Dynamic Simulation and Intelligent Management of Distributed Generation

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Abstract

Significantly large integration of distributed generation (DG) is expected in future power systems. Paving the way are the encouraging government policies, great concerns on environment and optimising economic benefits. This large integration is however raising a lot of concern on stability, security and reliability of power system network which will create many challenges in operating the network due to different characteristics possessed by DG. These concerns and operating challenges need to be investigated to identify the possible problems that may arise and then followed by finding a countermeasure for mitigation. Research work in this thesis addresses most important issues and challenges in operating power system with large DG penetration. The following research areas are performed:

- **Modeling of distributed generation**: New technology embraces by DG has totally different characteristics compared to conventional generation unit based on synchronous machine, thus making it necessary to perform integration studies on various operational aspects to assess the influence of this small scale generation unit on the power system network operation and control. The studies require an accurate and easy to understand dynamic model which closely imitates the dynamics of a real DG unit. In this thesis, development of different dynamic models of micro turbine generation system, fuel cell generation system and a generalized DG dynamic model to be used in power system studies is discussed. The performance of the model developed from the simulation results is found comparable to the reported performance in the literature.
- **DG fault ride-through capability**: Due to different characteristics possessed by DG, power system operator imposed stringent requirements on the DG connected to the grid. During critical time DG has to be able to withstand a temporary voltage dip due to fault occurrence in the grid even when the voltage reaches zero at the point of connection. At the same time, during this fault ride-through DG must also help the grid by injecting reactive power to support power system voltage recovery. Different types of DG technologies are investigated if they are able to fulfil this requirement and if not exploring the necessary modifications which has to be made on the specific DG unit. The investigation results indicate that in fulfilling new grid code requirements, modification inside DG power electronic converter hardware and controller is necessary.

- **Grid support by DG:** Massive DG integration in distribution network will interfere with current practices and control scheme inside the network. With appropriate coordination and control, this negative influence on network could be changed to positive. This thesis explores the possibility of participating DGs in voltage regulation and frequency control. Clearly the studies indicate that DG coupled to the grid through power electronic converter has potential to positively contribute to power system voltage regulation and frequency stabilisation.
- **Influence of DG on power system stability under new grid codes**: Power electronic converter utilised in DGs makes them have different characteristics in responding to grid fault and they are also demanded to provide reactive support during this period. This characteristic and new rule is feared to negatively influence the stability of a power system as to where these DG units are connected to. In this thesis the most important types of stability are analysed with different levels of DG penetration and control options. It can be concluded that if DG is properly located and controlled, DG integration will significantly improve the stability of power system network.
- **Predictive var management inside future distribution network**: Future distribution network will contain large number of DG units and the network will be integrated with advance communication facilities. This large number of DG will create technical challenges but the communication link available will provide the opportunity to control DG centrally in real time to optimise the benefits offered by DG integration. In this thesis, a predictive technique in managing DG reactive power to reduce power loss and to control the voltage inside a distribution network is proposed and discussed. The effectiveness of the proposed approach which are developed with two staged intelligent techniques namely, adaptive particle swarm optimisation and artificial neural network, is demonstrated and the results are quite promising.

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Chapter 1

Introduction

1. 1 Motivation

Distributed Generation (DG) is seen as a solution for solving environmental concerns and the need to secure an electricity supply to support sustainable development [1]. Of particular interest are DGs driven by free renewable energy resources (RES) such as wind, solar radiation and other sources with low emission of pollutant gases such as micro turbine (MT) and fuel cell (FC) [2]. Even though DGs powered by RES are receiving a lot of attention because they cause a little or no environmental damage but they are unreliable due to intermittent nature of their sources [3]. Their power generation at a time is beyond what's needed and then almost nonexistent at a critical moment in the demand cycle. This characteristic makes renewable energy powered DG unattractive for consumers who need power around the clock. Moreover their unreliability creates more technical challenges in operating and controlling the power system which they are connected to.

DG powered by MT and FC are the greenest and cleanest DG technologies after wind and solar. But considering the increasing need for electricity to support sustainable growth, MT and FC powered DG exceeds wind and solar based DG economically and in reliability [4]. These two DG technologies are seen as electrical energy sources that could fill the gap between unfriendly to environment of conventional power plant and pollution free power plant powered by RES. With advances in power electronic and material science technology, commercial units of MT and FC powered DG are now available at an affordable price. These two types of DG have already been deployed as onsite power generation operating in parallel with electricity grid for many years and the number of installation is expected to rise substantially to support the new power system paradigm Smart Grid [5-8] .

The challenges, however, lie in the fact that power system networks that we know today are evolved based on the synchronous generator (SG) characteristic which is centrally located. These new generation technologies, however, will be distributed and have different characteristics compared to their conventional counterpart. In terms of power production, DG outputs smaller power capacity. These new technologies are also interfaced to the electrical grid through power electronic converters which make them respond to network disturbances differently.

As the traditional power system network development is influenced by the characteristic of SG, the integration of DG into the existing power network at a large scale is expected to create many technical and operational challenges [8]. A thorough study needs to be performed to assess various operational aspects to identify problems that may arise and to find the best countermeasures that can be taken. The opportunities which can be provided by these new generation technologies also need to be explored.

1. 2 Objective of dissertation

Envisioning that DG will play an important role in future electricity supply chain, this thesis works looks into the most important issues regarding the DG integration inside power system network. Some expected technical and operational challenges are investigated and positive contributions which can be offered by DG utilisation to power system network are explored and demonstrated.

- **Modeling of distributed generation for power system studies**: new technology embraces by DG makes it posses different characteristics compared to conventional generation units which are synchronous machine based. These differences make it necessary to perform integration studies on various operational aspects to assess the influence of this small scale generation unit on the power system network operation and control. This requires an accurate and easy to understand dynamic model which imitates the dynamics of the real units. In this thesis, development of the dynamic models of MTGS, FCGS and generalised DG to be used in various power system studies is discussed.
- **New grid code and DG fault ride-through capability**: Due to different characteristics possessed by DG, power system operator imposed a stringent requirement on the DG connected to their grid. During steady state operation DG must not cause power quality problems and generated powers are controllable depending on the utility request. During critical times, DG has to be able to withstand a temporary voltage dip due to fault occurrence in the grid even though the voltage reaches zero at the point of connection. During this fault ride-through DG must also help the grid by injecting reactive power to help power system voltage recovery. Different types of DG technologies are investigated if they are able to fulfil these requirements and if not the necessary modifications to be made on the specific DG unit need to be explored.

- **Grid support by DG:** DG integration in distribution networks is seen interfering with current practices and voltage control scheme inside the network. With intelligently coordinating and controlling a group of DG the negative influences on voltage control could be changed to positive. DG connected to low voltage network presently does not participate in frequency control. This thesis also explores the techniques that can be applied to involve DG in this frequency stabilisation. Voltage support and frequency control contribution that could be provided by DG is discussed and demonstrated.
- **Influence of DG on power system stability under new grid codes**: Power electronic converters utilised in DG causes DG to have different characteristics in responding to grid fault and are demanded to provide reactive support during this critical period. Different characteristics and this new rule are feared to negatively influence the stability of a power system where these DG units are connected to. In this thesis the most important types of stability are analysed with different levels of DG penetration and different control strategies.
- **Predictive var management inside future distribution network**: Future distribution networks will contain a large number of DG and will be equipped with advanced communication facilities. A massive number of DG will create technical challenges but the communication link available will provide the opportunity to control DG centrally in real time to optimise the benefits offered by DG integration. In this thesis, an intelligent predictive technique in managing DG reactive power to minimise power losses and at the same time controlling the voltage inside distribution network is discussed and proposed.

1. 3 Thesis organisation

The introductory Chapter 1 discusses driving motivation, objective and contents of the thesis.

Chapter 2 provides an overview of DG starting from its confusing definitions to its roles in future power system network. This chapter views technologies available, benefits and drawbacks of its application, its expected tasks and management technique options that can be applied. As the power system operation and control is shifting toward Smart Grid, different control strategies that can be used to control DG inside this intelligent power system network are also discussed.

The most prospective DG technologies for grid integration utilise power electronic converter in grid interfacing. In Chapter 3 the basic of the converter and control methods employed for controlling the converter are described. The standard controller for controlling DG coupled to grid through power electronic converter is defined. The chapter ends with the comparison of the characteristic of conventional synchronous machine and special characteristics of the converter.

Chapter 4 discusses the modeling approach for modeling DG namely MTGS and FCGS to be used in power system studies. The model must be as accurate as possible to the commercially available DG. Depending on the nature of the studies, different types of models are required. The modeling approaches from detailed model to simplified model are discussed in this chapter.

In the future electrical grid, stringent requirements are expected to be demanded from DG connected to LV network such as fault ride-through requirement and reactive support during the fault event. Chapter 5 discusses this capability in identifying the problem that could arise so appropriate solutions can be proposed. The investigation starts with the DG employing standard power electronic converter and controller. The problems are then identified and possible solutions are proposed.

Chapter 6 investigates the voltage and frequency support that can be provided by DG in distribution network. DG interfaced to the electrical grid through power electronic converter uses different control techniques in controlling their outputs. Their control flexibilities are explored in how they can be manipulated to assist in voltage regulation and frequency stabilisation in the network they are connected to.

DG utilising power electronic converter has different characteristic and is expected to respond to grid fault differently compared to conventional generation unit. This difference is intended to help power system stabilisation after subjected to fault. Chapter 7 analyses the power system stability with significant integration of DG which employs different control strategies. The most important types of power system stability classes are investigated.

Chapter 8 proposes an intelligent predictive technique in managing multiple DG units' reactive power inside future distribution network. The proposed method is developed using two stages intelligent techniques and is intended to be used for online management. This method is demonstrated effectively predicting the reactive power from multiple DGs simultaneously with an acceptable accuracy.

Chapter 9 deduces the conclusion on the studies and investigation within the scope of the research work performed and reported in this thesis. A few possible directions for extending the research are highlighted.

Chapter 2

Distributed Generation: an Overview

2. 1 Introduction

This chapter overviews most important features and matters associated with DG. These include the definition, benefits as well as limitations, technology available, power electronic conversion techniques used in their grid interfacing, requirement to be fulfilled when connecting them to electrical grid, their role in future Smart Grid and possible control strategies in managing them in Smart Grid. Knowledge on these important features and matters will facilitate in understanding various technical problems and proposed solutions discussed throughout this thesis.

2. 2 Definition of DG

In the literature, DG is defined inconsistently with respect to term and capacity. The term embedded generation used in Anglo-American countries, dispersed generation used in North America and decentralised generation used in Europe can be deduced as referring to the same type of generation [9]. Generic definition then can be concluded thus: distributed generation is any grid connected generation located near consumers regardless of size or type of the unit. DG therefore may include any generation integrated into distribution network such as wind turbines, small hydro turbines, combined heat and power (CHP) units, photovoltaic (PV) cells, FC and MT. Some of the generation types listed belong to another confusing term which is renewable energy sources (RES). RES here is referred to generators in which the sources of power are coming from renewable energy. RES can be either the generator operated in a grid connected or in a standalone mode. Distributed energy resource (DER) is a more broad definition which includes DG, energy storage and manageable load. This means that a small scale of RES operating in grid connected mode belongs to DG and all DG technologies belong to DER. To avoid confusion, a DG term throughout this thesis refers to distributed generation. For a single unit of DG, DG unit term is used.

2. 3 Benefits and drawbacks of utilising DG

Addition of DG to distribution network will offer many benefits. These benefits can be categorised into economical and operational point of view. Economically DG utilisation can defer the investment on upgrading or building new transmission and distribution infrastructures. DG units are also manufactured in such a way that assembling them anywhere as a module is simple. In the operational point of view, DG can be used to support voltage and improves power quality, reduce system power losses, support the network frequency, release transmission and distribution capacity and improve reliability of the power system. While those mentioned benefits are mostly gained by utility company, for the consumer, installation of DG provides a backup power supply, shaving consumer's peak demand and providing uninterrupted service, to name the most important benefits [10-11].

In spite of many economical and operational benefits offered by DG, integration of DG however could violate existing planning and operational practice as conventional distribution network is not designed to accommodate DG [1,8,12]. Some problems which could surface are increasing short circuit level, interference with protection system coordination, lowering quality of power supply and affecting the stability of the network.

These operational problems however could be resolved by adapting new technologies into the network and by effectively managing DG units. New technology that can be utilised includes introduction of FACTS devices and energy storage inside the network. Another option is to apply new management strategies such as virtual power plant where a group of DG is centrally controlled [13].

2. 4 Distributed generation technologies

DG technology can be classified into traditional and non-traditional, as illustrated in Fig. 2.1 [14]. Internal combustion engines (ICE) which include low speed turbine, reciprocating engines and diesel engine are examples of traditional DG. MT, FC, PV, WT and small hydro (SH) are considered as non-traditional. Of these non-traditional DG, PV, WT and SH are powered by renewable resources. Their sources are sustainable and have low or no damaging impact on the environment. MT and FC however run on fossil fuel so they are considered as non-renewable technology. These two are still releasing carbon and green house gases to the environment but in very low quantity.

DG powered by PV, WT, MT, FC and some ICE is coupled to the grid through power electronics converter (PEC). Of these generators, PV and FC produce DC power which must be first converted to AC component before their power is usable. MT on the other hand produces very high frequency AC power which is only usable if this power is converted to the grid frequency 50/60 Hz. For ICE however, PEC is utilised for economic benefits and technical flexibility [15]. The following sections will discuss briefly non-traditional DG utilising PEC for power conversion.

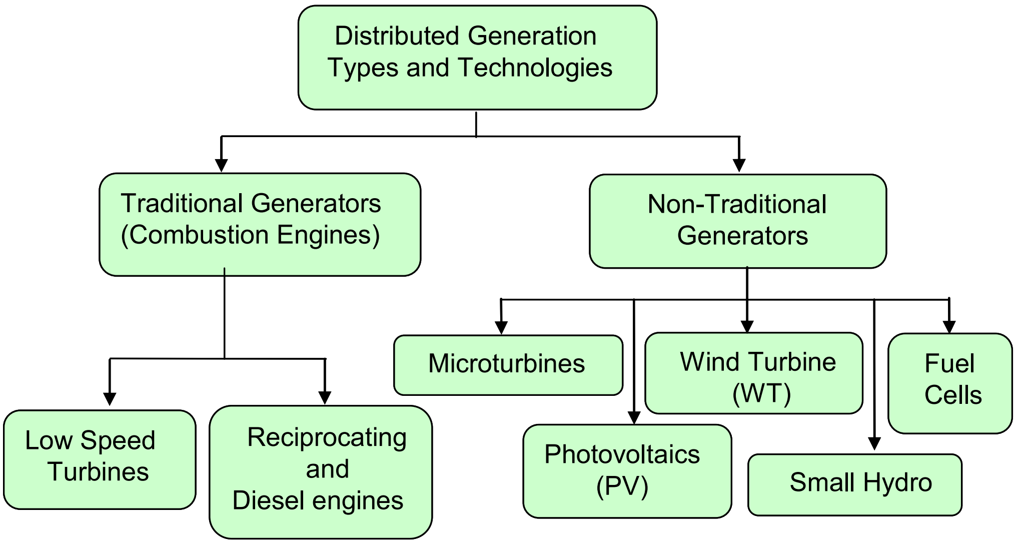


Fig. 2.1 DG technology overview [14]

2. 5 Power electronic based DG

Non-traditional DG powered by MT, FC, PV and WT depicted in Fig. 2.1 produces electrical power not in grid frequency. Before the power is usable it must be converted to the grid frequency 50/60 Hz which is normally performed by using power converter utilising power electronic devices. In this thesis to avoid confusion, the system comprises of MT and PEC is called micro turbine generation system (MTGS). Similarly other DG technologies with their PEC will be called FC generation system (FCGS), PV generation system (PVGS) and WT generation system (WTGS) for DG powered by FC, PV and WT respectively. The following subsection will discuss the relevant features of MTGS, FCGS, PVGS and WTGS. The basic theory and control method of the PEC will be discussed in more detail in Chapter 3.

2.5.1 Micro turbine generation system

Micro turbine used in MTGS was initially developed for transportation sector but it is then realised that the same technology could be used for power generation [16]. It is now one of the most promising technologies to be used as distributed generation application. MTGS is ideal for DG application due to its flexibility in connection methods and ability to be aggregated in parallel for bigger capacity. With fast start up time it is suitable for any application that requires fast start up such as peak shaving and backup power supply but most of MTGS is utilised for providing base load which are either in grid connected mode or off grid mode.

For distributed generation application, MTGS ranging from 25 kW to 500 kW are commercially available with the rating speed between 50,000 to 120,000 rpm [17] . Even though two shafts design is in market [18], a single shaft design [19-21] is more preferable due to less moving parts thus requiring less maintenance and the unit is also smaller. The layout of a single shaft MTGS is depicted in Fig. 2.2. The main components inside micro turbine are similar to a conventional gas turbine but are smaller in size and they comprise compressor, recuperator, combustion chamber and turbine. The compressor compresses ambient air and pushes it into the combustion chamber where it is mixed with the fuel and burned in a continuous combustion process. The hot pressurized gas is then converted into mechanical energy through the turbines and in turn rotates the shaft where compressor and generator are mounted [22].

Generator outputs a very high frequency power thus a power conditioning device is required to reduce this frequency to grid frequency. The combustion process also outputs a high temperature heat which is released through an exhaust. If this heat is captured and utilised, the efficiency could reach up to 80 % [17].

