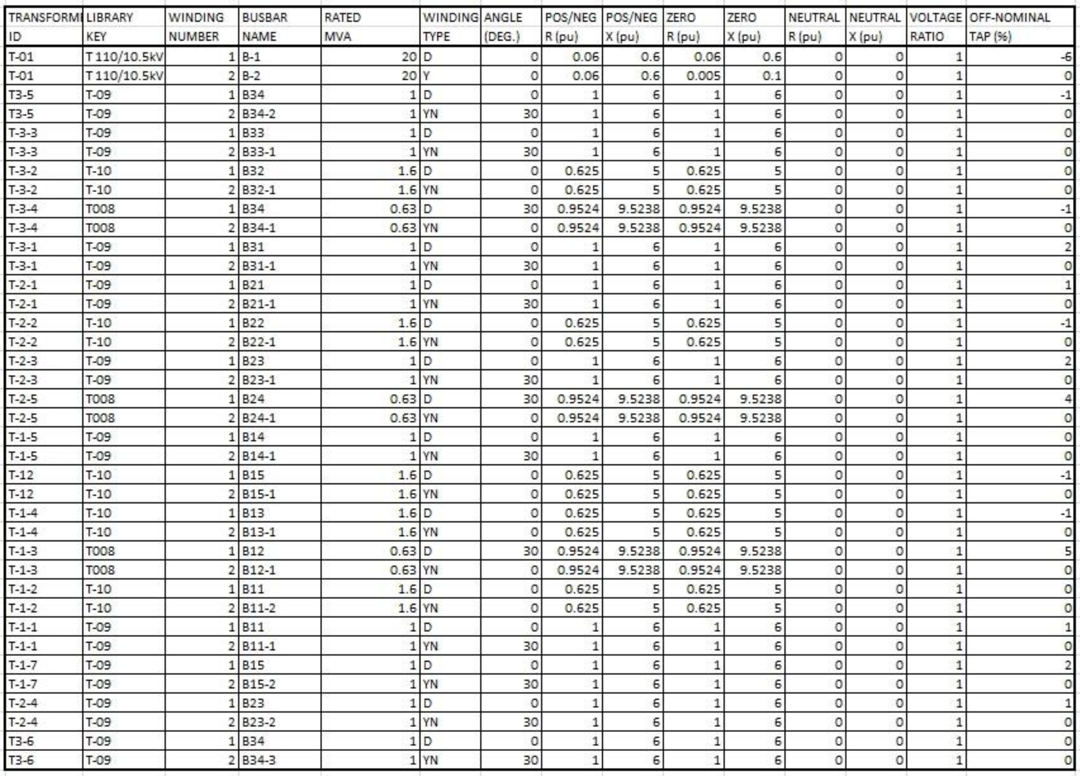
| BUSBAR NAME | NOMINAL VOLTS (kV) | NOMINAL FREQ (Hz) | THREE PHASE FAULT MVA | SINGLE PHASE FAULT MVA |
|---|---|---|---|---|
| B-1 | 110 | 50 | 4500 | 4500 |
| B31-1 | 0.415 | 50 | 31 | 31 |
| B34-1 | 0.415 | 50 | 31 | 31 |
| B33-1 | 0.415 | 50 | 31 | 31 |
| B32-1 | 0.415 | 50 | 31 | 31 |
| B24-1 | 0.415 | 50 | 31 | 31 |
| B23-1 | 0.415 | 50 | 31 | 31 |
| B22-1 | 0.415 | 50 | 31 | 31 |
| B21-1 | 0.415 | 50 | 31 | 31 |
| B15-1 | 0.415 | 50 | 31 | 31 |
| B14-1 | 0.415 | 50 | 31 | 31 |
| B13-1 | 0.415 | 50 | 31 | 31 |
| B34-2 | 0.415 | 50 | 31 | 31 |
| B-2 | 10.5 | 50 | 250 | 250 |
| B11 | 10.5 | 50 | 4500 | 4500 |
| B12 | 10.5 | 50 | 4500 | 4500 |
| B13 | 10.5 | 50 | 4500 | 4500 |
| B14 | 10.5 | 50 | 4500 | 4500 |
| B15 | 10.5 | 50 | 4500 | 4500 |
| B21 | 10.5 | 50 | 4500 | 4500 |
| B22 | 10.5 | 50 | 4500 | 4500 |
| B23 | 10.5 | 50 | 4500 | 4500 |
| B24 | 10.5 | 50 | 4500 | 4500 |
| B31 | 10.5 | 50 | 4500 | 4500 |
| B32 | 10.5 | 50 | 4500 | 4500 |
| B33 | 10.5 | 50 | 4500 | 4500 |
| B34 | 10.5 | 50 | 4500 | 4500 |
| B12-1 | 0.415 | 50 | 31 | 31 |
| B11-2 | 0.415 | 50 | 31 | 31 |
| B11-1 | 0.415 | 50 | 31 | 31 |
| B34-3 | 0.415 | 50 | 31 | 31 |
| B15-2 | 0.415 | 50 | 31 | 31 |
| B23-2 | 0.415 | 50 | 31 | 31 |
| B-2-1 | 10.5 | 50 | 250 | 250 |

Cable



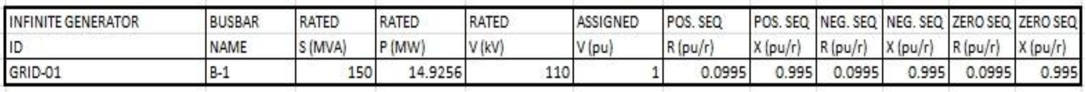
| CABLE ID | FIRST BUSBAR | SECOND BUSBAR | No. OF CIRCUITS | CABLE LENGTH | LIBRARY KEY | RATING (kA) | POS/NEG R (pu) | POS/NEG X (pu) | POS/NEG B (pu) | ZERO R (pu) | ZERO X (pu) | ZERO B (pu) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C-01 | B-2 | B11 | 1 | 1.2 | AB-11kV | 0.329 | 0.179 | 0.148 | 0 | 0.466 | 0.065 | 0 |
| C-02 | B11 | B12 | 1 | 1.5 | AB-11kV | 0.287 | 0.223 | 0.185 | 0 | 0.582 | 0.082 | 0 |
| C-03 | B12 | B13 | 1 | 1.8 | 11 10.5 24 | 0.329 | 0.204 | 0.214 | 0 | 0.633 | 0.091 | 0 |
| C-04 | B13 | B14 | 1 | 0.8 | 11 10.5 24 | 0.329 | 0.091 | 0.095 | 0 | 0.282 | 0.041 | 0 |
| CAB-0005 | B14 | B15 | 1 | 0.7 | AB-11kV | 0.329 | 0.104 | 0.086 | 0 | 0.272 | 0.038 | 0 |
| C-06 | B22 | B23 | 1 | 1.9 | WA 120m | 0.295 | 0.436 | 0.246 | 0 | 0.889 | 0.115 | 0 |
| C-07 | B23 | B24 | 1 | 1.2 | AB-11kV | 0.329 | 0.179 | 0.148 | 0 | 0.466 | 0.065 | 0 |
| C-08 | B-2 | B21 | 1 | 0.6 | AB-11kV | 0.329 | 0.089 | 0.074 | 0 | 0.233 | 0.033 | 0 |
| C-09 | B21 | B22 | 1 | 1.1 | 11 10.5 24 | 0.329 | 0.125 | 0.131 | 0 | 0.387 | 0.056 | 0 |
| C-10 | B31 | B32 | 1 | 1.3 | AB-11kV | 0.287 | 0.193 | 0.16 | 0 | 0.505 | 0.071 | 0 |
| C-11 | B32 | B33 | 1 | 1 | AB-11kV | 0.287 | 0.149 | 0.123 | 0 | 0.388 | 0.055 | 0 |
| C-12 | B33 | B34 | 1 | 1.5 | WA 120m | 0.295 | 0.344 | 0.195 | 0 | 0.702 | 0.091 | 0 |
| C-13 | B15 | B24 | 1 | 0.5 | AB-11kV | 0.287 | 0.074 | 0.062 | 0 | 0.194 | 0.027 | 0 |
| LINK | B-2 | B-2-1 | 1 | 0.01 | 11 10.5 24 | 0.329 | 0.001 | 0.001 | 0 | 0.004 | 0.001 | 0 |
| C-18 | B-2-1 | B31 | 1 | 0.7 | 11 10.5 24 | 0.329 | 0.079 | 0.083 | 0 | 0.246 | 0.036 | 0 |

Transformers



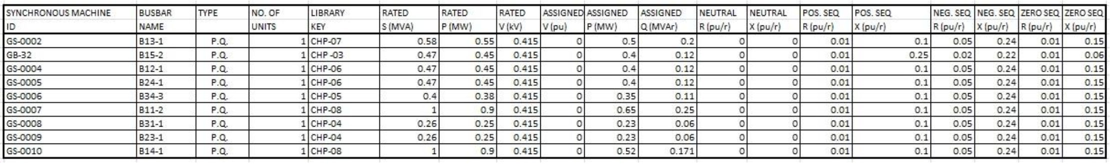
| TRANSFORMI ID | LIBRARY KEY | WINDING NUMBER | BUSBAR NAME | RATED MVA | WINDING TYPE | ANGLE (DEG.) | POS/NEG R (pu) | POS/NEG X (pu) | ZERO R (pu) | ZERO X (pu) | NEUTRAL R (pu) | NEUTRAL X (pu) | VOLTAGE RATIO | OFF-NOMINAL TAP (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T-01 | T 110/10.5kV | 1 | B-1 | 20 | D | 0 | 0.06 | 0.6 | 0.06 | 0.6 | 0 | 0 | 1 | -6 |
| T-01 | T 110/10.5kV | 2 | B-2 | 20 | Y | 0 | 0.06 | 0.6 | 0.005 | 0.1 | 0 | 0 | 1 | 0 |
| T3-5 | T-09 | 1 | B34 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | -1 |
| T3-5 | T-09 | 2 | B34-2 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-3-3 | T-09 | 1 | B33 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-3-3 | T-09 | 2 | B33-1 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-3-2 | T-10 | 1 | B32 | 1.6 | D | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-3-2 | T-10 | 2 | B32-1 | 1.6 | YN | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-3-4 | T008 | 1 | B34 | 0.63 | D | 30 | 0.9524 | 9.5238 | 0.9524 | 9.5238 | 0 | 0 | 1 | -1 |
| T-3-4 | T008 | 2 | B34-1 | 0.63 | YN | 0 | 0.9524 | 9.5238 | 0.9524 | 9.5238 | 0 | 0 | 1 | 0 |
| T-3-1 | T-09 | 1 | B31 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 2 |
| T-3-1 | T-09 | 2 | B31-1 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-2-1 | T-09 | 1 | B21 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 1 |
| T-2-1 | T-09 | 2 | B21-1 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-2-2 | T-10 | 1 | B22 | 1.6 | D | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | -1 |
| T-2-2 | T-10 | 2 | B22-1 | 1.6 | YN | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-2-3 | T-09 | 1 | B23 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 2 |
| T-2-3 | T-09 | 2 | B23-1 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-2-5 | T008 | 1 | B24 | 0.63 | D | 30 | 0.9524 | 9.5238 | 0.9524 | 9.5238 | 0 | 0 | 1 | 4 |
| T-2-5 | T008 | 2 | B24-1 | 0.63 | YN | 0 | 0.9524 | 9.5238 | 0.9524 | 9.5238 | 0 | 0 | 1 | 0 |
| T-1-5 | T-09 | 1 | B14 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-1-5 | T-09 | 2 | B14-1 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-12 | T-10 | 1 | B15 | 1.6 | D | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | -1 |
| T-12 | T-10 | 2 | B15-1 | 1.6 | YN | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-1-4 | T-10 | 1 | B13 | 1.6 | D | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | -1 |
| T-1-4 | T-10 | 2 | B13-1 | 1.6 | YN | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-1-3 | T008 | 1 | B12 | 0.63 | D | 30 | 0.9524 | 9.5238 | 0.9524 | 9.5238 | 0 | 0 | 1 | 5 |
| T-1-3 | T008 | 2 | B12-1 | 0.63 | YN | 0 | 0.9524 | 9.5238 | 0.9524 | 9.5238 | 0 | 0 | 1 | 0 |
| T-1-2 | T-10 | 1 | B11 | 1.6 | D | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-1-2 | T-10 | 2 | B11-2 | 1.6 | YN | 0 | 0.625 | 5 | 0.625 | 5 | 0 | 0 | 1 | 0 |
| T-1-1 | T-09 | 1 | B11 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 1 |
| T-1-1 | T-09 | 2 | B11-1 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-1-7 | T-09 | 1 | B15 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 2 |
| T-1-7 | T-09 | 2 | B15-2 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T-2-4 | T-09 | 1 | B23 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 1 |
| T-2-4 | T-09 | 2 | B23-2 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T3-6 | T-09 | 1 | B34 | 1 | D | 0 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |
| T3-6 | T-09 | 2 | B34-3 | 1 | YN | 30 | 1 | 6 | 1 | 6 | 0 | 0 | 1 | 0 |

Infinite busbar



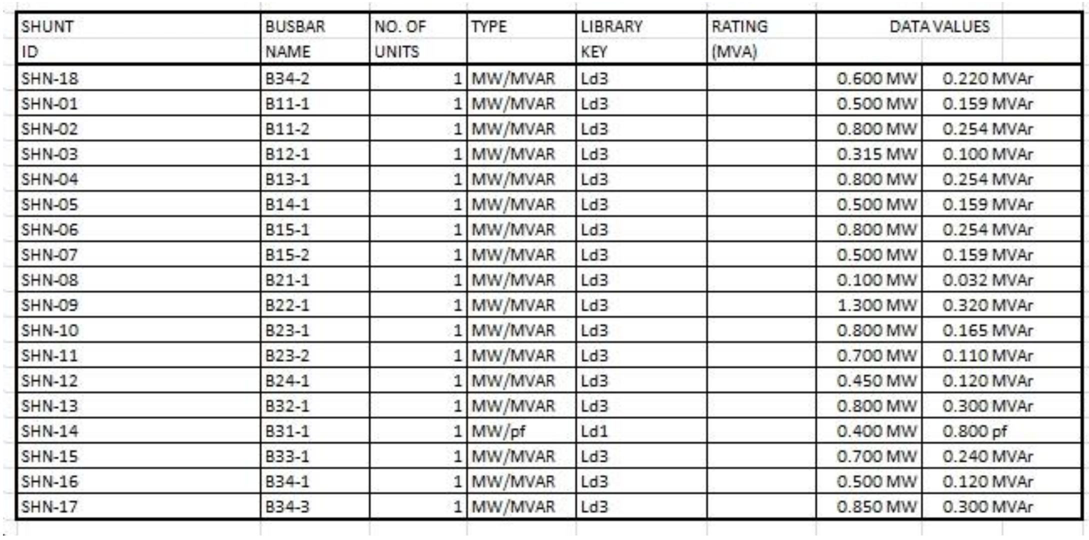
| INFINITE GENERATOR ID | BUSBAR NAME | RATED S (MVA) | RATED P (MW) | RATED V (kV) | ASSIGNED V (pu) | POS. SEQ R (pu/r) | POS. SEQ X (pu/r) | NEG. SEQ R (pu/r) | NEG. SEQ X (pu/r) | ZERO SEQ R (pu/r) | ZERO SEQ X (pu/r) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GRID-01 | B-1 | 150 | 14.9256 | 110 | 1 | 0.0995 | 0.995 | 0.0995 | 0.995 | 0.0995 | 0.995 |