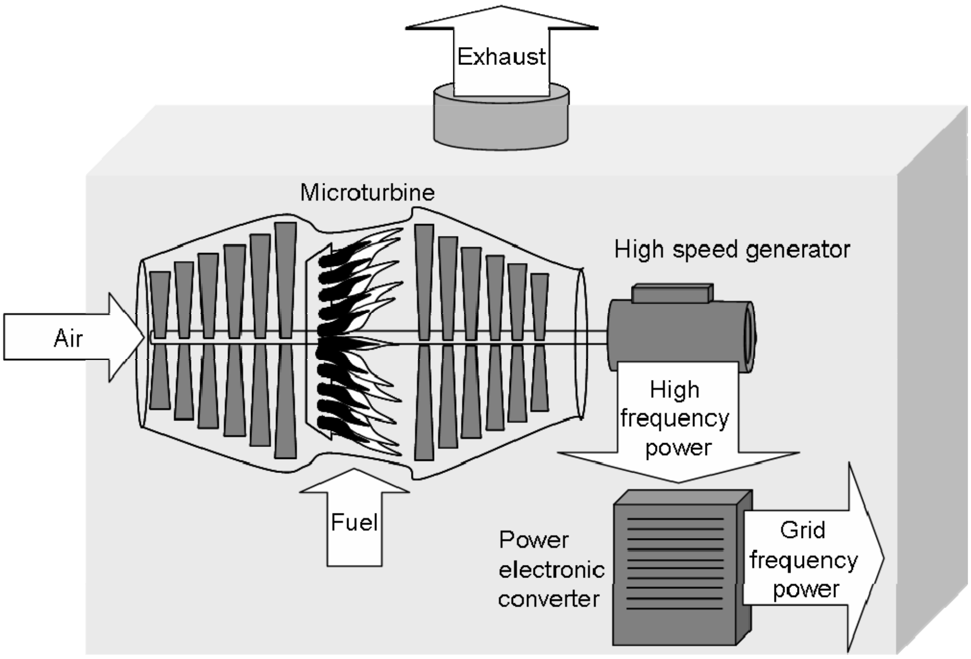


Fig. 2.2 Micro turbine generation system [15]

The main advantages of MTGS are low noise and vibration due to rotary motion in opposed to stroking, small size, small number of moving parts and it has long maintenance intervals and ability to run on various types of fuel such as natural gas, gasoline, kerosene, naphtha, alcohol, hydrogen, propane, methane, digester gas and diesel but the majority of commercially available MTGS units use natural gas as their primary fuel [17].

2.5.2 Fuel cell generation system

FC is a static energy conversion device that converts chemical energy directly to electricity without combustion process. This characteristic makes DG powered by FC nearly emission free. It is highly efficient and if its heat is reused for cogeneration 80% efficiency can be reached. FC was initially developed for space application, but it found its way in electrical power industry and is now one of the most promising technologies for DG application. As a DG application it is expected that FC will be used for providing base load because of its long start up time which is between 1- 4 hours [4].

Typical layout of FCGS is depicted in Fig. 2.3. FCGS mainly runs on hydrogen which is usually derived from natural gas. This hydrogen is fed to FC stack which through the chemical reaction, DC power is produced. This DC power needs to be converted to AC power using power electronic converter before it is usable. The chemical reaction also produces heat which can be utilised for heating.

Based on the electrolyte used in the stack, FC can be classified into five categories namely, proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), phosphoric acid fuel cell (PAFC), and aqueous alkaline fuel cell (AFC). Among various types of FC, PEMFC, SOFC and MCFC show great potential in DG application.

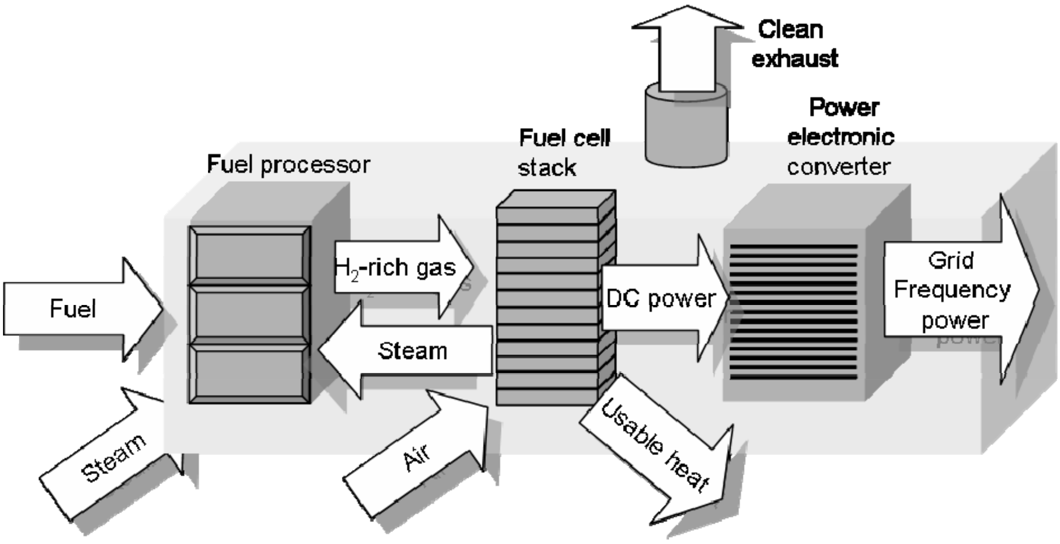


Fig. 2.3 Fuel cell generation system [4]

2.5.3 Photovoltaic generation system

Photovoltaic (PV) converts sunlight directly into electricity thus it is emission free and has very little operational cost and maintenance. Typical layout of PV generation system is depicted in Fig. 2.4. Energy from sun radiation is converted to DC power by the PV panel which comprises multiple PV cells connected in series or parallel. As the power generated by PV panel is in DC form, it must be converted to grid frequency by power electronic converter. PV application ranges from less than 10 kW to large system more than 100 kW. PV is normally installed on the rooftop of a house or building and connected to distribution network directly or indirectly. The main obstacles in PV penetration as distributed generation are its high turnkey cost, storage system required and lack of finalised standard for grid connection. In addition it is pruned to bad weather condition and requires a large area of installation. Penetration of PV so far is induced by financial incentives or favourable price for the produced electricity [3].

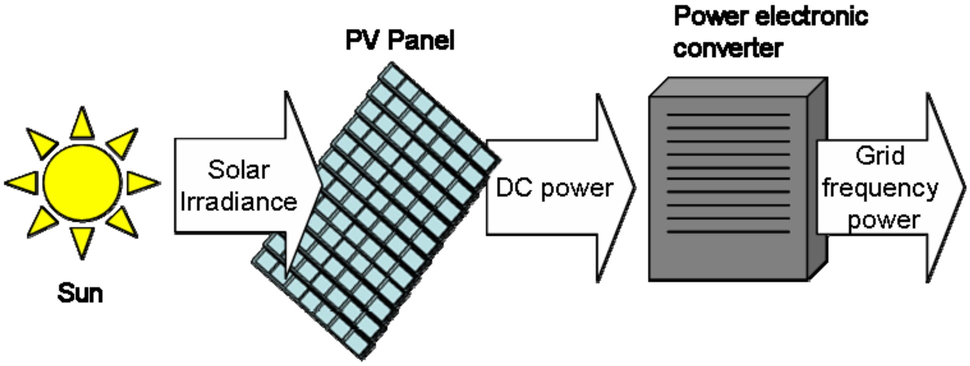


Fig. 2.4 Photovoltaic generation system [2]

2.5.4 Wind turbine generation system

Wind turbine (WT) converts kinetic energy in the wind into mechanical power that can be converted into electrical energy with generator. Induction generator or synchronous generator is normally used. Synchronous generators are typically interfaced to the grid through full size PEC. If induction generator is used as in most applications, power is doubly fed to the grid directly through the stator and through small size PEC through its rotor. WTGS which is based on doubly-fed induction generator (DFIG) has a typical layout as illustrated in Fig. 2.5 [15]. The power from WTGS is only generated when wind blows within cut-in and cut-off speed whose availability and speed vary over time. This results in WT being an unreliable energy source but like PV systems, there is no fuel needed but periodic maintenance is required [2-3].

Currently most of WTGS is installed in a group as a wind farm and located remotely from load consumption area. The scenario seems to have changed with the development of small scale WTGS which is designed to fit nicely in urban and commercial area. This small scale WTGS has received a lot of attention with the number of installation growing rapidly overtime [23].

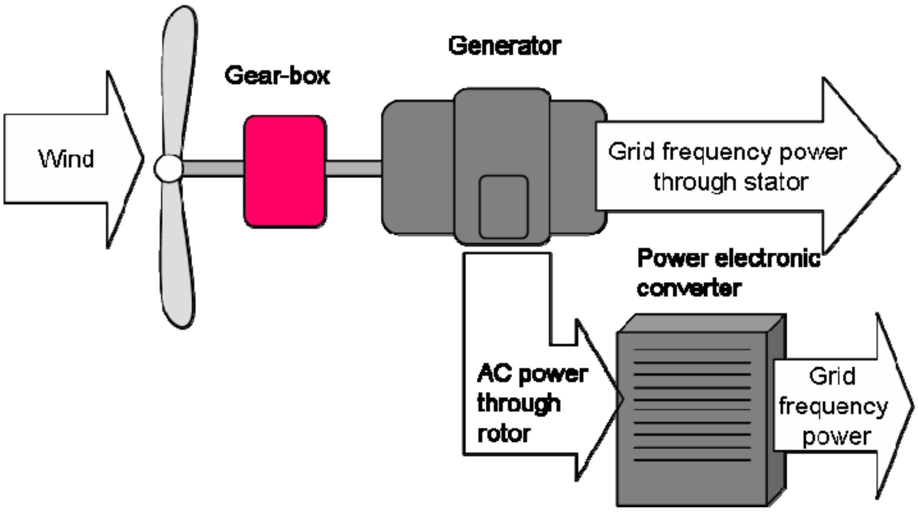


Fig. 2.5 Wind turbine generation system [15]

2. 6 Requirement of DG connected to power system

Due to their different characteristic, power system operator imposed stringent requirements for DG connected to electrical grid. These requirements are to make sure DG will not scrutinise power system stability, quality, security and reliability. The requirement of different types of generating units connected to electrical grid is normally different. For example, in Germany, grid codes are distinguished by the voltage level and described in different documents. Summarisation of the grid code requirement for PEC based generation unit can be divided into operation under steady state and under fault occurrence [24].

2.6.1 Requirements in steady state operation

In steady state operation, DG connected to electrical grid is obliged to meet the grid support requirements for normal operating condition. These requirements are listed below.

1. **Limitation of power-quality characteristic parameters**
    - Limitation of steady state voltage changed to 2% of the nominal value
    - Limitation of voltage fluctuation due to switching operation
    - Limitation of long-term flicker

- Limitation of current harmonics, inter-harmonics and higher frequency component up to 9 kHz

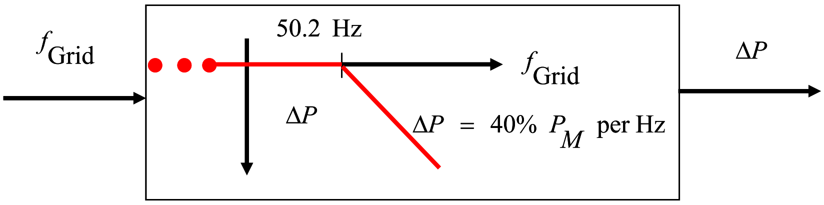
2. Active power control (reduction)

- Remote set-point control by distribution network operator for power generation limitation in case of network congestions or danger of power system collapse
- Automatic reduction of active power generation according to the power droop characteristic in situation of over frequency.

3. Reactive power control

- Set-point voltage control for voltage stability, also remotely by distribution network operator
- Reactive power supply corresponding with power factor of 0.95 leading as well as lagging

The reduction of active power generation listed in No. 2 is defined in more detailed in Fig. 2.6. All DG units must be capable of reducing their active power when generation exceeds consumption which resulted in grid frequency over than 50.2 Hz. The reference value (ΔP) is the active power generation time the factors based on the present frequency. This reference power must be reduced with a coefficient of at least 40%/Hz. If the frequency however increases to value of 51.5 Hz or beyond, generation unit must be disconnected. The disconnection is also to be initiated if the frequency decreases to 47.5 or less.



$$\Delta P = 20\ P_M \frac{50.2\,\text{Hz} - f_{\text{Grid}}}{50\,\text{Hz}} \quad \text{at}\ 50.2\,\text{Hz} \le f_{\text{Grid}} \le 51.5\,\text{Hz}$$

P_M = Currently Available Power

ΔP = Power Reduction

f_{Grid} = Grid Frequency

No Restrictions in the Range of $47.5\,\text{Hz} \le f_{\text{Grid}} \le 50.2\,\text{Hz}$

Disconnection at $f_{\text{Grid}} \le 47.5\,\text{Hz}$ and $f_{\text{Grid}} \ge 51.5\,\text{Hz}$

Fig. 2.6 Active power droop characteristic [24]

2.6.2 Requirements in fault condition

Power system is continuously subjected to various disturbances such as grid faults which results in momentary voltage dip throughout the network. In this critical situation fault ride-through requirements are demanded for DG.

1. Fault ride-through capability with

- No disconnection of the generation during the voltage dips
- No change of active power generation before and after the fault for frequency stabilisation.
- Feed in of reactive power during the fault for voltage stabilisation.

2. Limitation of short circuit current if necessary

For DG connected to HV network, requirement depicted in Fig. 2.7 is imposed [25] while for the DG connected to MV grid, requirement depicted in Fig. 2.8 is demanded [26]. Depending on the duration of faults and depth of voltage dips, DG must ride-through the fault and need to feed the same active power immediately after the fault is cleared. More specifically, DG is not allowed to disconnect if the fault leads to the voltage level above boundary line 1. If the voltage is in between boundary line 1 and 2, DG can only be disconnected with the agreement with network operator that the reconnection is performed after a maximum of 2.0 seconds. Active power must be restored to its previous value before fault with the gradient of at least 10 % of the rated capacity per second. For voltage dips below blue line, the disconnection of the DG with longer synchronisation time is allowed in any case. The main objective of keeping DG connected is to avoid sudden power loss which can lead to power system collapse.

Reactive current injection characteristic mentioned in previous paragraph is depicted in Fig. 2.9. The objective of the reactive support is to lift up the voltage magnitude during low voltage events and also to improve voltage recovery after this event. If the voltage drops below 90% of the rated voltage, capacitive reactive current is demanded. In contrast if the voltage rises beyond 110%, inductive reactive current is required to reduce the grid voltage. The amount of reactive current described is to be added to the actual reactive current already supplied during steady state operation.

The requirement discussed so far is for PEC-coupled generation units connected to HV and MV network. For DG connected to LV network, the grid code is still under review. These requirements are however adopted as a requirement for DG connected to LV network studies in this thesis.

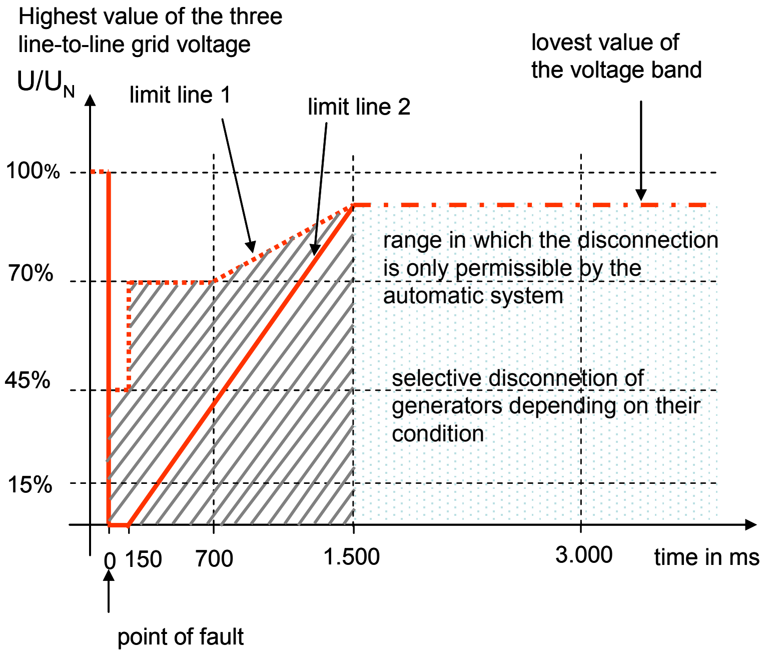


Fig. 2.7 FRT for PEC-coupled generation unit connected to HV grid [25]

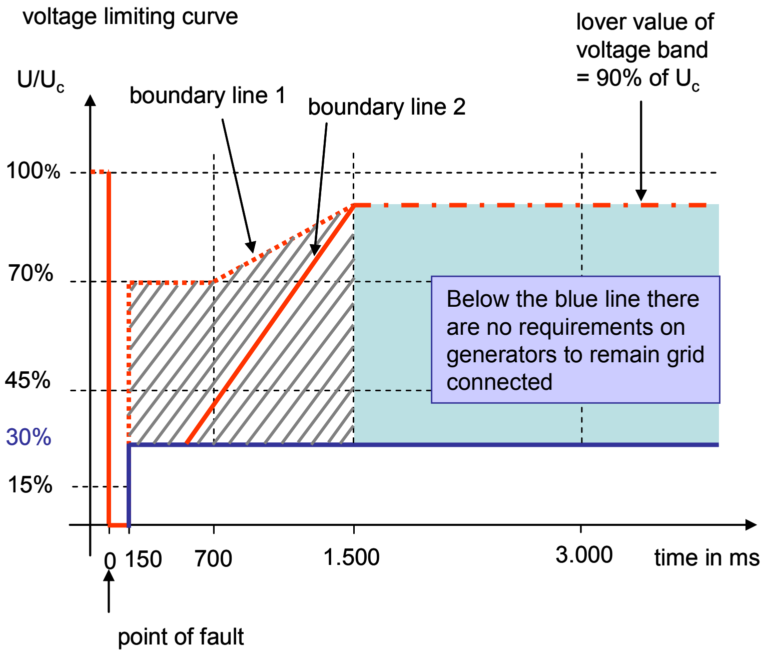


Fig. 2.8 FRT for PEC-coupled generation unit connected to MV grid [26]

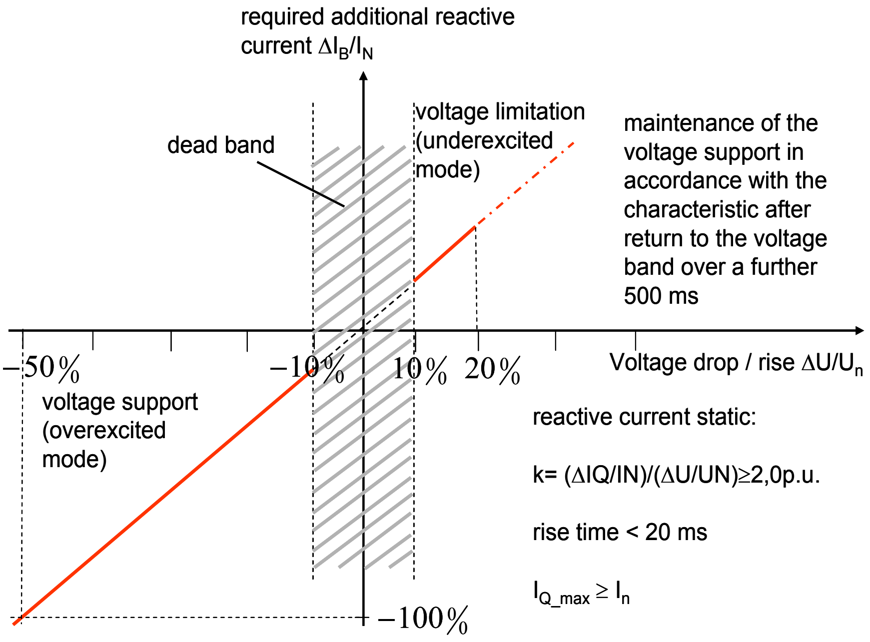


Fig. 2.9 Reactive current injection requirement for PEC-coupled generation units [26]

2. 7 Distributed generation roles in Smart Grid

2.7.1 Smart Grid

Smart Grid is seen necessary to support sustainable growth of the future. The need for Smart Grid is clearly due to various reasons such as responding to current climate change, depleting sources of fossil fuel and to overcome the threat on security, reliability, and quality of supplies due to aging infrastructures. Smart Grid is envisioned as an electricity network that employs innovative products and services together with intelligent monitoring, control, communication, and self healing technologies. Operation of electricity network in Smart Grid will be shared between central and distributed generators. DG, RES, demand response, demand side management and energy storage will replace a proportion of electricity generated by large conventional power plants. The electricity and information flows together in real time which allow the network to be interactive between power generation sources and power consumption. Network is also having near zero economic losses from the outages and power quality disturbances and a wide array of customised energy choices are available [5-7].