## Synchronous Generators

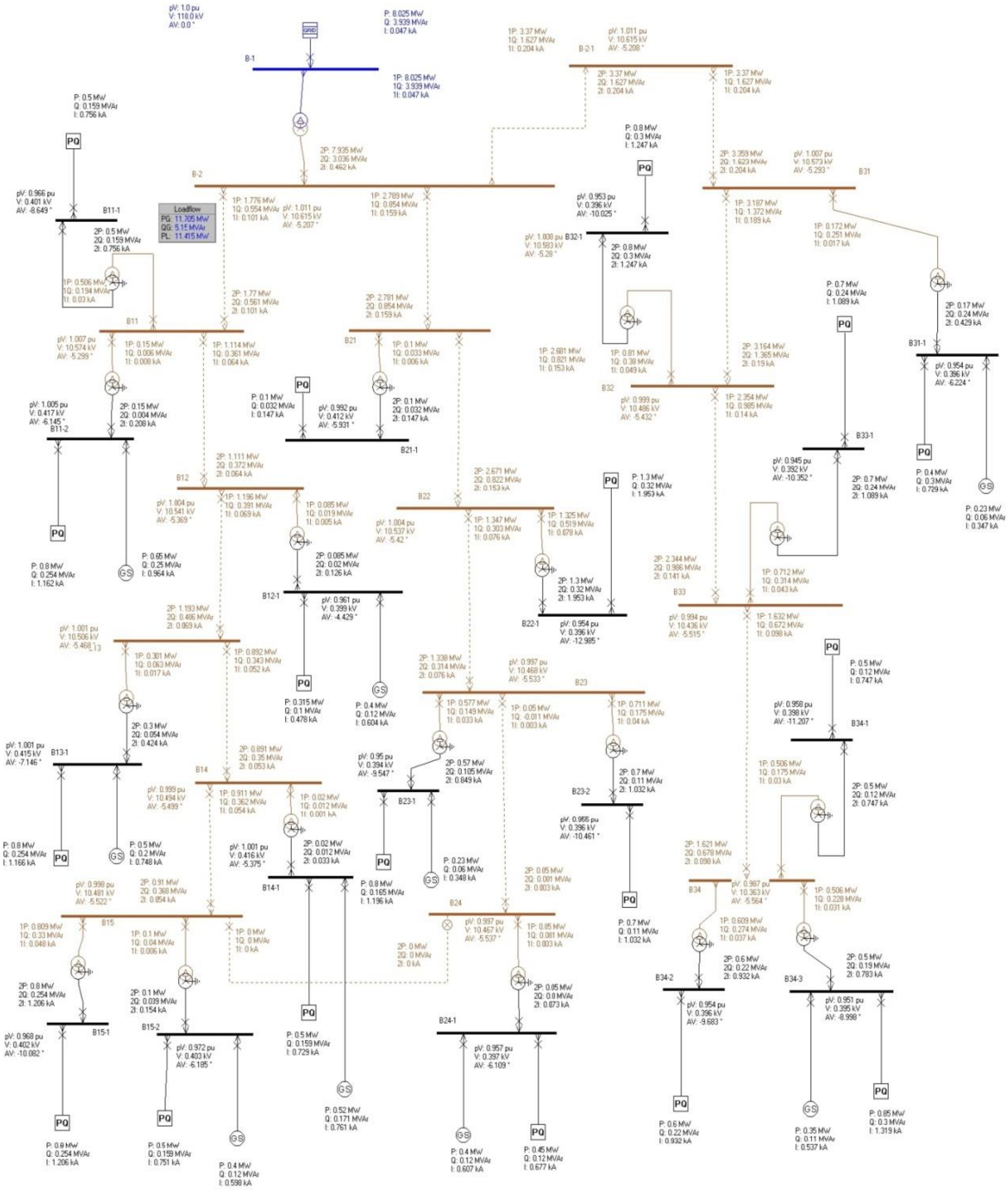


| SYNCHRONOUS MACHINE ID | BUSBAR NAME | TYPE | NO. OF UNITS | LIBRARY KEY | RATED S (MVA) | RATED P (MW) | RATED V (kV) | ASSIGNED V (pu) | ASSIGNED P (MW) | ASSIGNED Q (MVAr) | NEUTRAL R (pu/r) | NEUTRAL X (pu/r) | POS. SEQ R (pu/r) | POS. SEQ X (pu/r) | NEG. SEQ R (pu/r) | NEG. SEQ X (pu/r) | ZERO SEQ R (pu/r) | ZERO SEQ X (pu/r) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GS-0002 | B13-1 | P.Q. | 1 | CHP-07 | 0.58 | 0.55 | 0.415 | 0 | 0.5 | 0.2 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GB-32 | B15-2 | P.Q. | 1 | CHP -03 | 0.47 | 0.45 | 0.415 | 0 | 0.4 | 0.12 | 0 | 0 | 0.01 | 0.25 | 0.02 | 0.22 | 0.01 | 0.06 |
| GS-0004 | B12-1 | P.Q. | 1 | CHP-06 | 0.47 | 0.45 | 0.415 | 0 | 0.4 | 0.12 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GS-0005 | B24-1 | P.Q. | 1 | CHP-06 | 0.47 | 0.45 | 0.415 | 0 | 0.4 | 0.12 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GS-0006 | B34-3 | P.Q. | 1 | CHP-05 | 0.4 | 0.38 | 0.415 | 0 | 0.35 | 0.11 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GS-0007 | B11-2 | P.Q. | 1 | CHP-08 | 1 | 0.9 | 0.415 | 0 | 0.65 | 0.25 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GS-0008 | B31-1 | P.Q. | 1 | CHP-04 | 0.26 | 0.25 | 0.415 | 0 | 0.23 | 0.06 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GS-0009 | B23-1 | P.Q. | 1 | CHP-04 | 0.26 | 0.25 | 0.415 | 0 | 0.23 | 0.06 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |
| GS-0010 | B14-1 | P.Q. | 1 | CHP-08 | 1 | 0.9 | 0.415 | 0 | 0.52 | 0.171 | 0 | 0 | 0.01 | 0.1 | 0.05 | 0.24 | 0.01 | 0.15 |

## Loads



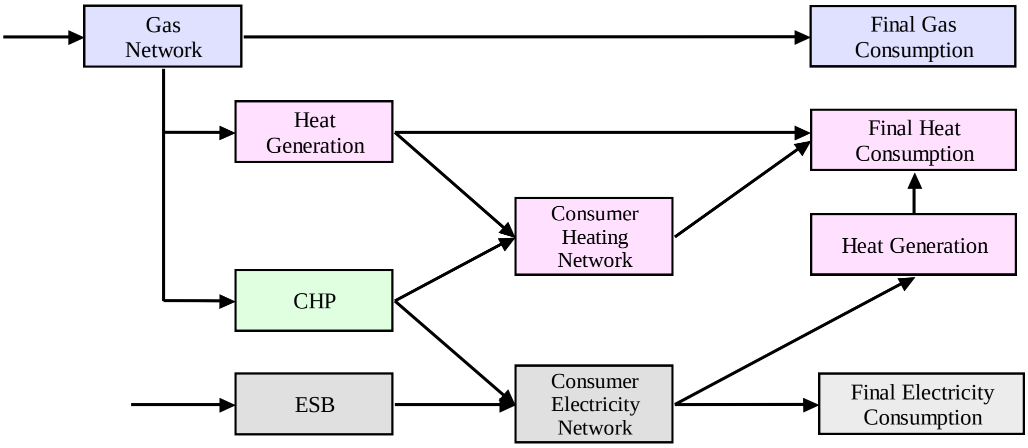
| SHUNT ID | BUSBAR NAME | NO. OF UNITS | TYPE | LIBRARY KEY | RATING (MVA) | DATA VALUES | |
|---|---|---|---|---|---|---|---|
| SHN-18 | B34-2 | 1 | MW/MVAR | Ld3 | | 0.600 MW | 0.220 MVAr |
| SHN-01 | B11-1 | 1 | MW/MVAR | Ld3 | | 0.500 MW | 0.159 MVAr |
| SHN-02 | B11-2 | 1 | MW/MVAR | Ld3 | | 0.800 MW | 0.254 MVAr |
| SHN-03 | B12-1 | 1 | MW/MVAR | Ld3 | | 0.315 MW | 0.100 MVAr |
| SHN-04 | B13-1 | 1 | MW/MVAR | Ld3 | | 0.800 MW | 0.254 MVAr |
| SHN-05 | B14-1 | 1 | MW/MVAR | Ld3 | | 0.500 MW | 0.159 MVAr |
| SHN-06 | B15-1 | 1 | MW/MVAR | Ld3 | | 0.800 MW | 0.254 MVAr |
| SHN-07 | B15-2 | 1 | MW/MVAR | Ld3 | | 0.500 MW | 0.159 MVAr |
| SHN-08 | B21-1 | 1 | MW/MVAR | Ld3 | | 0.100 MW | 0.032 MVAr |
| SHN-09 | B22-1 | 1 | MW/MVAR | Ld3 | | 1.300 MW | 0.320 MVAr |
| SHN-10 | B23-1 | 1 | MW/MVAR | Ld3 | | 0.800 MW | 0.165 MVAr |
| SHN-11 | B23-2 | 1 | MW/MVAR | Ld3 | | 0.700 MW | 0.110 MVAr |
| SHN-12 | B24-1 | 1 | MW/MVAR | Ld3 | | 0.450 MW | 0.120 MVAr |
| SHN-13 | B32-1 | 1 | MW/MVAR | Ld3 | | 0.800 MW | 0.300 MVAr |
| SHN-14 | B31-1 | 1 | MW/pf | Ld1 | | 0.400 MW | 0.800 pf |
| SHN-15 | B33-1 | 1 | MW/MVAR | Ld3 | | 0.700 MW | 0.240 MVAr |
| SHN-16 | B34-1 | 1 | MW/MVAR | Ld3 | | 0.500 MW | 0.120 MVAr |
| SHN-17 | B34-3 | 1 | MW/MVAR | Ld3 | | 0.850 MW | 0.300 MVAr |



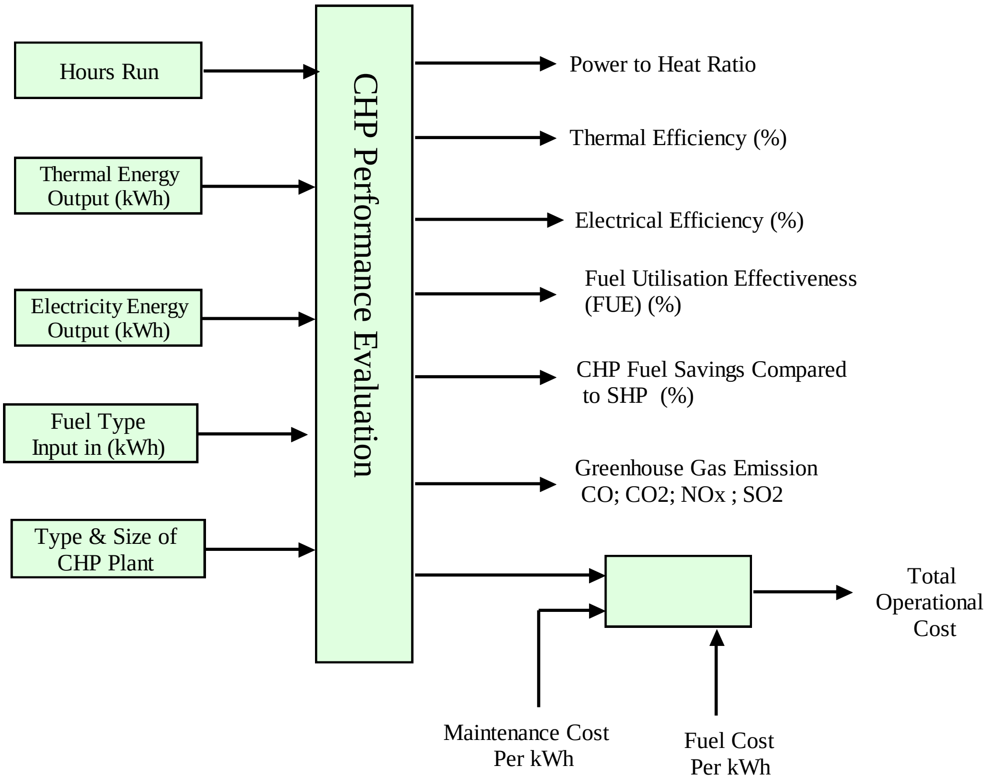
34 – Busbar network under test

# Appendix 7

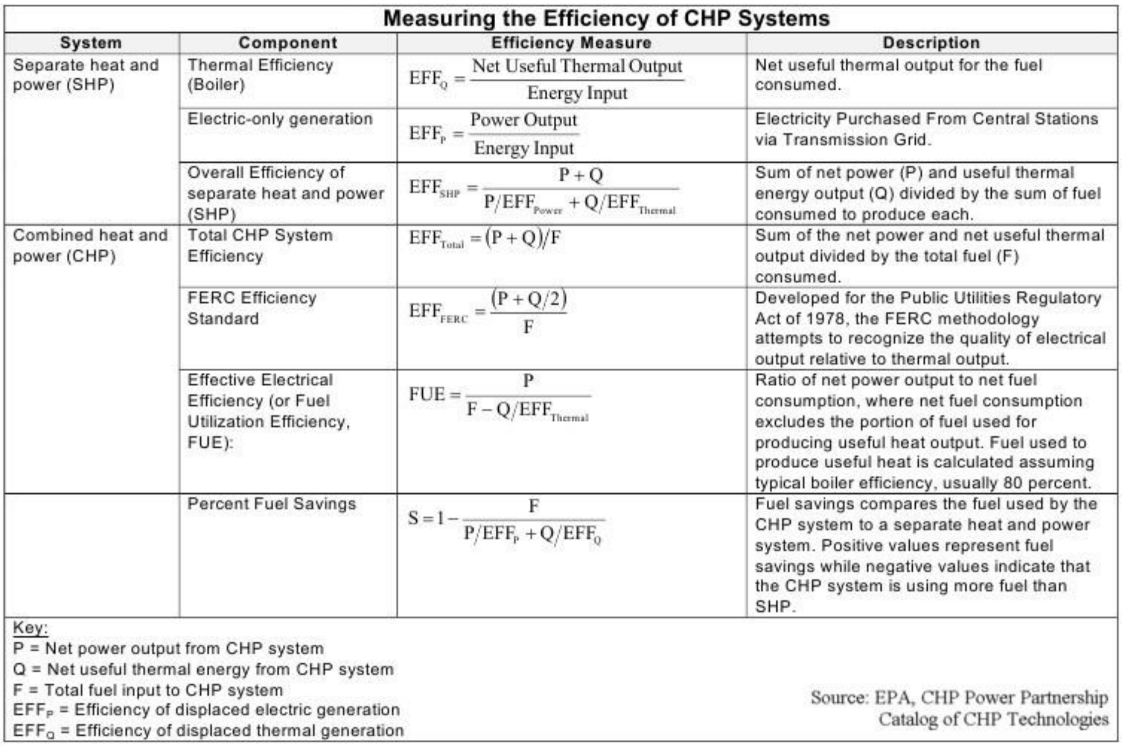
Many of the benefits of CHP system utilisation as a means of energy supply steam from the relatively high efficiency of CHP systems compared to other energy generation systems. Because CHP system simultaneously generate electrical and useful thermal energy; CHP system efficiency is measured and expressed in a number of different ways. Algorithm below summarises the key elements of efficiency as applied to CHP system incorporated in the Energy supply model.