The term Smart Grid is slightly different depending on the region. In Europe for example, Smart Grid is referred to as an electrical grid which is flexible to fulfil customers' need while adapting to the changes and challenges ahead, has connection access to all electric network users, especially RES and DG, reliable as it assures and improves security and quality of supply, adheres to meet digital age demand with excellent resilience to the hazards and uncertainties and economical as it provides best through innovation, efficient energy management and 'level playing field' competition and regulation [5]. In the United States, it is cited as an electricity network that is healing itself when subjected to a disturbance, enabling consumer active participation in responding to demand, acting resiliently against physical and cyber attack, supplying premium power quality, accommodating all generation and storage options, enabling new products, services and markets, and optimising its asset utilisation and operation efficiently [7,27]. Even though the definition is slightly different, Smart Grid can be concluded as a power system network which operates efficiently with the help of state of the art technologies.

In running a Smart Grid to achieve previously mentioned expectation tasks, there are four essential components needed which are sensors, advance communication infrastructures, control algorithms and actuator system. Sensors in power system are current transformers, voltage transformer, phasor measurement unit, smart meter, sensors to measure temperature, pressure, acoustic and so on. Communication infrastructure includes power line carrier, wireless radio, advance metering infrastructure, home area network and fibre-optic networks. Control algorithm is referred to wide area monitoring and control, Micro Grid management, distribution load balancing and reconfiguration, demand response, optimal power flow, voltage and var optimisation, fault detection, identification, and recovery, automatic generation control, inter-area oscillation damping, system integrity protection scheme and so on. Actuator system includes HVDC, FACTS, energy storage systems, reclosers, automatic switches, breakers, switchable shunts, on-load shunts, on-load tap changers, hybrid transformers and so on [5-7, 27].

2.7.2 Distribution network in Smart Grid

In Smart Grid concept, distribution network will share many responsibilities of transmission network. Distribution network needs to be changed from passive to active management. Distribution system must also accommodate bi-directional power flows. For achieving this envision active network, metering services and statistical metering tools are a gateway. Electronic meters and automated meter management system facilitates in optimising demand forecasting by informing customer preferences and opportunities in the network operation [5].

DG which is producing electricity at or close to the point of consumption provides many benefits to the distribution network. These benefits will be optimised in Smart Grid, where

DG is expected to be involved in demand participation, providing ancillary services such as regulating the network voltage and supporting the network during critical time due to fault or sudden changes of load. In order to positively supporting the grid in the ways mentioned previously, DG sources must be reliable, dispatchable and meeting various other operating criteria [6].

2.7.3 Distribution network control

Passive control within distribution network is unsuitable when there is a large number of DG interconnected into the network. This large integration is prognosed to interfere the operation of some of the network control devices such as line drop compensator for on load tap changer. Active network management however is seen capable in mitigating this problem. Moreover it enables the exploitation of DG capability as an individual unit, to participate in overall network management. This expectation had sparked recent studies in the area of active network management such as voltage control, power flow control, local congestion management and fault level control to name a few. Some examples of some of these studies include [28]:

- Using optimal power flow to determine optimal active and reactive power generation of DG units, the required reactive power compensation, and the OLTC tap position. Different objective functions are investigated depending on control objectives.
- Application of state estimator to estimate voltage levels at different nodes inside distribution network. If voltage limit is violated, the target voltage of the OLTC automatic voltage controller relay is altered to bring back voltage within limit.
- Using voltage/reactive power droop characteristic for controlling DG unit’s reactive power to reduce the voltage deviations while controlling the OLTC to reduce the reactive power generation from selected centrally located generator in the distribution network.

All these investigated schemes have an objective to increase DG penetration without violating many operation constraints inside distribution network.

2.7.4 Management of DG in Smart Grid

Presently, inside conventional distribution network, DG operates independently without any proper coordination. In a Smart Grid, DG is expected to be centrally controlled in real time by local energy management system. This coordinated online management is made possible with real time advance communication infrastructure which will be integrated into distribution network. This advance new infrastructure will open ways to a new concept of DG management such as virtual power plant, Micro Grid and Cell.

2.7.5 Virtual Power Plant

Virtual power plant is the concept of aggregating a group of low ratings DG and energy storage system into one large power plant with the rating being large enough to participate in energy markets and provide ancillary services to the distribution network [29]. The concept is enabled by the modern infrastructure of communication technology and advanced power electronic components. Every DG unit in principle can be a part of VPP. Looking into economical and technical parameters of each units however, VPP concept can be categorised into commercial VPP and technical VPP. Commercial VPP is the interface of DG with the markets. It manages commercial activities in energy and service markets. No geographical location restrictions are to be imposed on DG forming CVPP. Technical VPP on the other hand is to participate in real time operation. Unlike CVPP, it is restricted by geographical location [28]. VPP can be used to provide distribution network wide ancillary services such as voltage control, frequency control, system restoration, transmission system congestion management, transmission system loss optimisation and reserve management [30].

2.7.6 Micro Grid

A cluster of low generating units together with energy storage devices and controllable loads connected to a low voltage network and operated to supply the local area with heat and electrical power is called Micro Grid [31]. It is expected to be the likely direction of evolution of power system that comprises distributed generation. The unique features of Micro Grid are it can be operated as a part of medium voltage network and it can also operate autonomously in an islanded mode, which enhances reliability of supply in case of faults in upstream network. They can be resynchronised back to the network after restoration of the upstream network. In Micro Grid, DG will generate sufficient energy to supply most or all of the local load demand. Micro Grid architectures are being investigated in different research projects in EU, the USA, and Japan with some implemented demonstration project. Important components of a Micro Grid are central controller and energy storage.

2.7.9 Cell

The Cell concept introduced in Denmark in 2004 denoted a distribution network that is radially operated below 150/60 kV transformer [32]. Cell controller is utilised to maintain the Cell operation during regional emergencies by transferring it to controlled island operation. Also it should restore the Cell, subsequent to a black-out, using controlled island operation. The main objective of Cell concept is to optimally manage and actively utilise a large amount of DG inside the network. Similar to Micro Grid the control of all DG inside Cell is performed centrally.

2.7.7 Central controller

All three new strategies in managing a group of DG previously discussed require a central controller. Research projects on central controller are currently being demonstrated in managing DER and network. Different control options and strategies are investigated in each project. In the CERTS Micro Grid, USA, for example, the Micro Grid energy manager is responsible for dispatching the output power and terminal voltage of DER [33]. Similarly in the Hachinohe demonstration project, Japan, economic dispatch and weekly operation planning are performed centrally. On the other hand the Micro Grid central controller in EU Micro Grid architecture has several control functions that include optimising generation and load scheduling based on daily forecasts and market prices; ensuring that the Micro Grid satisfies the regulations of the distribution network operator; coordinating between different market agents in the Micro Grid; and supervising islanding operation, load shedding and restoration, generator blackstart, resynchronisation and system restoration [28].

In Cell concept, the functions provided by Cell controller include online monitoring of demand and production in the Cell, controlling active power of synchronous generators, wind farms and large wind turbines, controlling reactive power, controlling voltage and frequency through the voltage regulators and speed governors of synchronous generators, operating switchgears remotely, providing automatic and fast islanding of the Cell, providing automatic fast generator start-up and load shedding, providing black start and controlled island operation and resynchronising Cell with the main network [32].

2.7.8 Energy storage

With some DG units inside distribution network powered by fluctuating and unpredictable RES whose power is mostly generated during low load demand period, this extra energy should be stored to be used during high demand period. This clearly indicates the need for energy storage. Different functions and locations of energy storage units are to be used depending on the power network architectures. The storage can be centralised as demonstrated in the EU and the Japanese architectures [31] or each generator can have its own energy storage in CERTS Micro Grid [33]. The function of energy storage can be for grid formation, frequency control, and providing fault current during autonomous operation, as demonstrated in EU Micro Grid. In many of Japanese projects however energy storage is used to balance the local generation fluctuations such that Micro Grid can be reduced to a constant load from the distribution network's point of view.

2. 8 Conclusion

DG is seen as a very important component in the electricity network of the future. A large number of these small generation units will play a vital role in power system network operation and control. New technologies embraced in their connection create concern on their negative impact on the existing grid and in making sure they will not badly influence the grid, many stringent requirements are to be imposed and these requirements were also discussed. As DG penetration will be significant, a central coordinated control of multiple units dispersedly located is suggested and expected to harvest their potential optimally. A few concepts of DG control were discussed with the example of the test project currently going on. Some of the DG discussed in this chapter is powered by unreliable sources, which probably generates power when there is no demand. Energy storage seems to be required and a brief discussion on energy storage was also included.

Chapter 3

Distributed Generation and Power Electronics

3. 1 Introduction

Most of the non-traditional DG discussed in previous chapters requires specific power electronics capabilities to convert the power generated into useful power in nominal utility grid frequency before their output can be utilised. Depending on the nature of DG sources, different configuration of PEC is required. This chapter will discuss general topology of PEC for grid interfaces and its control principle for DG application.

3. 2 DG interfacing

Fig. 3.1 below depicts the general layout power conversion technique using DC-link circuit for converting frequency of DG output [15] . The power electronic module in general accepts power from DG source and converts it to power at the required voltage and frequency. The design of input converter depends on the DG source. On the source side, AC-DC converter is employed if the DG is producing DC output. If DG is already producing AC output, AC-DC conversion is used. This DC component must then be converted to AC with DC-AC converter. Between both converters, inside the DC circuit, a capacitor is added for energy storage. Filter and grid inductor are required to condition the AC output while monitoring and control module operates the interface, containing the protection for the DG and utility at a point of connection.

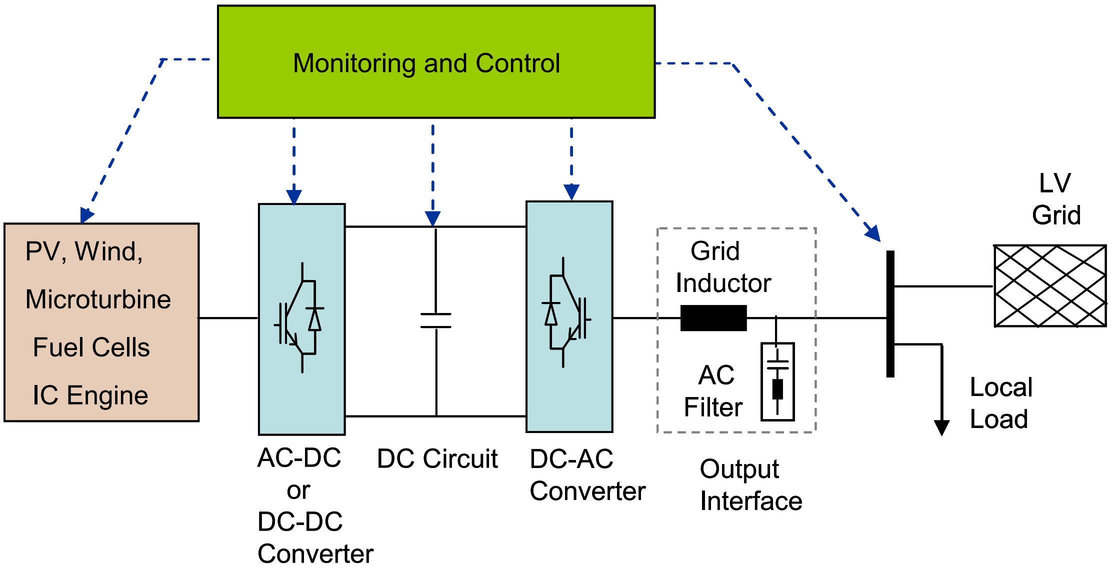


Fig. 3.1 General structure of DG units coupled to the grid through PEC [15]

The monitoring and control module contains protective functions for DG system and local electric power system that permits paralleling and disconnection from the electrical power system. These functions will typically meet the requirements of grid codes imposed by the distribution network operator for DG interconnected to the grid but have the flexibility for modifications of setting depending on the application or changes in grid interconnection requirement. In addition, monitoring and control module also has human-machine interface, communication interface and power management option.

Monitoring function typically includes real power, reactive power, and voltage monitoring at the point of DG connection with the utility. These functions are necessary because in order to synchronise DG, its output must have the same voltage magnitude, frequency, phase rotation, and phase angle as the grid. Synchronisation is an act of checking these four variables within an acceptable range before paralleling two energy sources.

Every power electronics circuit consists of power electronic devices (PEDs). Fundamentally, PED is the semiconductor-based switch, a technology that has existed for many decades, but is continuously being improved in terms of power density and reliability. In general, the term ‘power electronics’ refers to the device switches (e.g. IGBT and SCR), and the various modules that they comprise [34].

3.3 Power electronics converter

PEDs in every power electronics converter are semiconductor devices fabricated with appropriate impurities (known as doping) in order to achieve particular electrical properties such as conduction, resistance, turn on/turn-off times, power dissipation, etc. There are several types of PEDs that are available, such as diodes, thyristors, metal-oxide semiconductor field-effect transistors, Gate Turn-off Thyristors (GTO), Insulated Gate Bipolar Transistor (IGBT), MOS-controlled Thyristors (MCT), etc [35]. Power semiconductor devices, even diodes are more complicated in structure and operational characteristics than their low power counterparts. The added complexity arises from the modification made to the simple low power devices to make them suitable for high- power application.

Generally power electronic converters can be classified as self-commutated and line-commutated as depicted in Fig. 3.2. In line-commutated converter, thyristors are used as switching devices. Thyristors can be switched on by supplying a pulse but external commutation voltage is required for switching off. Since it relies on external voltage for commutating, a line-commutated converter is not used for DG interfacing because if DG has to operate on islanding mode, there is no line voltage to be relied on.

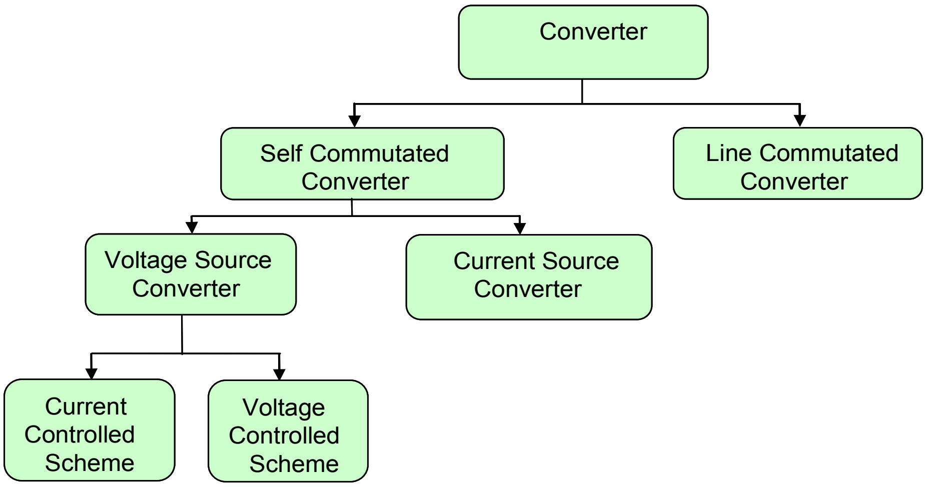


Fig. 3.2 Converter classifications [14]

In self-commutated converter, fast switching devices such as IGBT and MOSFET are employed. These switching devices can be switched on and off using control signal. Most of the DG interfaced with the grid, utilises self-commutated converter [15]. Self-commutated converter is further classified into two categories based on its DC-link circuit. If in the DC circuit consists of large inductor, the converter acts as a current source so it is called current source converter. On the other hand if the DC circuit inside contains a large capacitor, it acts as voltage source and it is called voltage source converter. As most of the DG sources resemble voltages sources more than current sources, most of the power electronic based DG typically employ voltage source converter. Following sections will mainly discuss pertinent principles of voltage source converter.

3.3.1 Three phase bridge

In three phase converter, six PEDs are generally set up in the form of a bridge where three legs are placed in parallel. Each leg consists of two PEDs in series as shown in Fig. 3.3. Diodes are added in parallel to PEDs to provide current flow path in case PEDs are turned off. Depending on the input/output connection and the type of PEDs, the same circuit can be used as rectifiers and inverters.