Energy Supply Model Incorporating CHP System



CHP System Performance Evaluation Algorithm



**Measuring the Efficiency of CHP Systems**

| System | Component | Efficiency Measure | Description |
|---|---|---|---|
| Separate heat and power (SHP) | Thermal Efficiency (Boiler) | $EFF_Q = \frac{\text{Net Useful Thermal Output}}{\text{Energy Input}}$ | Net useful thermal output for the fuel consumed. |
|  | Electric-only generation | $EFF_P = \frac{\text{Power Output}}{\text{Energy Input}}$ | Electricity Purchased From Central Stations via Transmission Grid. |
|  | Overall Efficiency of separate heat and power (SHP) | $EFF_{SHP} = \frac{P+Q}{P/EFF_{Power} + Q/EFF_{Thermal}}$ | Sum of net power (P) and useful thermal energy output (Q) divided by the sum of fuel consumed to produce each. |
| Combined heat and power (CHP) | Total CHP System Efficiency | $EFF_{Total} = (P+Q)/F$ | Sum of the net power and net useful thermal output divided by the total fuel (F) consumed. |
|  | FERC Efficiency Standard | $EFF_{FERC} = \frac{(P+Q/2)}{F}$ | Developed for the Public Utilities Regulatory Act of 1978, the FERC methodology attempts to recognize the quality of electrical output relative to thermal output. |
|  | Effective Electrical Efficiency (or Fuel Utilization Efficiency, FUE): | $FUE = \frac{P}{F - Q/EFF_{Thermal}}$ | Ratio of net power output to net fuel consumption, where net fuel consumption excludes the portion of fuel used for producing useful heat output. Fuel used to produce useful heat is calculated assuming typical boiler efficiency, usually 80 percent. |
|  | Percent Fuel Savings | $S = 1 - \frac{F}{P/EFF_P + Q/EFF_Q}$ | Fuel savings compares the fuel used by the CHP system to a separate heat and power system. Positive values represent fuel savings while negative values indicate that the CHP system is using more fuel than SHP. |

Key:
P = Net power output from CHP system
Q = Net useful thermal energy from CHP system
F = Total fuel input to CHP system
$EFF_P$ = Efficiency of displaced electric generation
$EFF_Q$ = Efficiency of displaced thermal generation

Source: EPA, CHP Power Partnership Catalog of CHP Technologies

# Emission $(\xi)$

Emission factor (ε) gram of greenhouse gas per kWh of fuel input
Boiler Thermal Energy Generation Efficiency EFFQ = 90%
Conventional Electrical Energy Generation Efficiency EFFP = 42%

CHP greenhouse gas emission

$$(\xi_{SHP})_{d,m,y} = \sum_i F_{d,m,y} * \varepsilon$$

Separate Heat & Power (SHP) generation greenhouse gas emission

$$(\xi_{SHP})_{d,m,y} = \sum_i (F_{Thermal})_{d,m,y} * 0.9 * \varepsilon + \sum_i (F_{Elec})_{d,m,y} * 0.42 * \varepsilon$$

Greenhouse gas emission produced by SHP generation for the energy output from the CHP system

Emission savings caused by use of CHP scheme

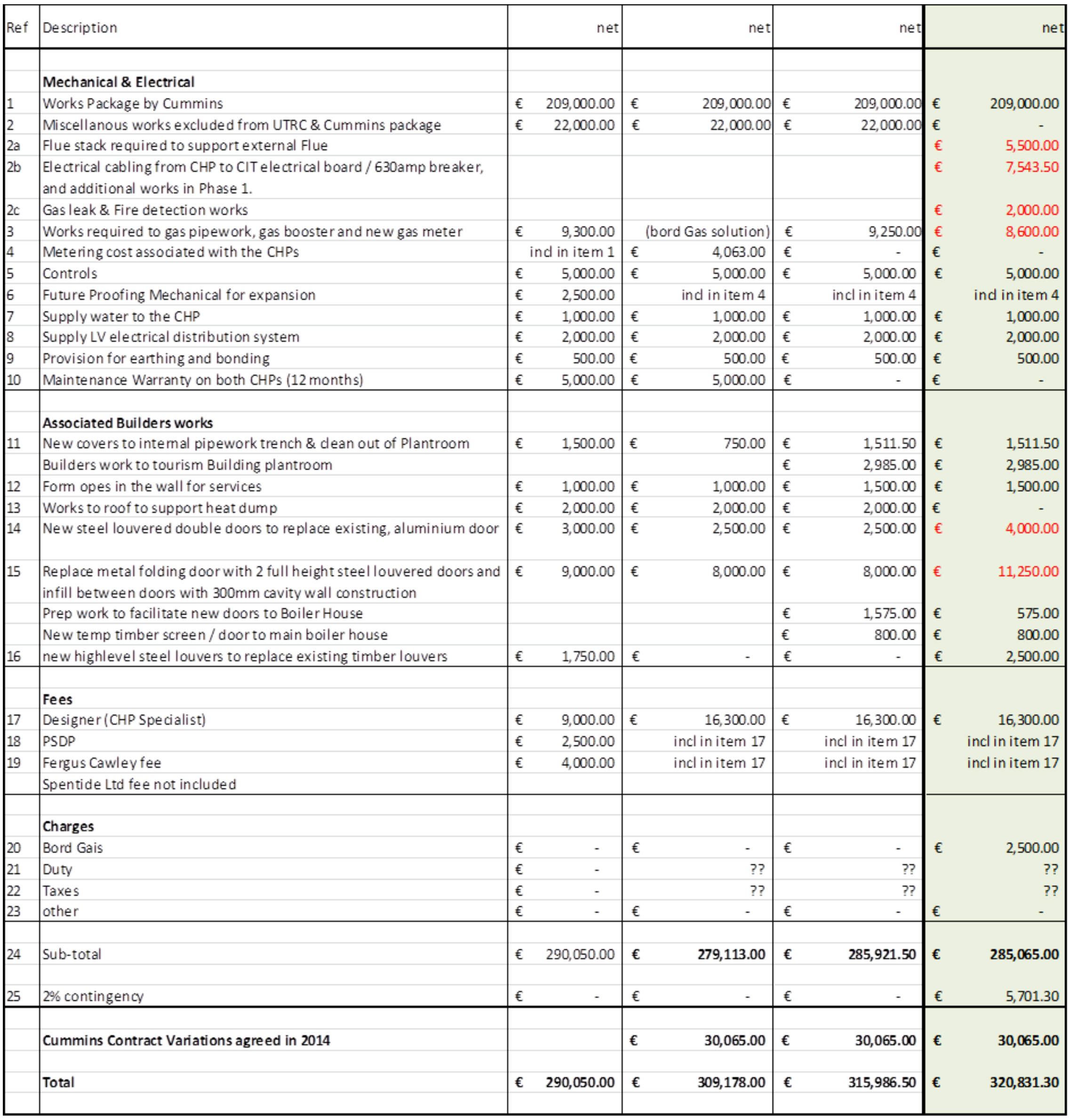
$$(\xi_{SHSavings})_{d,m,y} = (\xi_{SHP})_{d,m,y} - (\xi_{SHCHP})_{d,m,y}$$

**Appendix 8**

Typical cost break down for the CHP system connection in to the network.

Project Budget Cost Revision 4

02.04.15



| Ref | Description | net | net | net | net |
|---|---|---|---|---|---|
| | | | | | |
| | **Mechanical & Electrical** | | | | |
| 1 | Works Package by Cummins | € 209,000.00 | € 209,000.00 | € 209,000.00 | € 209,000.00 |
| 2 | Miscellanous works excluded from UTRC & Cummins package | € 22,000.00 | € 22,000.00 | € 22,000.00 | € - |
| 2a | Flue stack required to support external Flue | | | | € 5,500.00 |
| 2b | Electrical cabling from CHP to CIT electrical board / 630amp breaker, and additional works in Phase 1. | | | | € 7,543.50 |
| 2c | Gas leak & Fire detection works | | | | € 2,000.00 |
| 3 | Works required to gas pipework, gas booster and new gas meter | € 9,300.00 | (bord Gas solution) | € 9,250.00 | € 8,600.00 |
| 4 | Metering cost associated with the CHPs | incl in item 1 | € 4,063.00 | € - | € - |
| 5 | Controls | € 5,000.00 | € 5,000.00 | € 5,000.00 | € 5,000.00 |
| 6 | Future Proofing Mechanical for expansion | € 2,500.00 | incl in item 4 | incl in item 4 | incl in item 4 |
| 7 | Supply water to the CHP | € 1,000.00 | € 1,000.00 | € 1,000.00 | € 1,000.00 |
| 8 | Supply LV electrical distribution system | € 2,000.00 | € 2,000.00 | € 2,000.00 | € 2,000.00 |
| 9 | Provision for earthing and bonding | € 500.00 | € 500.00 | € 500.00 | € 500.00 |
| 10 | Maintenance Warranty on both CHPs (12 months) | € 5,000.00 | € 5,000.00 | € - | € - |
| | | | | | |
| | **Associated Builders works** | | | | |
| 11 | New covers to internal pipework trench & clean out of Plantroom | € 1,500.00 | € 750.00 | € 1,511.50 | € 1,511.50 |
| | Builders work to tourism Building plantroom | | | € 2,985.00 | € 2,985.00 |
| 12 | Form opes in the wall for services | € 1,000.00 | € 1,000.00 | € 1,500.00 | € 1,500.00 |
| 13 | Works to roof to support heat dump | € 2,000.00 | € 2,000.00 | € 2,000.00 | € - |
| 14 | New steel louvered double doors to replace existing, aluminium door | € 3,000.00 | € 2,500.00 | € 2,500.00 | € 4,000.00 |
| 15 | Replace metal folding door with 2 full height steel louvered doors and infill between doors with 300mm cavity wall construction | € 9,000.00 | € 8,000.00 | € 8,000.00 | € 11,250.00 |
| | Prep work to facilitate new doors to Boiler House | | | € 1,575.00 | € 575.00 |
| | New temp timber screen / door to main boiler house | | | € 800.00 | € 800.00 |
| 16 | new highlevel steel louvers to replace existing timber louvers | € 1,750.00 | € - | € - | € 2,500.00 |
| | | | | | |
| | **Fees** | | | | |
| 17 | Designer (CHP Specialist) | € 9,000.00 | € 16,300.00 | € 16,300.00 | € 16,300.00 |
| 18 | PSDP | € 2,500.00 | incl in item 17 | incl in item 17 | incl in item 17 |
| 19 | Fergus Cawley fee | € 4,000.00 | incl in item 17 | incl in item 17 | incl in item 17 |
| | Spentide Ltd fee not included | | | | |
| | | | | | |
| | **Charges** | | | | |
| 20 | Bord Gais | € - | € - | € - | € 2,500.00 |
| 21 | Duty | € - | ?? | ?? | ?? |
| 22 | Taxes | € - | ?? | ?? | ?? |
| 23 | other | € - | € - | € - | € - |
| | | | | | |
| 24 | Sub-total | € 290,050.00 | € **279,113.00** | € **285,921.50** | € **285,065.00** |
| | | | | | |
| 25 | 2% contingency | € - | € - | € - | € 5,701.30 |
| | | | | | |
| | **Cummins Contract Variations agreed in 2014** | | € 30,065.00 | € 30,065.00 | € **30,065.00** |
| | | | | | |
| | **Total** | € **290,050.00** | € 309,178.00 | € 315,986.50 | € **320,831.30** |

## Appendix 9

Matrix Approach to Multiple Linear Regression

In fitting a multiple regression model, it is much more convenient to express the mathematical operations using matrix notation. Suppose that there a m regressor variables and n observations, ($x_{i1}, x_{i2}, \ldots\ldots\ldots\ldots, x_{im}, y_i$), i = 1,2, ......, n and that the model relating the regressors to the response is

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots\cdots + \beta_m x_m + \varepsilon_i \qquad i = 1,2, \ldots\ldots, n$$

This model is a system of n equations that can be expressed in matrix notation as

$$y = X\beta + \varepsilon \qquad (1)$$

where

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \vdots \\ y_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdot & \cdot & \cdot & x_{1m} \\ 1 & x_{21} & x_{22} & \cdot & \cdot & \cdot & x_{2m} \\ \cdot & \cdots & \cdots & \cdot & \cdot & \cdot & \cdot \\ \vdots & \cdots & \cdots & \cdot & \cdot & \cdot & \cdot \\ 1 & x_{n1} & x_{n2} & \cdot & \cdot & \cdot & x_{nm} \end{bmatrix} \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \cdot \\ \cdot \\ \beta_m \end{bmatrix} \text{ and } \quad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdot \\ \cdot \\ \cdot \\ \varepsilon_n \end{bmatrix}$$

In general, y is an (n x 1) vector of the observations, X is an (n xP) matrix of the levels of the independent variables, β is a (p x 1) vector of the regression coefficients, and ε is a (n x 1) vector of random errors

The goal is to find the vector of least squares estimators, $\hat{\beta}$, that minimises

$$L = \sum_{i=1}^{n} \varepsilon_i' = \varepsilon'\varepsilon = (y - X\beta)'(y - X\beta)$$

The least squares estimator $\hat{\beta}$ is the solution for β in the equations

$$\frac{\partial L}{\partial \beta} = 0$$

The resulting equations that must be resolved are

$$X'X\hat{\beta} = X'y \qquad (2)$$

Equations (2) are the least squares normal equations in matrix form. They are identical to scalar form of the normal equations shown below.

$$n\hat{\beta}_0 + \hat{\beta}_1 \sum_{i=1}^{n} x_{i1} + \hat{\beta}_2 \sum_{i=1}^{n} x_{i2} + \cdots\cdots + \hat{\beta}_m \sum_{i=1}^{n} x_{im} = \sum_{i=1}^{n} y_i$$

$$\hat{\beta}_0 \sum_{i=1}^{n} x_{i1} + \hat{\beta}_1 \sum_{i=1}^{n} x_{i1}^2 + \hat{\beta}_2 \sum_{i=1}^{n} x_{i1}x_{i2} + \cdots\cdots + \hat{\beta}_m \sum_{i=1}^{n} x_{i1}x_{im} = \sum_{i=1}^{n} x_{i1}y_i$$

$$\hat{\beta}_0 \sum_{i=1}^{n} x_{im} + \hat{\beta}_1 \sum_{i=1}^{n} x_{im}x_{i1} + \hat{\beta}_2 \sum_{i=1}^{n} x_{im}x_{i2} + \cdots\cdots + \hat{\beta}_m \sum_{i=1}^{n} X_{im}^2 = \sum_{i=1}^{n} x_{im}y_i$$

To solve the normal equations, multiply both sides of equations (2) by the inverse of $X'X$ . Therefore, the least squares estimate of $\beta$ is

$$\hat{\beta} = (X'X)^{-1}X'y \qquad (3)$$

Note that there are p= m + 1 normal equations in p = m + 1 unknowns ( the values of $\hat{\beta}_0$, $\hat{\beta}_1$, ......... $\hat{\beta}_m$). Additionally, the matrix $X'X$ is always nonsingular, as was assumed.

It is obvious that the matrix form of the normal equations is identical to scalar form.

Writing equation (2) in detail we obtain

$$\begin{bmatrix} n & \sum_{i=1}^{n} x_{i1} & \sum_{i=1}^{n} x_{i2} \;\cdots\cdots\cdots\; \sum_{i=1}^{n} x_{im} \\ \sum_{i=1}^{n} x_{i1} & \sum_{i=1}^{n} x_{i1}^2 & \sum_{i=1}^{n} x_{i1}x_{i2} \;\cdots\cdots\; \sum_{i=1}^{n} x_{i1}x_{im} \\ & & \cdot \\ & & \vdots \\ \sum_{i=1}^{n} x_{im} & \sum_{i=1}^{n} x_{im}x_{i1} & \sum_{i=1}^{n} x_{im}x_{i2} \;\cdots\cdots\; \sum_{i=1}^{n} x_{im}^2 \end{bmatrix} \begin{bmatrix} \widehat{\beta_0} \\ \widehat{\beta_1} \\ \vdots \\ \cdot \\ \widehat{\beta_m} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_{i1}y_i \\ \cdot \\ \cdot \\ \cdot \\ n\sum_{i=1}^{n} x_{im}y_i \end{bmatrix}$$

If the indicated matrix multiplications is performed, the scalar form of the normal equations shown above will result. In this form it is obvious to see that $X'X$ is a (p x p) symmetric matrix and $X'y$ is a (p x 1) column vector. The diagonal elements of $X'X$ are the sums of squares of the elements in the columns of X, and the off-diagonal elements are the sums of cross-products of the elements in the columns of X. Additionally, the elements of $X'y$ are the sums of the columns of X and the observations $\{y_i\}$.