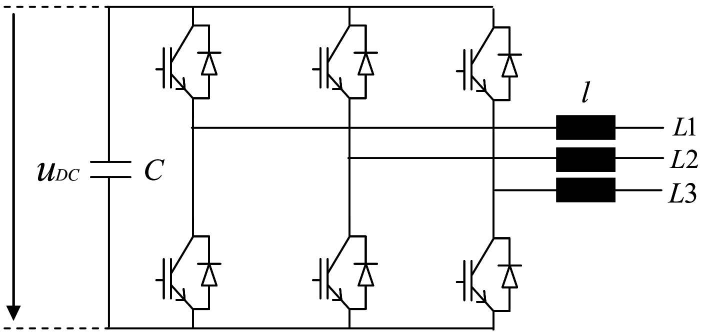


Fig. 3.3 Three phase bridge VSC connected to the grid through grid inductor

3.3.2 PWM converter control

Sinusoidal voltage from DC voltage can be achieved using a modulating circuit [35]. The objective is to generate sinusoidal converter output which has controllable magnitude and frequency. This is basically the process of blocking and passing through DC voltage under very high frequency which produces rectangular pulses that induce a sinusoidal current in inductors.

In order to produce rectangular pulses, a sinusoidal control signal u_{ref} at the desired frequency is compared with a symmetrical triangle wave u_{tri}. This method is called sub-harmonic method [36] and is graphically shown in Fig. 3.4. Converter switching frequency is equal to the triangular wave frequency which is higher than required output frequency. If u_{ref} is higher than triangle signal u_{tri} the output signal will be ‘high’, in the other case ‘low’. This produces a block signal with varying width or duty cycle. This block signal has short width at the edges and increasingly longer width towards the center of the waveform. DC voltage will be passed through during ‘high’ and will be blocked during ‘low’.

In getting a high quality sine wave, the switching frequency needs to be as high as possible. Higher switching frequency will produce higher quality of sine wave voltage but if the frequency is too high it will increase switching losses thus making the converter less efficient. For DG application, 5 to 15 kHz switching frequency is normally used.

The line to line AC voltage magnitude produced by PWM method is given by

$$\hat{u}_{AC} = m.\frac{\sqrt{3}}{2\sqrt{2}}u_{DC} \qquad (3.\ 1)$$

where m is called modulation depth. This modulation depth is defined by the ratio of the amplitude of the reference voltage to the amplitude of the triangular voltage as given by

$$m = \frac{\hat{u}_{ref}}{\hat{u}_{tri}} \qquad (3.\ 2)$$

By controlling this amplitude of modulation depth, the output voltage can be controlled independently from the grid voltage. In converter operation value of m is limited between $0 <= m < 1$ because for the values greater than one, converter starts to saturate and the level of low order harmonics starts to increase. The output voltage produced by the converter through sub-harmonic method however is not a perfect sinusoidal wave and contains voltage components around fundamental frequency. A grid inductor and filter is usually connected between the converter and grid to reduce these harmonic components.

3.3.3 Output interface

In interfacing VSC to the grid, grid inductor and AC filter as depicted in Fig. 3.1 are required to control harmonic distortion. Grid inductor here is also known as chokes or line inductor in some reports or literatures. It is a simplest but a very effective method in controlling harmonic distortion created by PWM–type converter. AC filter is only considered when grid inductor alone is not able to lower harmonic content. Different types of passive AC shunt filters are available to be used in interfacing converter with the grid such as single tuned, 1st order and 2nd order filter to name a few. These filters can be tuned to suppress certain harmonic components. These AC filters however have the disadvantage of potentially interacting adversely with the power system because it will create a sharp parallel resonance just below the tuned frequency [37].

For the DG application, most of the converters are reportedly employing IGBT powered electronic devices [38] resulting only very small amount of harmonics injected into the grid. For DG interfacing, simple grid inductor is already effectively limiting the harmonics from DG below the value specified by most of the interconnection standard [39-41] and this will be shown in later chapter. For all the studies performed in this thesis, only grid inductor is considered for DG grid interfacing.

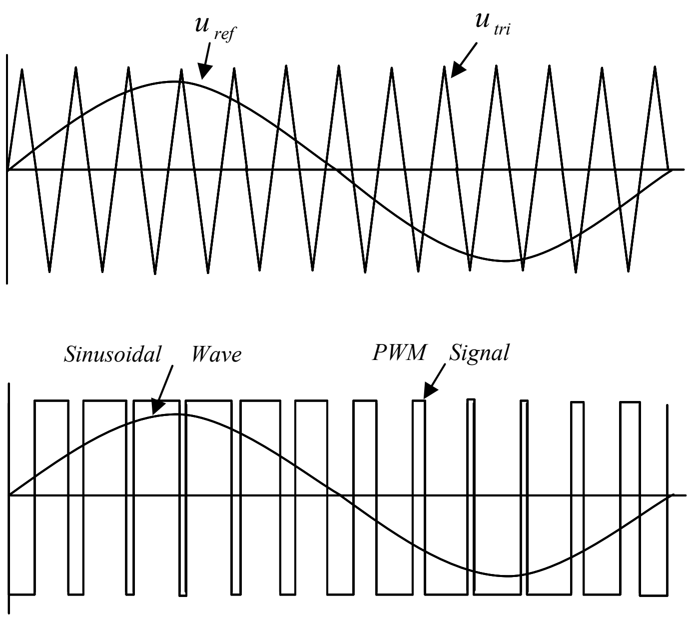


Fig. 3.4 PWM Technique

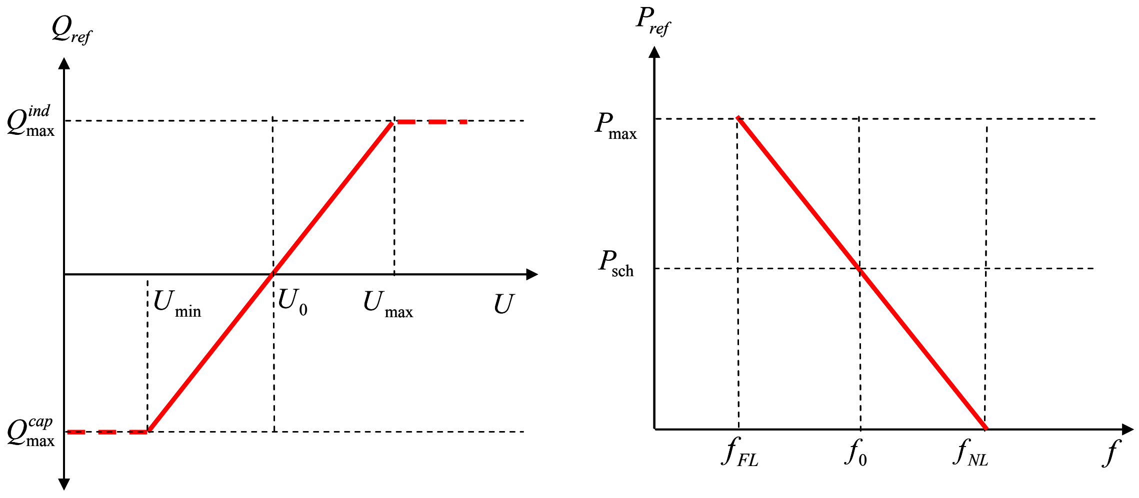
3.3.4 Converter control

Converter control is the most important feature in controlling DG coupled to grid through PEC. The control is normally realised in *d-q* reference frame which enables active and reactive power to be controlled independently. For controlling the output of DG, a few control techniques are commonly used [42].

Constant power control and DC voltage control are most commonly used techniques. In constant power control, required active power is used as a reference. In this technique, the converter will try to maintain its converter power output according to the reference value. DC power control is basically a modification of the constant power control. In this technique, instead of using directly active power reference, DC bus voltage is used as a power reference. Here DC bus voltage is regulated while a constant power source representing a prime mover is the input to the converter. The output of DC link voltage regulator is proportional to the active power. When DC link voltage varies, this indicates imbalance between power transfer from prime mover and converter. The power output of the converter will be increased or reduced until DC link voltage returns to its nominal value.

In DC voltage control technique, there are two cascaded control loops. A slow external voltage control loop controls the DC link voltage and a fast internal current loop controls the converter current. The DC link voltage controller is designed for balancing power transfer and is responsible for unit's stability. Internal current loop is responsible for improving quality of power and also incorporates converter overcurrent protection.

If the voltage regulation is required, reactive power output of DG can be controlled depending on the voltage variation using a voltage/reactive power droop characteristic. Similarly if the frequency regulation is required by DG, a frequency/active power droop characteristic can be incorporated inside the controller. Typical voltage/reactive power and frequency /active power droop characteristic is illustrated respectively in Fig. 3.5 (a) and Fig. 3.5 (b) [28]. The implementation of these droop characteristics in DG control will be demonstrated in the voltage regulation and frequency stabilisation study later in the thesis.



(a) (b)

Fig. 3.5 Typical droop characteristics for voltage and frequency control [28]

3.3.6 Converter controller for grid connected mode

The converter control is performed in *d-q* coordinate which is originated from the technique of field oriented or vector control of electrical machines [43]. Using *a-b-c* to *d-q* transformation, the complexity of coupled electrical quantities is simplified and reduces the complexities in modeling and simulation. This is an integral part of generalised electrical machines theory where all three phase machines can be considered as two phase primitive machines with fixed stator windings and rotating rotor windings.

Converter controller is used to control DG's DC-link voltage, reactive power and power factor. Converter control loop can be derived from the relationship between converter and grid voltage behind its grid inductor (refer Fig. 3.6).

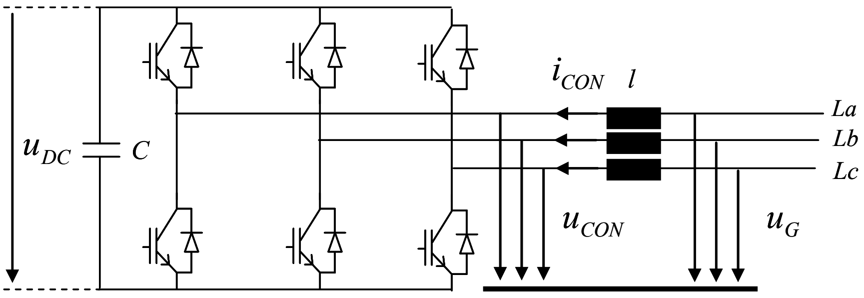


Fig. 3.6 VSC connected to grid through grid inductor

The relation between grid voltage $\underline{u}_G$ and converter voltage $\underline{u}_{CON}$ considering voltage drop across inductor in stationary reference frame can be written as [44]

$$\underline{u}_G^{\angle 0} = l\frac{di_{CONd}^{\angle 0}}{dt} + u_{CON}^{\angle 0} \tag{3. 3}$$

In *α-β* coordinate this grid voltage can be written as

$$\underline{u}_G^{\angle 0} = u_{G\alpha}^{\angle 0} + j\cdot u_{G\beta}^{\angle 0} \tag{3. 4}$$

After transformation to rotating reference frame in the positive direction of grid voltage

$$\underline{u}_G^{\angle ug} = u_{Gd}^{\angle ug} + j\cdot u_{Gq}^{\angle ug} \tag{3. 5}$$

Similarly converter current $\underline{i}_{CON}$ can be written in fix reference frame as

$$\underline{i}_{CON}^{\angle 0} = i_{CON\alpha}^{\angle 0} + j\cdot u_{CON\beta}^{\angle 0} \tag{3. 6}$$

and in rotating reference frame can be expressed as

$$\underline{i}_{CON}^{\angle ug} = i_{CONd}^{\angle ug} + j\cdot u_{CONq}^{\angle ug} \tag{3. 7}$$

The real part of the grid voltage is given by

$$u_{Gd}^{\angle ug} = l\frac{di_{CONd}^{\angle ug}}{dt} - \omega l\cdot i_{CONq}^{\angle ug} + u_{CONd}^{\angle ug} \tag{3. 8}$$

and imaginary part can be expressed as

$$u_{Gq}^{\angle ug} = l\frac{di_{CONq}^{\angle ug}}{dt} - \omega l\cdot i_{CONd}^{\angle ug} + u_{CONq}^{\angle ug} \tag{3. 9}$$

To rearrange the equation in terms of converter voltage $\underline{u}_{CON}$ gives

$$u_{CONd}^{\angle ug} = u_{Gd}^{\angle ug} - l\frac{di_{CONd}^{\angle ug}}{dt} + \omega l\cdot i_{CONq}^{\angle ug} \tag{3. 10}$$

$$u_{CONq}^{\angle ug} = u_{Gq}^{\angle ug} - l\frac{di_{CONq}^{\angle ug}}{dt} - \omega l\cdot i_{CONd}^{\angle ug} \tag{3. 11}$$

In this rotating voltage oriented reference frame, $u_{Gd}^{\angle ug} = \left|\underline{u}_{Gd}^{\angle ug}\right|$ and $u_{Gq}^{\angle ug} = 0$. Even though $u_{Gq}^{\angle ug} = 0$, it is not eliminated from the equations to facilitate the derivation of controller equation. The relationship of the grid voltage, converter voltage and converter current is illustrated in phasor diagram as shown in Fig. 3.7.

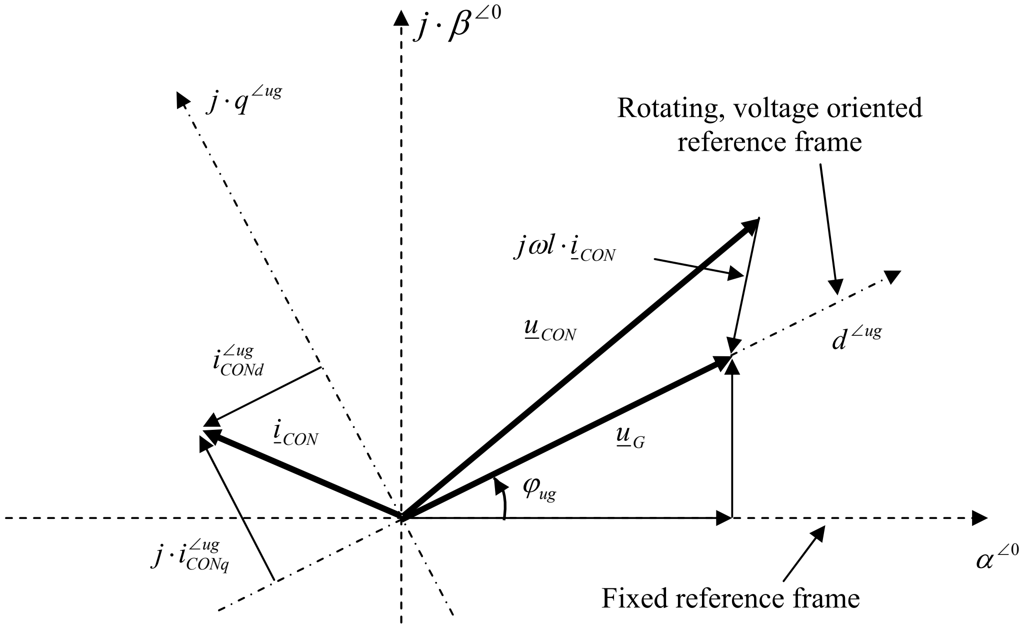


Fig. 3.7 Phasor diagram of voltage and current in *d*-*q* coordinate

For controller derivation voltage drop across inductor $l\frac{di^{\angle ug}_{CONd}}{dt}$ and $l\frac{di^{\angle ug}_{CONq}}{dt}$ are treated as an output of PI controllers and are given by

$$l\frac{di^{\angle ug}_{CONd}}{dt} = K_P\left(1+\frac{1}{sT_I}\right)\cdot\left(i^{\angle ug}_{CONd\_ref} - i^{\angle ug}_{CONd}\right) \tag{3. 12}$$

$$l\frac{di^{\angle ug}_{CONq}}{dt} = K_P\left(1+\frac{1}{sT_I}\right)\cdot\left(i^{\angle ug}_{CONq\_ref} - i^{\angle ug}_{CONq}\right) \tag{3. 13}$$

Substituting Eqn. (3.12) into Eqn. (3.10) and Eqn. (3.13) into Eqn. (3.11), converter voltage reference can be obtained and are given by

$$u^{\angle ug}_{CONd\_ref} = -K_P\left(1+\frac{1}{sT_I}\right)\cdot\left(i^{\angle ug}_{CONd\_ref} - i^{\angle ug}_{CONd}\right) + u^{\angle ug}_{Gd} + \omega l \cdot i^{\angle ug}_{CONq} \tag{3. 14}$$

$$u^{\angle ug}_{CONq\_ref} = -K_P\left(1+\frac{1}{sT_I}\right)\cdot\left(i^{\angle ug}_{CONq\_ref} - i^{\angle ug}_{CONq}\right) + u^{\angle ug}_{Gq} - \omega l \cdot i^{\angle ug}_{CONd} \tag{3. 15}$$

The inner current control loops for converter controller can be derived from Eqn. (3.14) and (3.15) and both are depicted in Fig. 3.8.

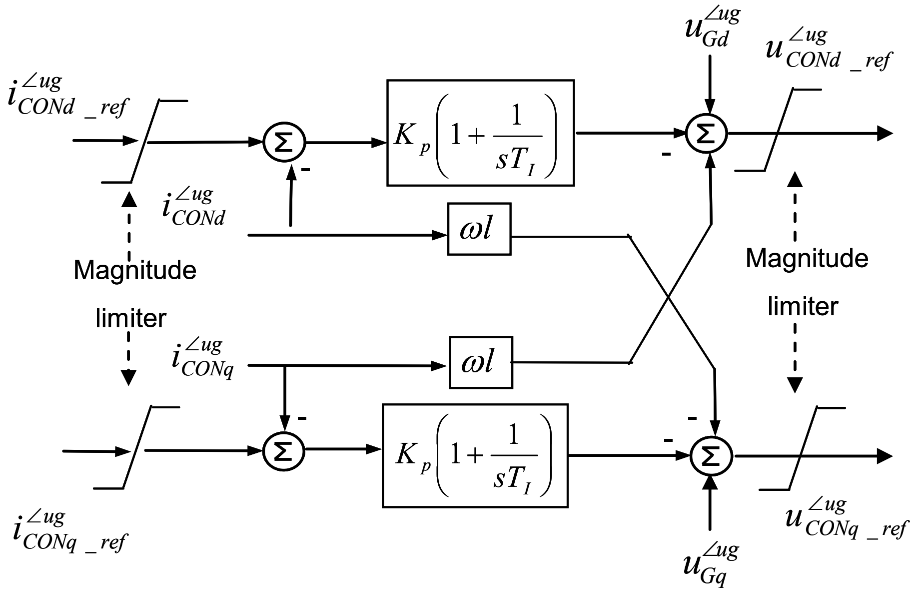


Fig. 3.8 Converter inner control loop

In this voltage oriented reference frame, $i_{CONd}^{\angle ug}$ is equal to active current and $i_{CONq}^{\angle ug}$ is equal to negative reactive current. This active current is calculated from control loop which controls DC-link voltage for *d*-component and reactive current is generated by the one which controls AC output voltage for *q*-component; both are shown in Fig. 3.9. In the outer DC voltage control loop, active current from DG source is fed forward to enhance the performance of the controller. This loop is based on *P*-*Q* control scheme which is enabling the control of active and reactive power output independently performed.