The fitted notation, the fitted model is $\hat{y} = X\hat{\beta}$

The difference between the observation $y_i$ and the fitted value $\hat{y_i}$ is a residual, say

$e_i\ y_i - \hat{y_i}$ . The (n x 1) vector of residuals is denoted by $e = y - \hat{y}$

## Appendix 10

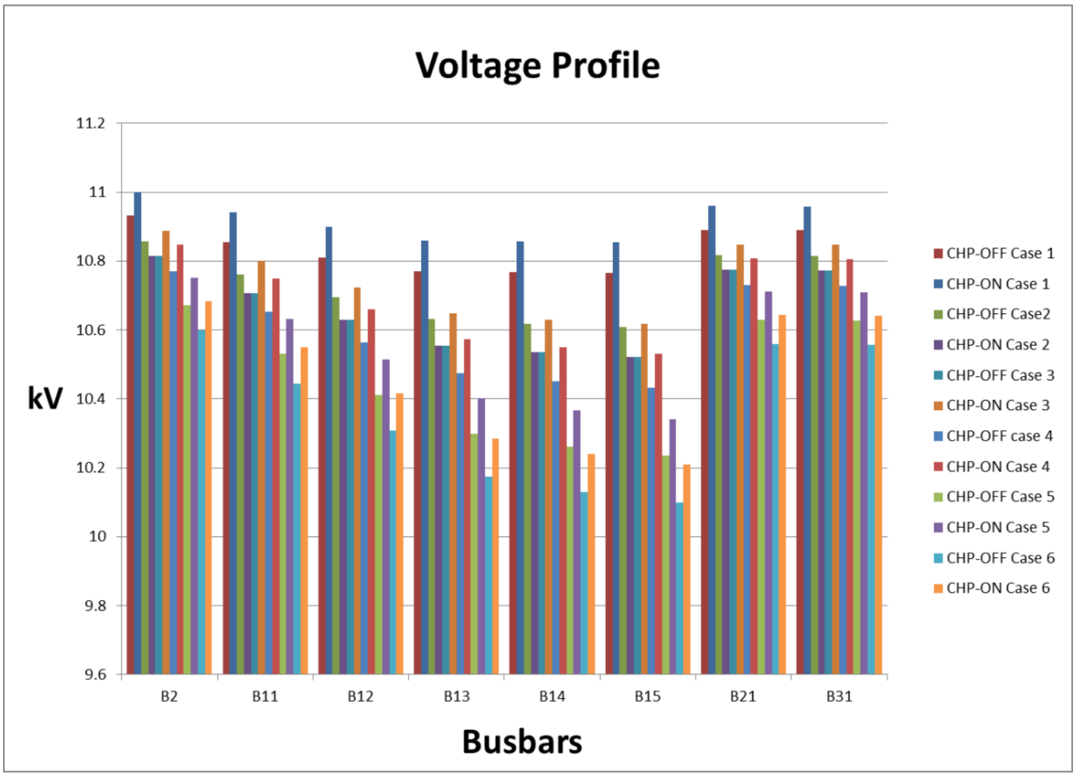
Results presented below are obtained using the calculation methodology described in Chapter 3 for the scenario where CHP plant is connected on busbar B11-1 for the same loading scenarios applied in the calculations where CHP plant is connected on B14-1.

### Loading scenarios

| **Busbar ID** | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Scenario 4** | **Scenario 5** | **Scenario 6** |
|---|---|---|---|---|---|---|
| **B14-1** | **200kW**<br>**65kVAr** | **400kW**<br>**130kVAr** | **500kW**<br>**170kVAr** | **600kW**<br>**200kVAr** | **800kW**<br>**270kVAr** | **950kW**<br>**310kVAr** |
| **B15-1** | **320kW**<br>**100kVAr** | **640kW**<br>**220kVAr** | **800kW**<br>**270kVAr** | **960kW**<br>**320kVAr** | **1280kW**<br>**400kVAr** | **1420kW**<br>**455kVAr** |
| **B15-2** | **200kW**<br>**65kVAr** | **400kW**<br>**130kVAr** | **500kW**<br>**170kVAr** | **600kW**<br>**200kVAr** | **800kW**<br>**270kVAr** | **950kW**<br>**310kVAr** |

### Voltage Profile on the busbars under analysis (CHP plant connected at B11-1)

| Busbar | CASE 1 | | CASE 2 | | CASE 3 | | CASE 4 | | CASE 5 | | CASE 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | V (kV) | | V (kV) | | V (kV) | | V (kV) | | V (kV) | | V (kV) | |
| | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON | CHP OFF | CHP ON |
| B2 | 10.931 | 11 | 10.857 | 10.814 | 10.814 | 10.888 | 10.771 | 10.847 | 10.671 | 10.751 | 10.6 | 10.684 |
| B11 | 10.854 | 10.942 | 10.76 | 10.707 | 10.707 | 10.801 | 10.654 | 10.749 | 10.531 | 10.632 | 10.445 | 10.55 |
| B12 | 10.811 | 10.9 | 10.695 | 10.629 | 10.629 | 10.723 | 10.563 | 10.659 | 10.412 | 10.515 | 10.308 | 10.415 |
| B13 | 10.771 | 10.86 | 10.632 | 10.554 | 10.554 | 10.649 | 10.475 | 10.573 | 10.298 | 10.402 | 10.175 | 10.284 |
| B14 | 10.767 | 10.856 | 10.618 | 10.535 | 10.535 | 10.63 | 10.451 | 10.549 | 10.262 | 10.366 | 10.131 | 10.24 |
| B15 | 10.766 | 10.854 | 10.609 | 10.522 | 10.522 | 10.617 | 10.433 | 10.531 | 10.235 | 10.34 | 10.099 | 10.209 |
| B21 | 10.891 | 10.961 | 10.817 | 10.774 | 10.774 | 10.848 | 10.73 | 10.807 | 10.63 | 10.711 | 10.559 | 10.643 |
| B31 | 10.89 | 10.959 | 10.815 | 10.772 | 10.772 | 10.847 | 10.729 | 10.805 | 10.628 | 10.709 | 10.557 | 10.642 |



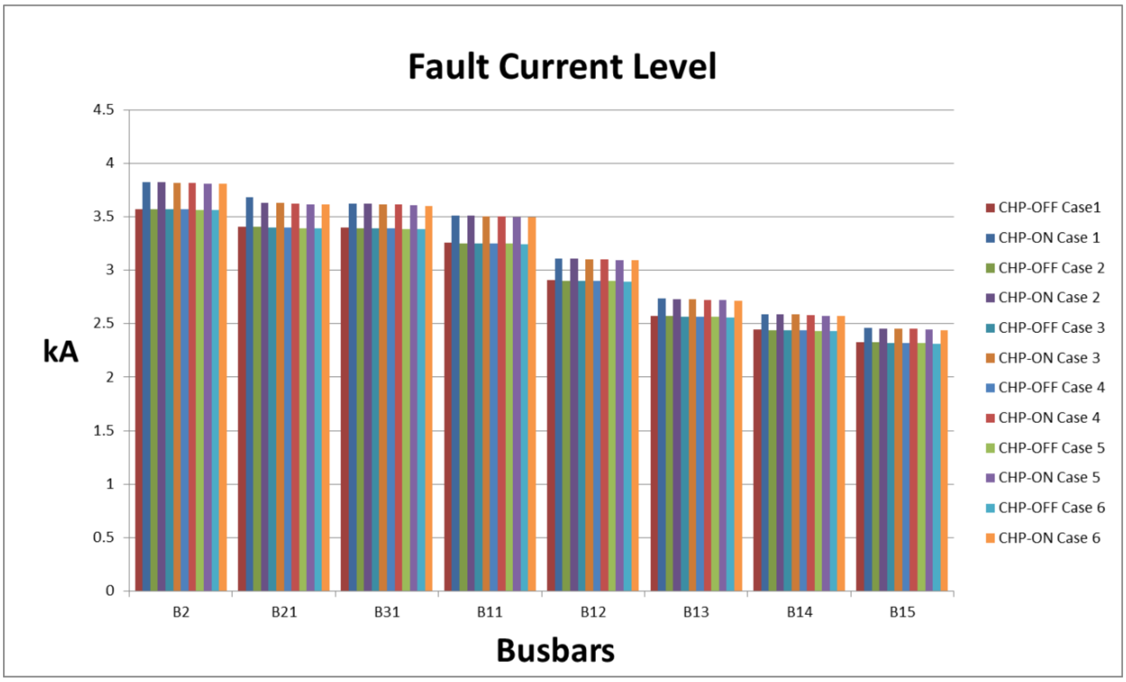
**Voltage profile on the busbars under analysis**

## Three Phase Fault Current on busbars under analysis CHP plant OFF

| Three Phase Fault Level CHP OFF | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Case 1 | | Case 2 | | Case 3 | | Case 4 | | Case 5 | | Case 6 | |
| Busbar ID | Specified Rating (kA) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) | Calculated Fault Level (kA) | Rating Capacity Used (%) |
| B2 | 13.746 | 3.572 | 25.986 | 3.57 | 25.971 | 3.569 | 25.964 | 3.568 | 25.957 | 3.566 | 25.942 | 3.565 | 25.935 |
| B21 | 13.746 | 3.408 | 24.793 | 3.404 | 24.764 | 3.402 | 24.749 | 3.4 | 24.734 | 3.395 | 24.698 | 3.392 | 24.676 |
| B31 | 13.746 | 3.397 | 24.713 | 3.393 | 24.684 | 3.391 | 24.669 | 3.389 | 24.654 | 3.385 | 24.625 | 3.381 | 24.596 |
| B11 | 13.746 | 3.254 | 23.672 | 3.252 | 23.658 | 3.251 | 23.651 | 3.25 | 23.643 | 3.248 | 23.629 | 3.246 | 23.614 |
| B12 | 13.746 | 2.904 | 21.126 | 2.902 | 21.112 | 2.901 | 21.104 | 2.899 | 21.090 | 2.897 | 21.075 | 2.894 | 21.053 |
| B13 | 13.746 | 2.572 | 18.711 | 2.569 | 18.689 | 2.568 | 18.682 | 2.566 | 18.667 | 2.563 | 18.645 | 2.561 | 18.631 |
| B14 | 13.746 | 2.443 | 17.772 | 2.441 | 17.758 | 2.439 | 17.743 | 2.438 | 17.736 | 2.434 | 17.707 | 2.432 | 17.692 |
| B15 | 13.746 | 2.328 | 16.936 | 2.325 | 16.914 | 2.323 | 16.899 | 2.321 | 16.885 | 2.316 | 16.849 | 2.313 | 16.827 |

## Three Phase Fault Current on busbars under analysis CHP plant ON

| Three Phase Fault Level CHP ON | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Case 1 | | Case 2 | | Case 3 | | Case 4 | | Case 5 | | Case 6 | |
| Busbar | Specified | Calculated | Rating | Calculated | Rating | Calculated | Rating | Calculated | Rating | Calculated | Rating | Calculated | Rating |
| ID | Rating | Fault | Capacity | Fault | Capacity | Fault | Capacity | Fault | Capacity | Fault | Capacity | Fault | Capacity |
| | (kA) | Level (kA) | Used (%) | Level (kA) | Used (%) | Level (kA) | Used (%) | Level (kA) | Used (%) | Level (kA) | Used (%) | Level (kA) | Used (%) |
| B2 | 13.746 | 3.825 | 27.826 | 3.821 | 27.797 | 3.818 | 27.775 | 3.816 | 27.761 | 3.811 | 27.724 | 3.808 | 27.703 |
| B21 | 13.746 | 3.683 | 26.793 | 3.632 | 26.422 | 3.628 | 26.393 | 3.625 | 26.371 | 3.617 | 26.313 | 3.612 | 26.277 |
| B31 | 13.746 | 3.625 | 26.371 | 3.619 | 26.328 | 3.616 | 26.306 | 3.612 | 26.277 | 3.605 | 26.226 | 3.6 | 26.189 |
| B11 | 13.746 | 3.513 | 25.557 | 3.509 | 25.527 | 3.506 | 25.506 | 3.504 | 25.491 | 3.499 | 25.455 | 3.495 | 25.426 |
| B12 | 13.746 | 3.111 | 22.632 | 3.107 | 22.603 | 3.104 | 22.581 | 3.102 | 22.567 | 3.096 | 22.523 | 3.093 | 22.501 |
| B13 | 13.746 | 2.734 | 19.889 | 2.73 | 19.860 | 2.728 | 19.846 | 2.725 | 19.824 | 2.72 | 19.788 | 2.716 | 19.758 |
| B14 | 13.746 | 2.591 | 18.849 | 2.586 | 18.813 | 2.584 | 18.798 | 2.582 | 18.784 | 2.576 | 18.740 | 2.572 | 18.711 |
| B15 | 13.746 | 2.462 | 17.911 | 2.457 | 17.874 | 2.454 | 17.852 | 2.452 | 17.838 | 2.445 | 17.787 | 2.441 | 17.758 |



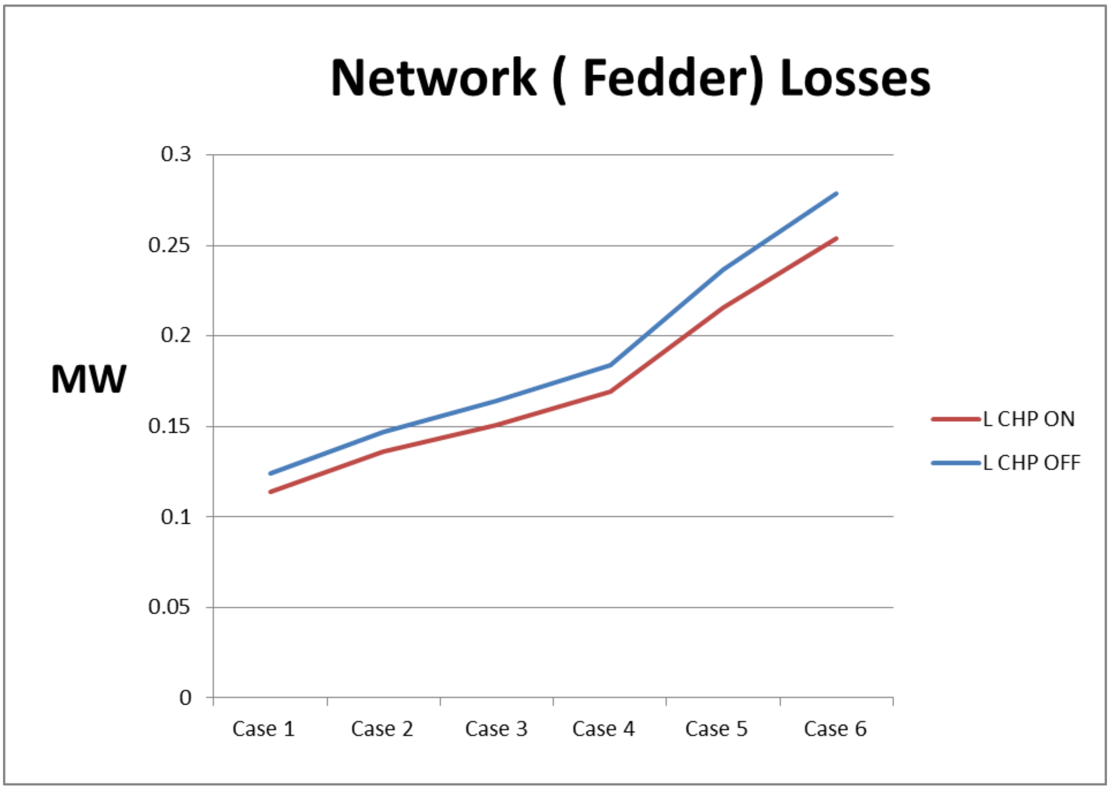
**Three Phase Fault Current on busbars under analysis - CHP plant OFF/ON**

## Total Losses on the feeder under analysis

| Total Losses in (MW) | | | | | | |
|---|---|---|---|---|---|---|
| Scenarios | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
| TL CHP OFF | 0.124 | 0.147 | 0.164 | 0.184 | 0.237 | 0.279 |
| TL CHP ON | 0.114 | 0.136 | 0.151 | 0.169 | 0.216 | 0.254 |

TL CHP OFF – Total Losses CHP plant at B11-1 is OFF

TL CHP ON – Total Losses CHP plant at B11-1 is ON



**Total Feeder Losses with CHP plant OFF/ON**