These two control loops are general structure of the controller for the DG model used for studying various problems in this thesis. Depending on the study, some modification is made on the controller or different control scheme will be used. If there is a modification made or other control scheme employed, it will be mentioned in the thesis under the respective section.

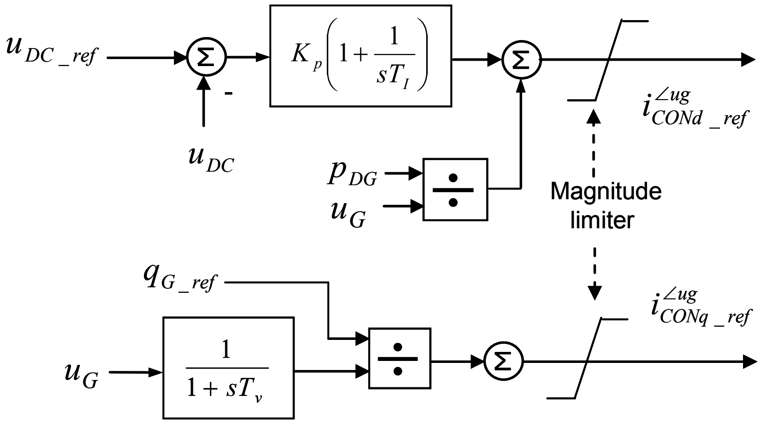


Fig. 3.9 Converter outer control loop

3. 4 Characteristic of electrical machines and converter

The control techniques using *d-q* theory employed in DG converters make them more flexible in controlling their output quantities. Active and reactive power can be controlled independently and the current or voltage limitation capability can be added easily. This capability certainly makes DG behaving in different characteristic when operating during fault occurrence. Power system network development history however is influenced by the characteristic of synchronous generators. For example, a synchronous generator short-term over current rating influences the protection scheme relay setting in discriminating faults. In turn the fault clearing times are set based on the over-swing and loss of synchronism characteristic of the synchronous generators. In summary, typical characteristics of synchronous generator are [45]:

- Operates as a voltage source whose amplitude can be adjusted by controlling exciting current in the exciter of the machine.
- Sinusoidal voltage is a feature designed into the construction of the machine.
- Magnitude of short circuit current is high due to low source impedance and no current limiting devices or control is equipped.
- Current rating is subjected to the withstand capability of the winding insulation to the rise of temperature. Short circuit current up to 10 times of the nominal current can be tolerated for a few cycles due to relatively large thermal time-constant of the winding and surrounding steel.
- Real power exchange is proportional to the applied torque to the rotor shaft. Power output can be made proportional to the frequency by applying closed loop governor setting.

Even though power electronic converters are well established in the field of power supplies and industrial drives but their characteristic did not influence the development of conventional power system network. The corresponding characteristics of the power electronic converter are [45]:

- Operate as a voltage source (although current source versions are available) with near instantaneous and independent control of the magnitude of each phase.
- Sinusoidal wave voltage is achieved with modulation technique.
- Short circuit current can be limited with the current limiting circuit.

- Current rating is determined by withstand capability of semiconductor devices against temperature. Large over currents will cause device failure due to very short thermal time-constant of the semiconductor devices.
- Power exchange is controlled by providing power set-point to the controller subjected to the converter rating.

Different characteristics compared above clearly create concerns on operating power system with DG coupled to the grid through PEC. A thorough study on power system operation and control with the large penetration of DG based PEC is greatly important. Influence of this new technology on the traditional power system operation and control therefore must be thoroughly studied to evaluate any necessary modifications to be carried out in ensuring the stability, reliability and quality of electrical power system.

3. 5 Conclusion

In this chapter general structure of various DG technologies coupled to grid through PEC is described. This PEC utilised power electronics devices which require a special technique and controller for its operation. The technique employed is described and the controller structure is derived. The utilising of PEC makes DG characteristically different compared to conventional synchronous generator. These differences are compared at the end of the chapter.

Chapter 4

Modeling of Distributed Generation Units for Grid Integration Studies

4. 1 Introduction

In studying the grid integration with DG, an accurate and easy to understand dynamic model which imitates the dynamics of the real commercial units is required. Among DG technologies, MTGS and FCGS are the most promising technologies when consideration of the need of continuous electricity supply to support a sustainable growth is prioritised. The benefits offered by MTGS and FCGS are exceeding their disadvantages and are expected to be employed in a large number in the foreseen future. MTGS and FCGS are cleanest and greenest DG technologies after DG powered by wind and solar. The latter technologies have downsides due to intermittent nature of their sources even though they produce nearly zero environment pollution. In this chapter, discussion starts with the modeling of specific MTGS and FCGS units and then is followed by the simplified and generalised model of DG unit. The focus is specially given to MTGS and FCGS since these are the most prospective DG technologies and they will mainly be used to investigate various issues with DG integration throughout this thesis. These two DG technologies are already commercially available and have been operating as onsite power generation for many years and are expected to be deployed in tremendous scale for supporting sustainable Smart Grid power system in the coming years.

4. 2 MTGS power conversion topology

Typical layout of a single shaft design is depicted in Fig. 4.1. Converting AC to DC is performed by either active or passive rectifier. DC to AC conversion is performed using voltage source converter (VSC). This converter in some literatures is called as line side converter (LSC) or grid side converter (GSC) as it is connected to the line of utility grid. On the machine side, the choice of using passive or active rectifier depends on the expected task. For example, if MTGS is used for shaving peak and only go online for a certain period in the day, regular start up is needed. In this case, IGBTs based active rectifier is employed which enabled bidirectional flow of power. During start up, the power is extracted from the grid to bring PMSM up to an operation speed before it can be operated as a generator. Additional equipment for start up in this case is eliminated.

If MTGS is used to supply part of base load and is operated continuously, start up process could be only during initial commissioning and after major overhaul which happens only once in a few years. In this case, diode rectifier for AC-DC conversion is normally utilised. Even though configuration in Fig. 4.1 (a) offers more flexibility, most of commercial MTGS are constructed using configuration in Fig. 4.1 (b) to lower its production cost and to reduce control complexity [46].

VSC normally embraces self commutated devices controlled by pulse modulated circuits. Its circuit consists of normally six IGBTs and six anti parallel diodes. IGBTs are preferred because they allow more higher switching frequencies compared to other self commutated devices. For MTGS converter, switching frequency of up to 18 kHz is used which varies depending on its manufacturer [46].

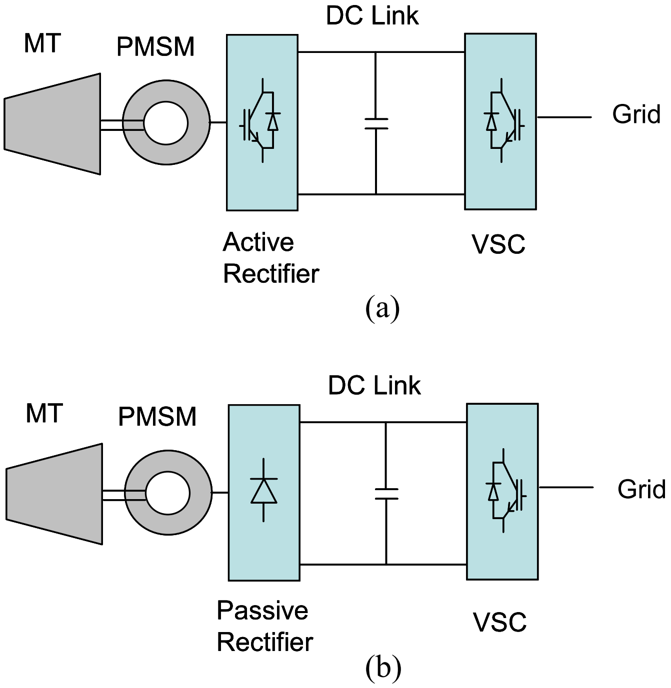


Fig. 4.1 MTGS power conversion

4. 3 Dynamic model of MTGS

Basic MTGS component has already been discussed in Chapter 2 so it will not be repeated here. In the next section, the discussion jumps directly to the dynamic modeling of each main component that constitutes MTGS as illustrated in Fig. 4.2. For this model, active power is controlled through generator speed. DC link voltage, reactive power and power factor is controlled through its converter.

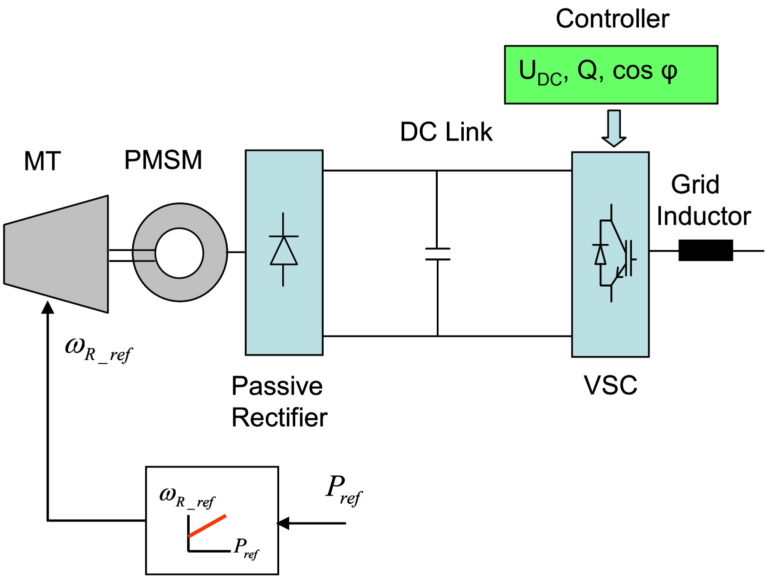


Fig. 4.2 Typical layout of MTGS

4.3.1 Micro turbine

Dynamics of micro turbine can be modeled based on gas turbine model presented in [47]. The model was successfully adopted for micro turbine modeling by several other authors in [48-50] and [51]. Graphically, the control diagram for micro turbine dynamic is depicted in Fig. 4.3. The main symbols in the figure are as follows:

K_{GV}	is gain of the speed governor
P_{ref}	is active power reference
t_m	is mechanical torque
w_F	is fuel input signal
w_{MIN}	is fuel demand at no load
ω_R, ω_{R_ref}	are rotor angular speed and rotor angular speed reference
T_X	is lead-time constant of speed governor
$T_Y, T_{VP}, T_{FS}, T_{CD}$	are lag-time constants of the speed governor, the valve positioner, the fuel system, and the compressor discharge respectively.

An output of this model is the mechanical torque t_m which is linear and is a function of fuel flow and turbine angular speed and is given by the following equation [47]

$$f = 1.3(w_F - w_{MIN}) + 0.5(\omega_{R\_ref} - \omega_R) \tag{4. 1}$$

The input to this dynamic equivalent is PMSM generator rotor instantaneous speed, ω_R while the output is mechanical torque t_m. MT and PMSM share the same shaft so the rotational speed of MT is equivalent to the generator speed.

In modeling the dynamics of micro turbine delays associated with its valve positioner, fuel system, compressor discharged control are considered and treated as first order transfer function. The speed controller works based on speed errors between reference speed and micro turbine actual speed. Speed controller is modeled using lead lag transfer function. The output of the speed controller represents fuel signal for the turbine. The value of fuel signal is scaled by the gain value and then is offset by a minimum fuel value at no load operation.

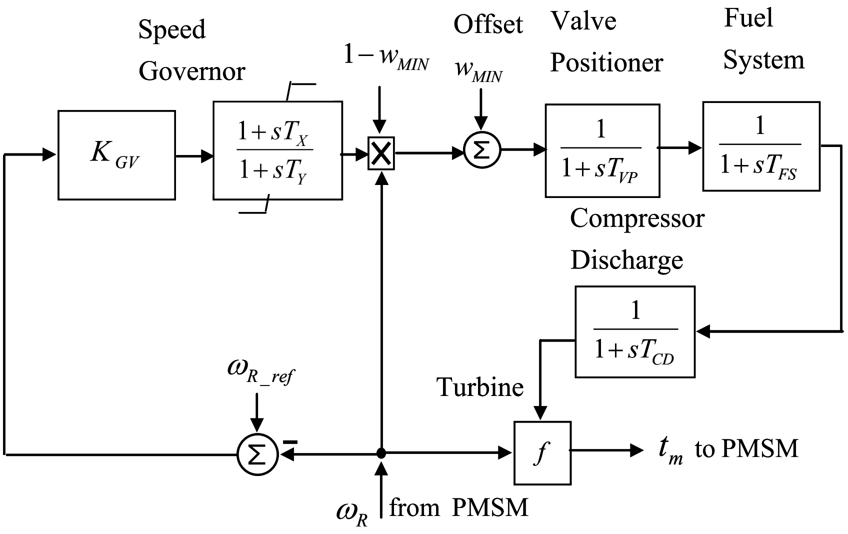


Fig. 4.3 Micro turbine dynamic

4.3.2 Permanent magnet synchronous machines

Micro turbine usually drives permanent magnet synchronous machine (PMSM). PMSM model equations can be derived from full order model of synchronous machine (SM) by making field current constant. By assuming the winding is sinusoidal-distributed and by neglecting saturation, eddy currents and hysteresis losses, mathematical equations of PMSM can be derived [52].

In *d-q* rotor coordinate system, equivalent circuits of PMSM are depicted in Fig. 4.4 and Fig. 4.5 respectively. Referring to Fig. 4.4 and Fig. 4.5, stator voltage equations are:

$$u_d = r_S i_d - \omega_R \psi_q + \dot{\psi}_q \tag{4. 2}$$

$$u_q = r_S i_q + \omega_R \psi_d + \dot{\psi}_d \tag{4. 3}$$

The rotor voltage equations are given by

$$0 = r_{Dd} i_{Dd} + \dot{\psi}_{Dd} \tag{4. 4}$$

$$0 = r_{Dq} i_{Dq} + \dot{\psi}_{Dq} \tag{4. 5}$$

Flux linkage is required to complete the PMSM model. Stator flux linkages can be expressed as

$$\psi_d = (l_{hd} + l_{\sigma S}) i_d + l_{hd} i_{fd0} + l_{hd} i_{Dd} \tag{4. 6}$$

$$\psi_q = (l_{hq} + l_{\sigma S}) i_q + l_{hq} i_{Dq} \tag{4. 7}$$

and rotor flux linkages are:

$$\psi_{Dd} = l_{hd} i_d + l_{hd} i_{fd0} + (l_{hd} + l_{\sigma Dd}) i_{Dd} \tag{4. 8}$$

$$\psi_{Dq} = l_{hq} i_q + (l_{hq} + l_{\sigma Dq}) i_{Dq} \tag{4. 9}$$

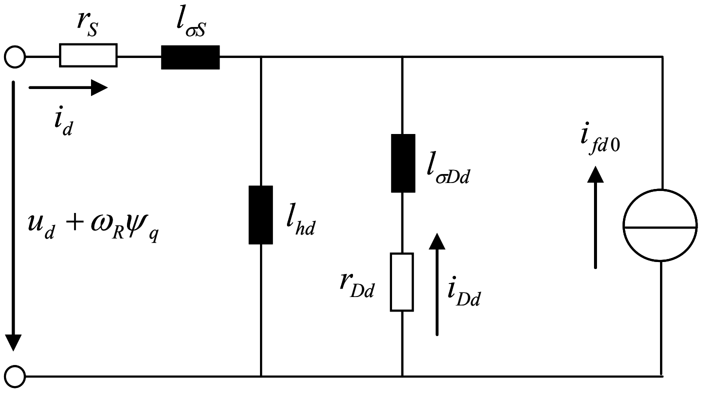


Fig. 4.4 PMSM *d*-axis steady-state equivalent circuit

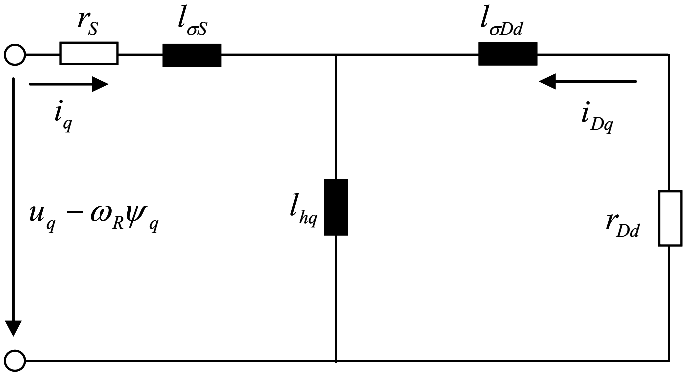


Fig. 4.5 PMSM *q*-axis steady-state equivalent circuit

Electrical torque is given by

$$t_e = \psi_d i_q - \psi_q i_d \tag{4. 10}$$

Equations of motion are given by

$$\dot{\omega}_R = \frac{1}{T_m}(t_e + t_m) \tag{4. 11}$$

$$\dot{\delta}_R = \omega_R - \omega_0 \tag{4. 12}$$

T_m in Eqn. (4.11) is mechanical starting time constant which is defined as a time required to accelerate the rotor from standstill to its rated speed when the nominal torque is applied. It is equivalent to per-unit inertia constant, H times two.

Terminal voltage of PMSM in steady state no load operation corresponds with

$$u_{d0} = 0 \tag{4. 13}$$

$$u_{q0} = \omega_R l_{hd} i_{fd0} \tag{4. 14}$$

4.3.3 Operation under grid connected mode

The controllers shown in Fig. 3.8 and Fig. 3.9 are for operation under grid connected mode. In grid connected mode, MTGS is operated as a current source with the objective to export a certain amount of power in reference to the available grid voltage. This amount of power is based on the power set-point set by the owner or control entity.

The performance of MTGS in adhering to requirement during steady state operation is investigated. Section 2.6.1 highlights that during a steady state, there are three main requirements demanded which are low power quality characteristic parameters, ability to reduce active power generation and ability to perform voltage regulation by providing reactive power. Power quality detrimental effect is beyond the scope of the thesis so it will not be discussed in detail. This concern however is addressed in the grid code so it will be briefly discussed here.

Output from DG connected to electrical grid through IGBT converter is known to contain small amount of harmonic components which is considered acceptable by the interconnection standard. This criterion is also true for MTGS because most of the commercial units available employed IGBT converter on the grid side. To prove that MTGS outputs small harmonic content, phase voltages and currents measured at the connection point is depicted in Fig. 4.6. The measurement is taken after the grid inductor. With more detailed analysis using Fourier transform and calculating total harmonic distortion (THD), the result is tabulated in Table 4.1. This value of THD is considered low compared to the 8 % limit published in European standard EN50160 [41] which defines the voltage characteristic of the electricity supplied by public distribution network.

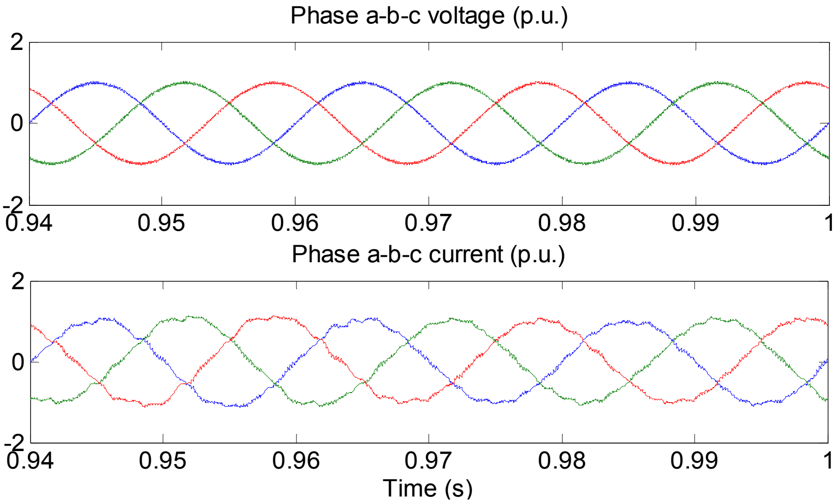


Fig. 4.6 MTGS steady state voltage and current

Table 4.1 Voltage and current THD of MTGS output

Voltage	THD (%)	Current	THD (%)
Phase a	2.48 %	Phase a	5.27 %
Phase b	2.47 %	Phase b	5.49 %
Phase c	2.47 %	Phase c	5.03 %

As a DG unit, MTGS must be able to reduce its generated active power when requested by network operator as stated in the grid code discussed in section 2.6. This capability is investigated to determine how well MTGS responds to the requested active power.

Fig. 4.7 shows the output of MTGS responding to step changes of reference active power. MTGS is initially delivering 1.0 p.u. active power but at t = 1.0 s, reference set-point is reduced to 0.8 p.u. Active power reference is further reduced to 0.5 p.u. at t = 5.0 s. Reactive power reference is at all time equalised to zero. Simulation results show that MTGS follows the power demand according to the reference. The supplied power is however not changing instantly according to the reference signal given but with some delay. This delay is associated with the delay in micro turbine valve positioner, fuel system and compressor discharge. For example reducing active power from 1.0 p.u. to 0.8 p.u. takes more than 1.3 s before the power generation reaches steady state at 0.8 p.u. For changing the power from 0.8 p.u. to 0.5 p.u. starting from the changing power reference until power generation reaching steady state at 0.5 p.u. takes about 2.0 s.

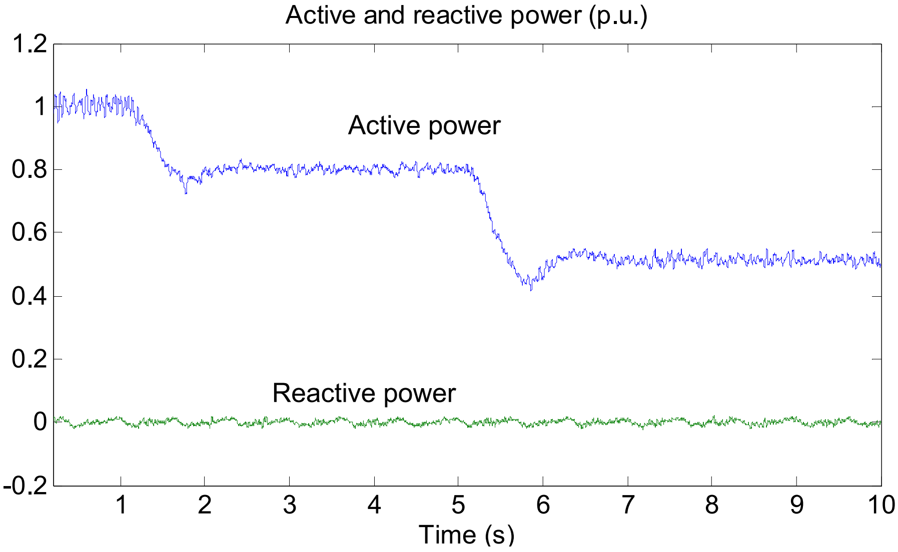


Fig. 4.7 MTGS active and reactive power

As MTGS utilises PMSM for high speed generator, the power generate is proportional to its turbine shaft speed. Fig. 4.8 shows the speed of the turbine shaft. It is evident that active power generated has similar shape as the shaft speed. It is clear even though the reaction of power electronic converter is fast responding to any operation changes, still the dynamics of the micro turbine influence the total reaction time of the whole units in steady state operation. The power generation seems to be proportional to the speed of the micro turbine shaft which is rotating at the same speed as PMSM generator. But the fast action of converter is evident by observing that power transfer from generator is transferred almost instantly to the grid.

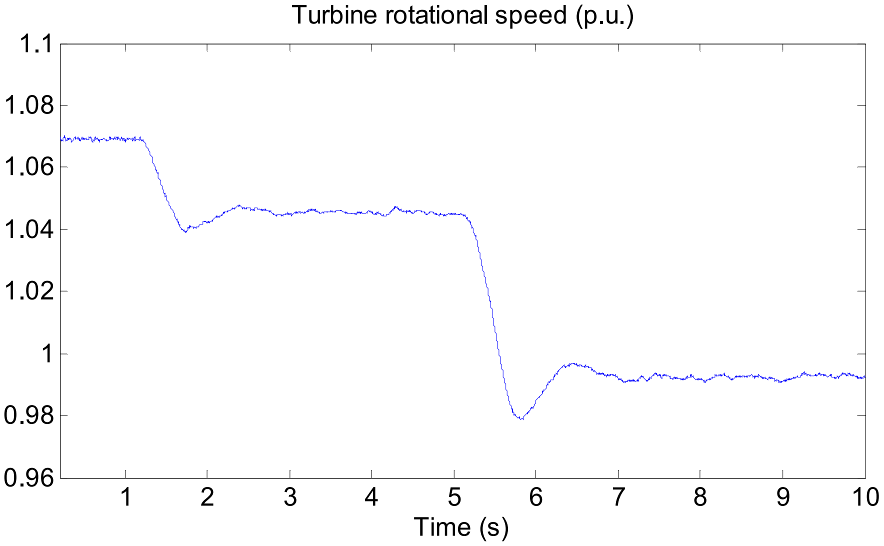


Fig. 4.8 Micro turbine shaft speed

4. 4 Dynamic model of fuel cell generation system

FCGS is a DG powered by FC in which the system comprises FC stacks, power electronic converter and control module. Typical layout of FCGS is depicted in Fig. 4.9 [15]. VSC used in FCGS is quite similar to the one used in MTGS so the discussion will not be repeated. The next section will predominantly focus on FC part of the FCGS.

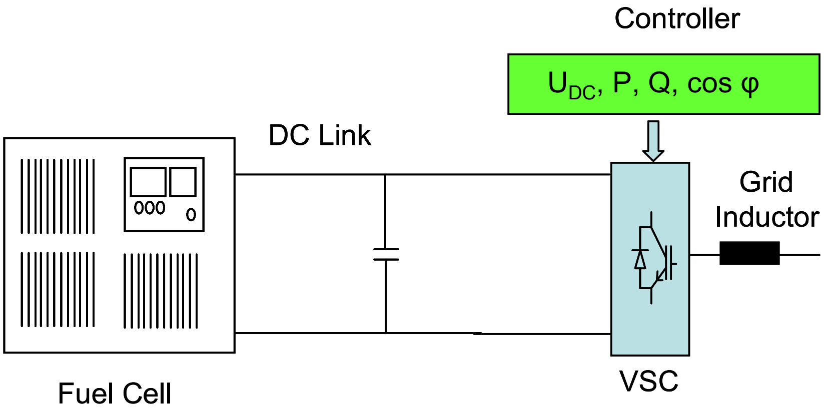


Fig. 4.9 Typical layout of FCGS

4.4.1 Fuel cell

Main construction of fuel cell contains anode, cathode and electrolyte as shown in Fig. 4.10 [4]. Main input into fuel cell unit is hydrogen and oxygen gas. The basic physical structure of a fuel cell comprises two porous electrodes (anode and cathode) and an electrolyte layer in the middle. Fuel in typical fuel cell is fed continuously to the anode while oxidant is fed continuously to the cathode. Freed electrons from pressurised hydrogen molecules are conducted through anode into outer circuit. Cathode, the positive connection, carries back electron from external circuit to the catalyst.

Catalyst is the material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder coated on a carbon paper or cloth. In the catalyst electrons combine with oxygen to form water which is a by product of the fuel cell. The electrolyte is a special treated material that only allows positively charged ions electron to pass through it while blocking negatively charged ions. The type and chemical properties of electrolyte used in fuel cell are very important to their operating characteristic such as their operating temperatures.

Typical voltage-current characteristic of fuel cell is shown in Fig. 4.11. A sharp drop in voltage in activation region is associated with the chemical reaction at small current. The voltage drop in ohmic region is associated with losses in electrode and electrolyte. At a very high current, the voltage drop is associated with the rate of diffusion, causing a sharp drop in voltage.

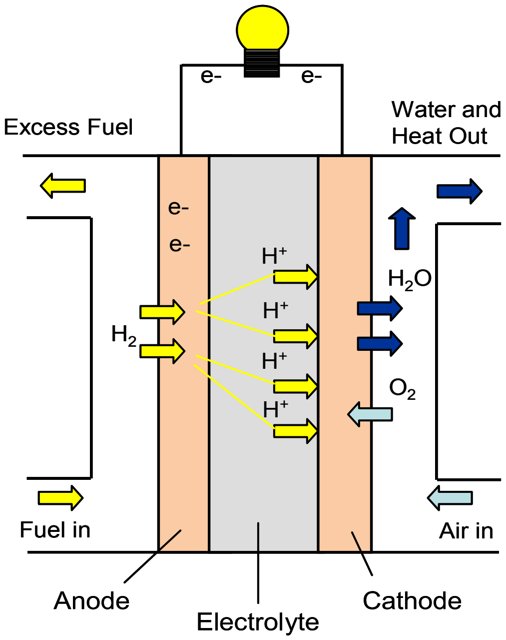


Fig. 4.10 Fuel cell chemical reaction [4]

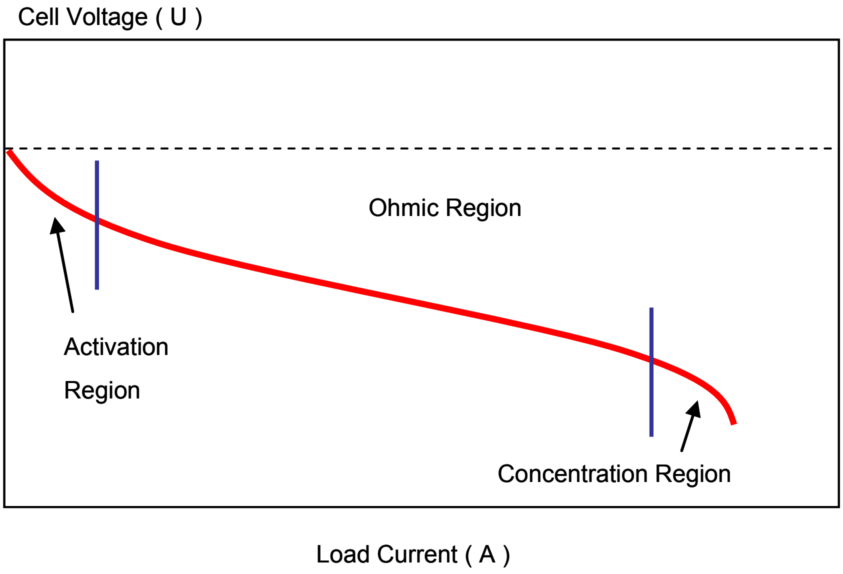


Fig. 4.11 Fuel cell voltage –current characteristic [4]

4.4.2 Modeling of fuel cell dynamic

Overall FC chemical reaction is [53]

$$H_2 + O_2 \to H_2O \tag{4. 15}$$

where H_2, O_2 and H_2O are hydrogen, oxygen and water, respectively. Anode is assumed to be supplied with only hydrogen and the cathode with oxygen only. These gas molarities create potential difference between the anode and cathode which is called Nernst voltage and can be calculated by [54-55]

$$U_{NERNST} = N_0\left(U_{NL} + \left(\frac{k_{UGC}\, t_k}{2F}\right)\ln\left(\frac{p_{H_2}\sqrt{p_{O_2}}}{P_{H_2O}}\right)\right) - R^{\text{int}} I_{FC} \tag{4. 16}$$

where $p_{H_2}, p_{H_2O}, \text{and}\, p_{O_2}$ are partial pressure of $H_2, H_2O\,\text{and}\, O_2$ respectively. N_0 is the number of series FC in the stack, U_{NL} is the standard no load voltage, k_{UGC} is the universal gas constant, t_k is the absolute temperature, R^{int} is internal resistance of FC and I_{FC} is FC stack current.

The proportional relationship of the flow of gas through a valve with its partial pressure is given by [55-56]

$$\frac{q_{H_2}}{p_{H_2}} = \frac{k_{an}}{\sqrt{M_{H_2}}} = k_{H_2} \tag{4. 17}$$

and

$$\frac{q_{H_2O}}{p_{H_2O}} = \frac{k_{an}}{\sqrt{M_{H_2O}}} = k_{H_2O} \tag{4. 18}$$

where q_{H_2} is molar flow of hydrogen, q_{H_2O} is molar flow of water, p_{H_2} is hydrogen partial pressure, p_{H_2O} is water partial pressure, k_{H_2} is hydrogen valve molar constant, k_{H_2O} is water valve molar constant, k_{an} is anode valve constant, M_{H_2} is molar mass of hydrogen and M_{H_2O} is molar mass of water. For hydrogen, the derivative of partial pressure can be calculated using the perfect gas equation as follows [55]

$$\frac{d}{dt} p_{H_2} = \frac{k_{UGC}\, t_k}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}\right) \tag{4. 19}$$

where V_{an} is volume of the anode, $q_{H_2}^{in}$ is hydrogen input flow, $q_{H_2}^{out}$ is hydrogen output flow, $q_{H_2}^{r}$ is hydrogen flow that reacts. The relationship between the hydrogen flow and stack current can be written as [55]

$$q_{H_2}^{in} = \frac{N_0 I_{FC}}{2F} = 2k_r I_{FC} \tag{4. 20}$$

where F is Faraday's constant and k_r is modeling constant. Substituting Eqn. (4.20) into (4.19) and applying Laplace transform, partial pressure of hydrogen can be written in the *s* domain as [55]

$$p_{H_2} = \frac{1/k_{H_2}}{1 + sT_{H_2}}\left(q_{H_2}^{in} - 2k_r I_{FC}\right) \tag{4. 21}$$

where T_{H_2} is a hydrogen time constant given by [55]

$$T_{H_2} = \frac{V_{an}}{k_{H_2} R^{\text{int}} t_k} \quad s \tag{4. 22}$$

By similar substitution, partial pressures of water p_{H_2O} and oxygen p_{O_2} can also be derived. The output voltage which describes the polarisation curve for FC is the sum of three terms which mathematically can be expressed by the equation [57-58]:

$$U_{FC} = U_{NERNST} + \eta_{act} + \eta_{ohmic} \tag{4. 23}$$

where η_{act} is a function of the oxygen concentration and stack current while η_{ohmic} is a function of the stack current and the stack internal resistance. By assuming constant temperature and oxygen concentration, Eqn. (4.23) can be rewritten as [59-60]:

$$U_{FC} = U_{NERNST} - \ln(CI_{FC}) - R^{\text{int}} I_{FC} \tag{4. 24}$$

All these equations completing the equation are needed in modeling the dynamics of FC. Graphically the whole dynamic model of FC is depicted in Fig. 4.12 for PEMFC. For other models some modification has to be made into the equation for example by eliminating the function of the oxygen concentration η_{act}, SOFC model can be derived. The dynamic model of SOFC is illustrated in Fig. 4.13.

4.4.3 Operation under grid connected mode

The performance of FCGS in adhering to requirement under steady state operation is investigated in this subsection similarly to what has been done with MTGS. Small amount of harmonic components in output voltage and current is also true for FCGS because most of the commercial units available employ IGBT based converter. Phase voltage and current measured at the connection point is depicted in Fig. 4.14. With more detailed analysis using Fourier transform and calculating total harmonic distortion (THD), the result is tabulated in Table 4.2. Similar to the MTGS, value of THD is considered low compared to the published limit in European standard EN50160 [41].

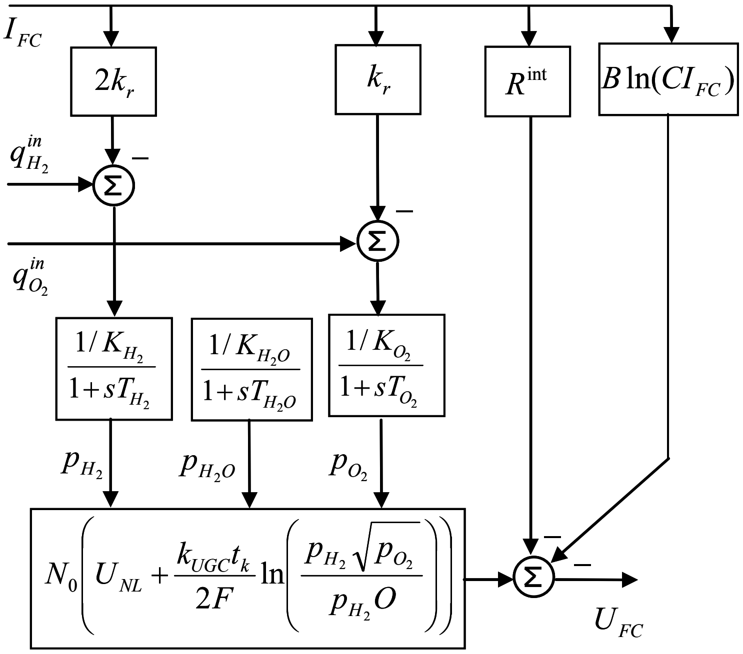


Fig. 4.12 PEM fuel cell model

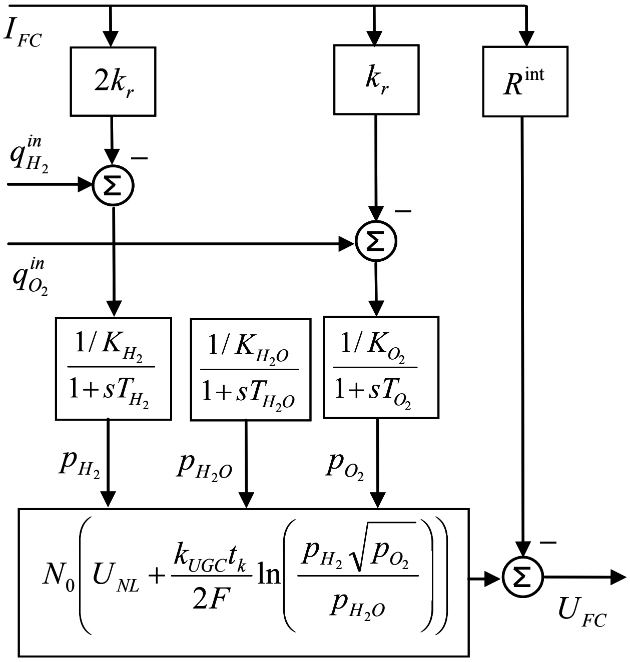


Fig. 4.13 SOFC fuel cell model

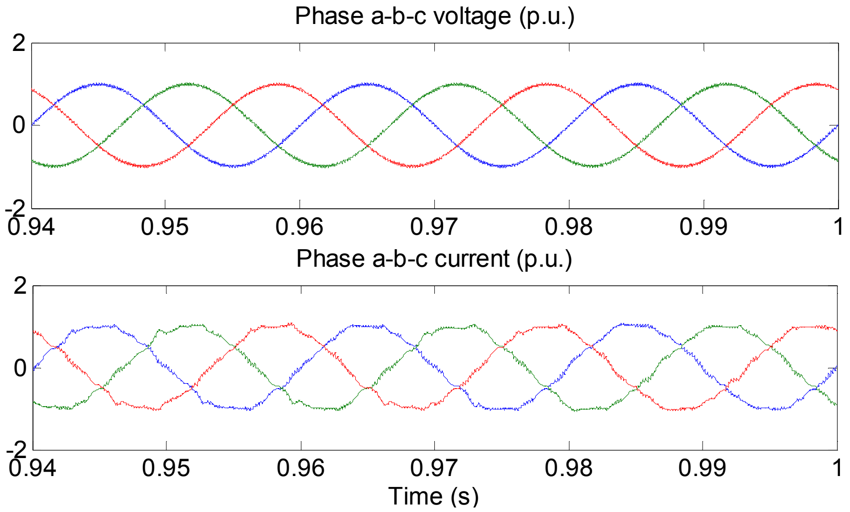


Fig. 4.14 FCGS steady state voltage and current

Table 4.2 Voltage and current THD of FCGS

Voltage	THD (%)	Current	THD (%)
Phase a	2.59 %	Phase a	4.89 %
Phase b	2.58 %	Phase b	5.29 %
Phase c	2.58 %	Phase c	4.88 %

Active power reduction capability is also investigated for FCGS. FCGS performance in responding to the demanded active power is depicted in Fig. 4.15. FCGS is initially delivering 1.0 p.u. of its active power but at *t* =1.0 s active power demand is reduced to 0.8 p.u. At *t* = 5.0 s the active power generation is again reduced to 0.7 p.u. The response of the FCGS is smoother when compared to the response of the MTGS when power reduction is demanded.

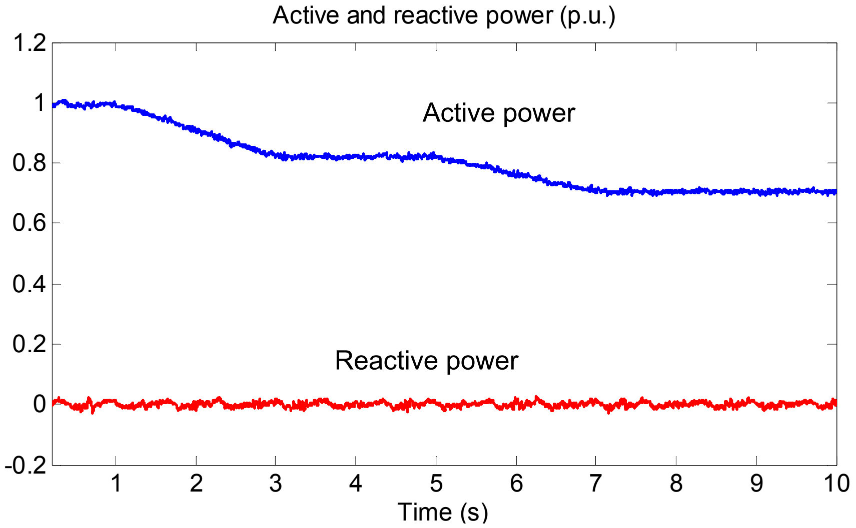


Fig. 4.15 FCGS active and reactive power

4. 5 Simplified model of MTGS and FCGS

Simplified model of DG can be derived under assumption that DC voltage is constant. This assumption can be justified by the large capacitance in the DC circuit and by the DC voltage controller which keeps the voltage at near nominal value. With this assumption, DG can be represented by a voltage source converter fed by a constant DC source.

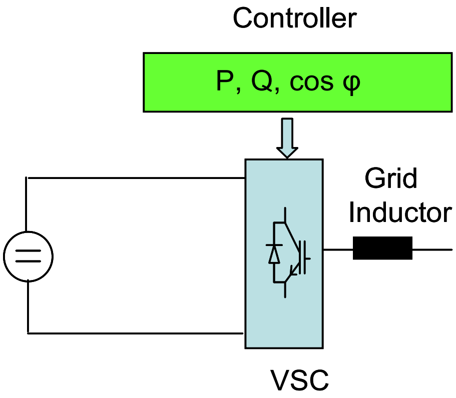


Fig. 4.16 VSC fed by constant DC source

For this model the controller for converter is similar to the one depicted in Fig. 3.8 but i_{CONd_ref} can be calculated with only

$$i_{CONd\_ref} = \frac{p_{ref}}{u_d} \tag{4. 25}$$

DG dynamic models discussed so far are detailed models which include detailed representation of power electronic converter switching and modulation. These models take three phase voltage and current from the connecting mode and transformed into *d-q* coordinated for control purposes. The output again is a voltage and current in three phase quantities. This model requires a very small time integration step in time domain simulation. Moreover each model is modelled based on the specific rating. These models are suitable for controller design or power system integration studies in the small network involving one or a few generation units.

Power system studies such as stability analysis is very time consuming with previously described models. To perform power system studies a simplified model is required. The model must also possess flexibility in changing power rating because in performing a power system studies a lot of possibilities must be considered.

For example the reduction of MTGS model is explained here. Reduction can be achieved by ignoring the modulation and the switching of IGBTs of the converter. For converter, only its active power, voltage and current are considered. On the side of the machine, the output active power of PMSM passed through a diode rectifier is required. By comparing the active power from converter and active power from PMSM, time behaviour of DC link circuit voltage can be derived. Here DC link will only be represented by time behaviour of the DC voltage described by [61]

$$\frac{du_{DC}}{dt} \approx \frac{p_{DG+losses} + p_{CON}}{u_{DC} \cdot c_{DC}} \tag{4. 26}$$

where

p_{DG} is active power from DG

p_{CON} is active power of converter

c_{DC} is the capacitance inside DC-link

u_{DC} is a DC-link voltage

The diagram of simplified model of MTGS is illustrated in Fig. 4.17. The control of the MTGS is still performed in *d-q* coordinate but the outputs are only the RMS magnitude and angle of the voltage instead of time variant voltage.

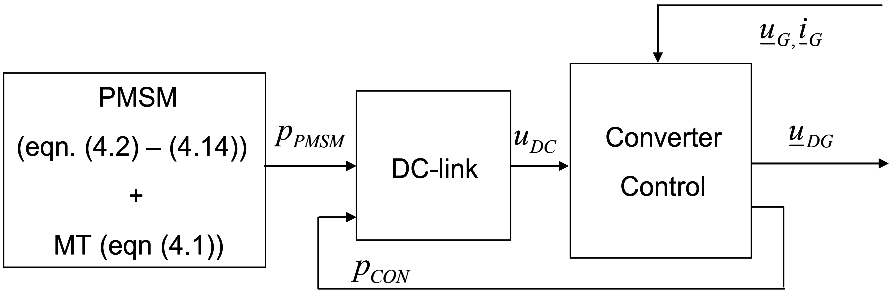


Fig. 4.17 Simplified model of MTGS

The simplified model of FCGS can be reduced by similar method but the equations are replaced by FC dynamic equivalent Eqn. (4.15) – (4.24). In the later chapter of the thesis, various power system integration studies will be performed. Depending on the nature of the study, different types of DG model are used and they will be mentioned in the respective sections.

4. 6 Conclusion

Different types of power system studies with integration of DG require different types of DG dynamic model. Various methods in modeling DG were discussed in this chapter. At the beginning of the chapter, specific MTGS and FCGS model were described. This model considers the switching of PED and needs very small time integration step to perform the simulation. This model is suitable for studying harmonics during steady state operation and other studies involving one or two DG units. In performing power system studies in the network which comprises multiple synchronous generators and multiple DG units, simplified models are required to reduce simulation time. Simplified models of MTGS and FCGS and general model of DG that can be used in such studies are introduced in this chapter. The performance of the developed model is compared to the reported performance in the literature and the results are found comparable.

Chapter 5

Fault Ride-through of Distributed Generators

5. 1 Introduction

Power system is subjected to various grid faults during its operation leading to abnormal system behaviour. These faults can be caused by insulation failure of the equipments or flashover of lines initiated by lightning stroke or through accidental faulty operation. The majority of system faults involve one line to ground or occasionally two lines to ground. Even though three-phase faults are rare, this symmetrical fault study must be carried out as this type of fault generally leads to most severe fault current flow in the system. In this chapter, capability of two DG technologies MTGS and FCGS in riding through low voltage event is investigated.

5. 2 Fault response of DG units

Present grid code does not allow generation units connected to low voltage level to ride-through a fault [62-63]. The units must be temporarily disconnected until a fault is cleared. The method of fault clearing is beyond the scope of this thesis and will not be discussed. In the near future it is expected that not only generation units connected into low voltage network are required to ride-through a fault but at the same time injecting reactive current to support the network voltage is also required. In conventional generation units, fault current could reach a few times of the magnitude of nominal current. In new technology of generation units utilising power electronic converter for power conversion, due to current limiting capability, fault current could be limited. The magnitude of the maximum current injected to the grid depends on the thermal withstand capability of the semiconductor devices utilised in the converter. Even though the maximum current that could be injected by a converter during a fault could reach 2.0 p.u. [46], in this thesis 1.5 p.u. is considered. This 1.5 p.u. is the total current and the priority during the fault is to inject reactive component with the characteristics defined in the grid code [26]. This characteristic is depicted in Fig. 2.9 in Chapter 2.

If the requirements are imposed on the generation units connected to low voltage bus, the question arises whether these generation units will be able to adhere to this new requirement without operating beyond its design capability. During this fault ride-through event, the generation units will operate in abnormal operation for a short duration and this will put stress on the electrical part as well as on its mechanical components. In the following sections fault ride-through capability of MTGS and FCGS units are discussed and investigated.

5. 3 LVRT of MTGS

A number of MTGS units have already been installed in low voltage network for nearly a decade. This unit has been programmed to operate according to current utility requirements. The question arises whether these units are able to meet new grid codes requirements as was discussed in Chapter 2 and if required what necessary modification needs to be made.

Not many publications report the study on MTGS LVRT capability. In [48,50,64,65] only performance on load following capability is reported. MTGS dynamic model with corresponding PEC controller presented in these studies will not be able to support continuous operation during low voltage ride-through (LVRT). During LVRT, the converter will be under stress and DC-link voltage will increase due to imbalance of power transfer. Controlling the unit to enable this fault ride-through is more complicated thus requires some modification in the power electronic converter controller. This chapter identifies the problems and proposes counter measures to enable MTGS to adhere to new grid requirements without damaging its hardware components.

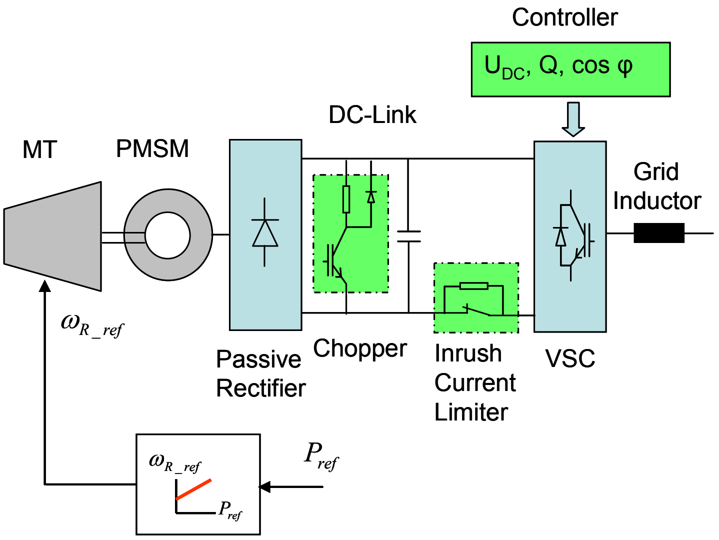


Fig. 5.1 MTGS layout

To show the capability of LVRT with standard power electronic converter, MTGS which is modeled in detail is connected to the distribution network as shown in Fig. 5.2. This is part of the distribution network introduced in reference [66]. The standard power electronic converter here is referred to the basic power DC-link power conversion topology which contains no additional protective devices as was shown in Fig. 4.2. The controller for converter does not have a fast voltage control loop for providing reactive support during low voltage event. This basic controller is already shown earlier in Chapter 3. The momentary fault for 150 ms is applied near the interconnection bus. This fault results in zero voltage at the MTGS connection node.

5.3.1 LVRT with standard power electronic converter

Fig. 5.4 depicts the response of MTGS following voltage dip at the point of interconnection for 150 ms. Technically the voltage should become zero but it is not the case here. This voltage is due to the current injected by MTGS which gives rise to voltage potential across its grid inductor. But from the figure, it can be seen obviously there are two main problems which need to be mitigated.

The first problem is a large magnitude of inrush current reaching nearly 8 p.u. of the rated current. This inrush current is due to sudden changes of voltage occurs across DC capacitor. This current also flows through the converter and this will damage the converter. The other problem is the rise of DC voltage beyond 1.2 p.u. of rated DC voltage. This overvoltage in DC circuit could also cause problem to the power electronic converter circuit. The rise of the DC voltage is due to imbalance of active power transfer from PMSM generator and the active power transfer through converter to the grid. Due to drop in grid voltage, a power transfer to the grid through converter is less than the power generated by the generator. This excess power accumulates inside DC circuit and leads to DC overvoltage.

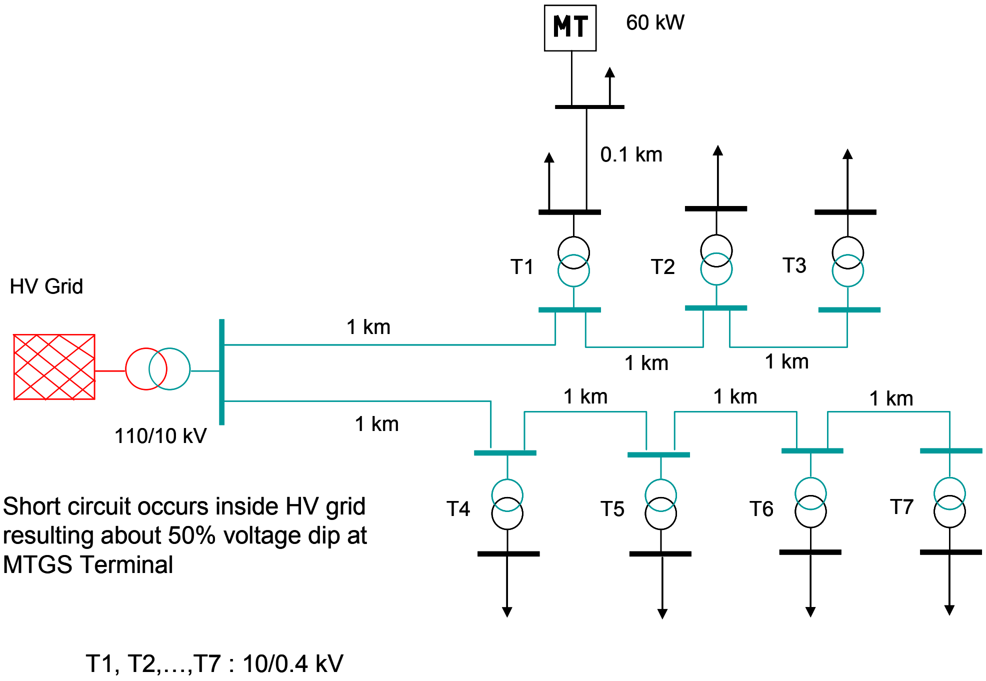


Fig. 5.2 Test Network for LVRT study

5.3.2 Modification of power electronic converter

For mitigating the problem with the inrush current, inrush current limiting circuit is suggested. This protective circuit uses similar technique in limiting capacitor’s charging inrush current in AC drive [67-68]. This circuit effectively protects the drives during power up, power dip or line loss event. This technique is implemented by placing a series resistor in the DC bus circuit. The circuit is triggered by solid state switch such as SCR or transistor connected parallel with the resistor. This circuit is added inside DC-link circuit as shown in Fig. 5.1 and only activated when the sudden drop of voltage is detected at the point of connection.

For mitigating the problem with DC overvoltage, the excess active power which causes the problem needs to be dissipated. This can be achieved using DC chopper which is basically a resistor circuit controlled by power electronic devices. The extra power will be dissipated through a resistor by switching it on and off. This method could limit DC voltage within acceptable range. This range depends on the insulation provided by manufacturers. In this study it is assumed that this maximum limit is 1.1 p.u. of the rated DC-link voltage.

The other option of limiting the rise of DC voltage is to increase the size of the DC capacitor. The effect of increasing the size of capacitor is found to be able to limit the DC voltage through performed dynamic simulation studies. This option however will require additional space inside the unit. If the unit is already installed this option probably is not feasible because there may be no extra space available inside the unit. Even though the simulation study with this option is also performed, the simulation result is not shown here.

Additional protection devices (DC chopper and inrush current limiter) could eliminate the problem in operating FCGS in temporary very low voltage events. In responding to the reactive support requirement an additional control loop has to be incorporated inside the converter voltage controller. This fast voltage controller is only activated when the voltage dip is more than 10 % of the effective value which means the real voltage magnitude before the voltage dip event occurs. This additional voltage control loop is depicted in Fig. 5.3 inside a green coloured box.

During this LVRT, negative reactive current needs to be injected into the grid at least with the gain of two as detailed in Fig. 2.9. This current is added to the original reactive current reference. During this critical time, priority is given to reactive current but an additional injected current into the grid means overloading the converter. The maximum current to be injected during LVRT must not exceed the permissible limit and has to be limited according to

$$\left|\underline{i}_{CON}\right| = \sqrt{i_{CONd}^2 + i_{CONq}^2} \leq i_{CON\max} \qquad (5.\ 1)$$

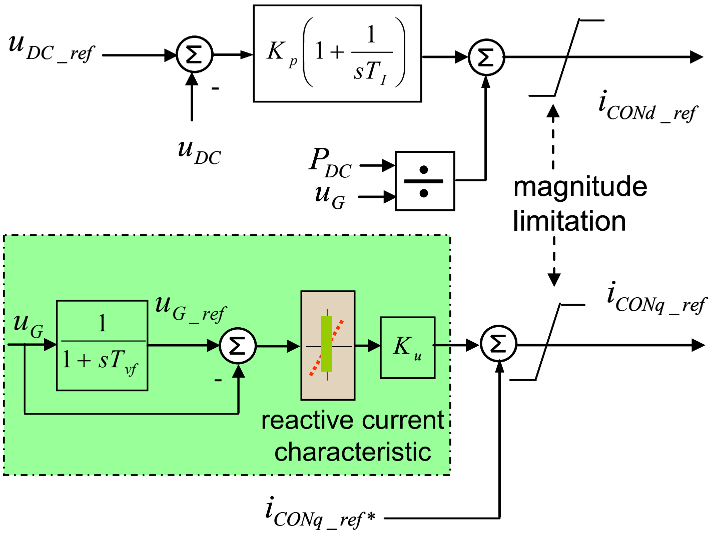


Fig. 5.3 Reference current generation scheme for LVRT

Maximum converter current that can be tolerated by specific MTGS is different depending on the manufacturers. This maximum current is difficult to determine because all of the manufacturers are still new in the business thus technical information is considered confidential. Technical information provided in [46] however is considered reliable and can be used to approximate the magnitude of permissible current for MTGS converter. The data provided is tabulated in Table 5.1. From the table, it can be generalised that MTGS is capable of withstanding up to 2 times the magnitude of its rated current up to 1,000 seconds.

Table 5.1 MTGS converter permissible overload current

Magnitude (%)	Time (ms)
300 %	40
200 %	1.000
150 %	10.000
125 %	30.000
110 %	60.000

As indicated by the grid code, the DG unit must ride-through the low voltage event for at least 150 ms. Although Table 5.1 indicates that 2.0 p.u. rated current can withstand for up to 1,000 ms, in the investigation studies throughout this thesis, the maximum permissible current is set at 1.5 p.u. of converter rated current.

5.3.2 LVRT with modified power electronic converter

The time domain simulation is performed again with a new MTGS dynamic model equipped with additional protective devices (DC chopper and inrush current limiter) and additional fast voltage control loop. The results are depicted in Fig. 5.5. Comparing with the simulation results depicted in Fig. 5.4, it can be observed now the problem with inrush current and DC over voltage as depicted before is eliminated. Transient current is now only approximately 2 p.u. of rated current and DC voltage is now limited to 1.1 p.u. An improvement is also noticed on the active power output of MTGS. Previously with the standard power electronic converter, MTGS takes about 1450 ms to return its active power to the prefault value (refer Fig. 5.4). With the improvement made to the power electronic converter, the time is reduced to 950 ms as shown in Fig. 5.5.

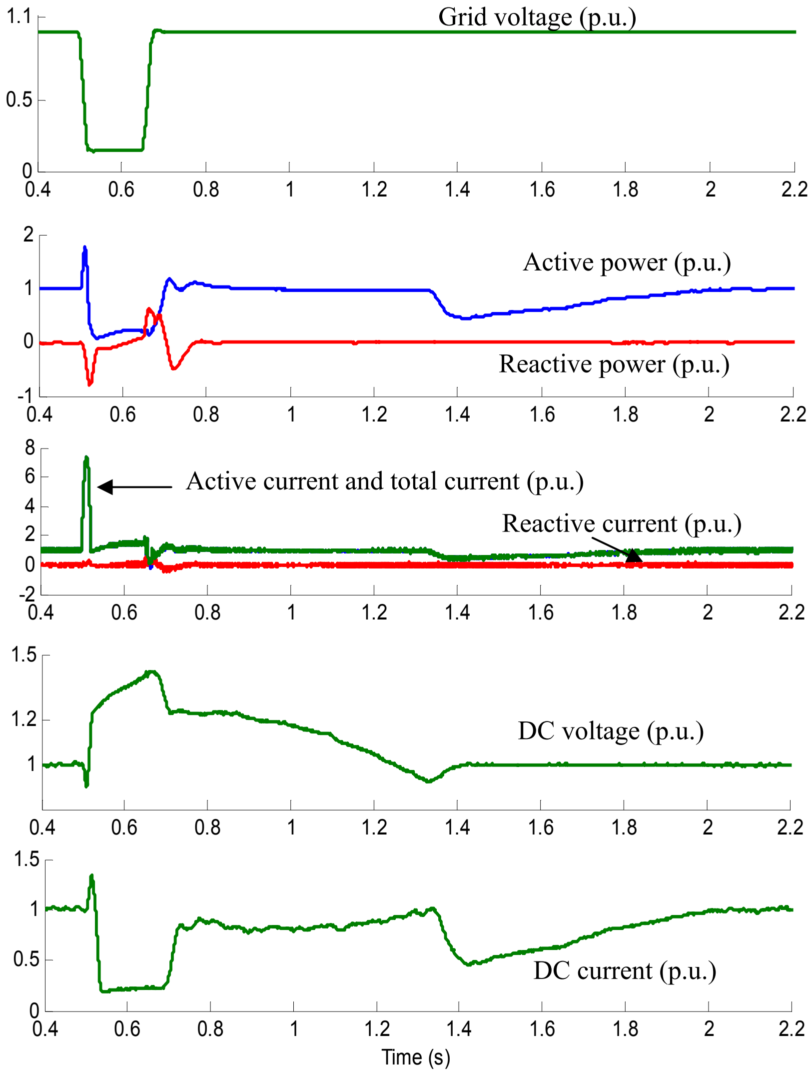


Fig. 5.4 LVRT with standard power electronic converter

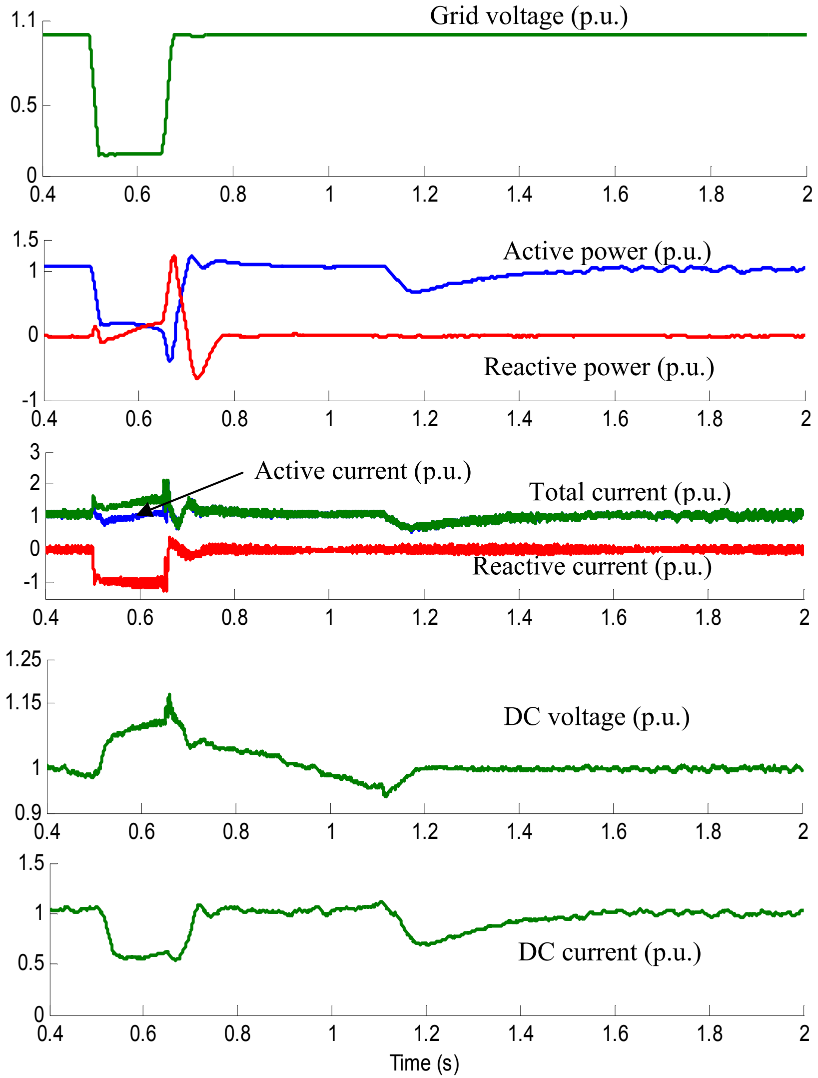


Fig. 5.5 LVRT with modified power electronic converter

5.3.3 Micro turbine generator speed during LVRT

The simulation results which had been discussed previously concentrated on electrical output of MTGS. It is also of interest to know the mechanical response of MTGS during this LVRT. Fig. 5.6 shows the shaft speed, DC-link current on the rectifier side and DC-link voltage. During steady state, the generator is operating at 1.06 p.u. of rated speed. The low voltage event due to the disturbance is also sensed by the micro turbine-generator even though there is no direct coupling between this mechanical part and the grid. It can be seen that the shaft speed accelerates during the low voltage event. Immediately after fault is cleared, the shaft starts decelerating until a certain point before it starts to accelerate again and return slowly to prefault speed. There is an obvious difference in the oscillations of shaft speed between standard and modified power electronic converter. The time taken to return to prefault speed is longer with the standard power electronic converter. The difference in speed deviation results in different current and voltage inside power electronic converter. The stress experienced by mechanical rotating part and power electronic converter circuit is also less with the modification.

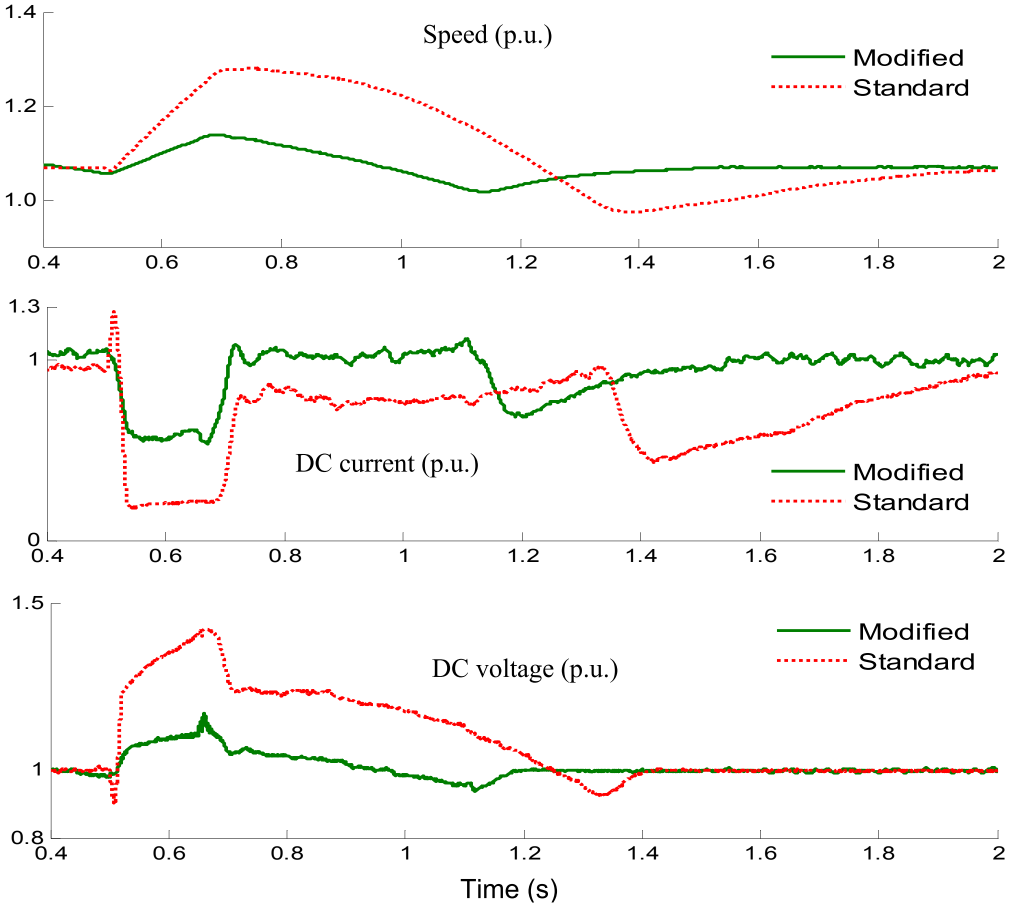


Fig. 5.6 MTGS speed, DC current and DC voltage

5. 4 LVRT with FCGS

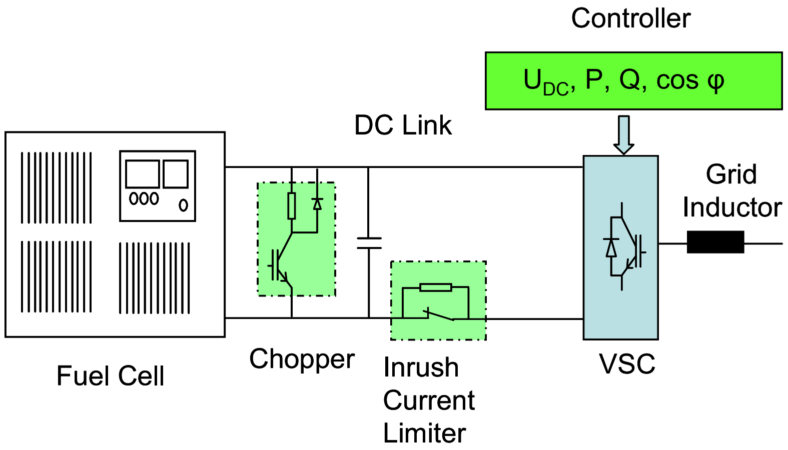


Fig. 5.7 Layout of FCGS

To simulate the performance of FCGS in riding through low voltage event the same simplified power system network is used as in investigating MTGS discussed earlier but this time using FCGS dynamic model. FCGS is also equipped with standard power electronic converter which contains no additional protective devices (chopper and inrush current limiter circuit is not activated) and using only basic controller for converter control (as depicted in Fig. 3.8 and Fig. 3.9). Similarly as with MTGS, during the steady state operation, the total current is limited to 1.0 p.u. of rated value but is temporarily changed to 1.5 p.u. during low voltage event.

5.4.1 LVRT with standard power electronic converter and controller

FCGS is initially delivering its active power at 1.0 p.u. when a self cleared three phase fault is subjected for 150 ms on the grid side at $t = 0.5$ s. This fault results in nearly zero voltage at the interfacing bus. Without FCGS connected the voltage at the measurement bus is zero but due to output from FCGS there is small voltage potential exists at the interconnection bus.

Similarly compared to the simulation results for MTGS, there are two main problems that can be noticed from Fig. 5.8. The first problem is the large transient current which reaches up to 8 p.u. of rated current. This large magnitude of current will definitely destroy the line side converter. The second problem is the rise of DC voltage to a level beyond the operation point of FC which is only set to operate within ohmic region depicted earlier in Fig. 4.11. This high DC voltage stops the operation of FC as can be seen from the DC current curve settling at zero value for approximately 60 ms.

It is clear that these two problems have to be mitigated to make sure fuel cell can stay connected to the grid without ceasing its operation. The next subsection will discuss the solution to mitigate the problems and the performance of FCGS with modified power electronic converter circuit and controller is compared.

5.4.2 LVRT with protection devices and modified controller

The rise of the DC voltage is due to imbalance of active power transfer from FC and the active power transfer through converter to the grid. This problem similarly happens, as demonstrated with MTGS which requires excess power to be dissipated. Similarly DC chopper is suggested to limit this DC voltage to 1.1 p.u. For mitigating the problem of very large magnitude of transient current, similar inrush current limiter circuit as embedded inside MTGS power electronic converter circuit is suggested.

These two additional protection devices (DC chopper and inrush current limiter) could eliminate the problem in operating FCGS in temporary very low voltage events. For responding to the reactive support requirement similarly as in MTGS, an additional control loop has to be incorporated inside the line side voltage controller (depicted in Fig. 5.7) and is only activated when the voltage dip is more than 10 % of the effective value.

The time domain simulation is performed again with a new FCGS dynamic model equipped with additional protective devices and additional voltage control loop. The simulation results are depicted in Fig. 5.9. It can be observed now the problem with transient current and DC voltage as mentioned before it is eliminated. Transient current is now only below 2 p.u. and DC voltage is now limited to below 1.1 p.u.

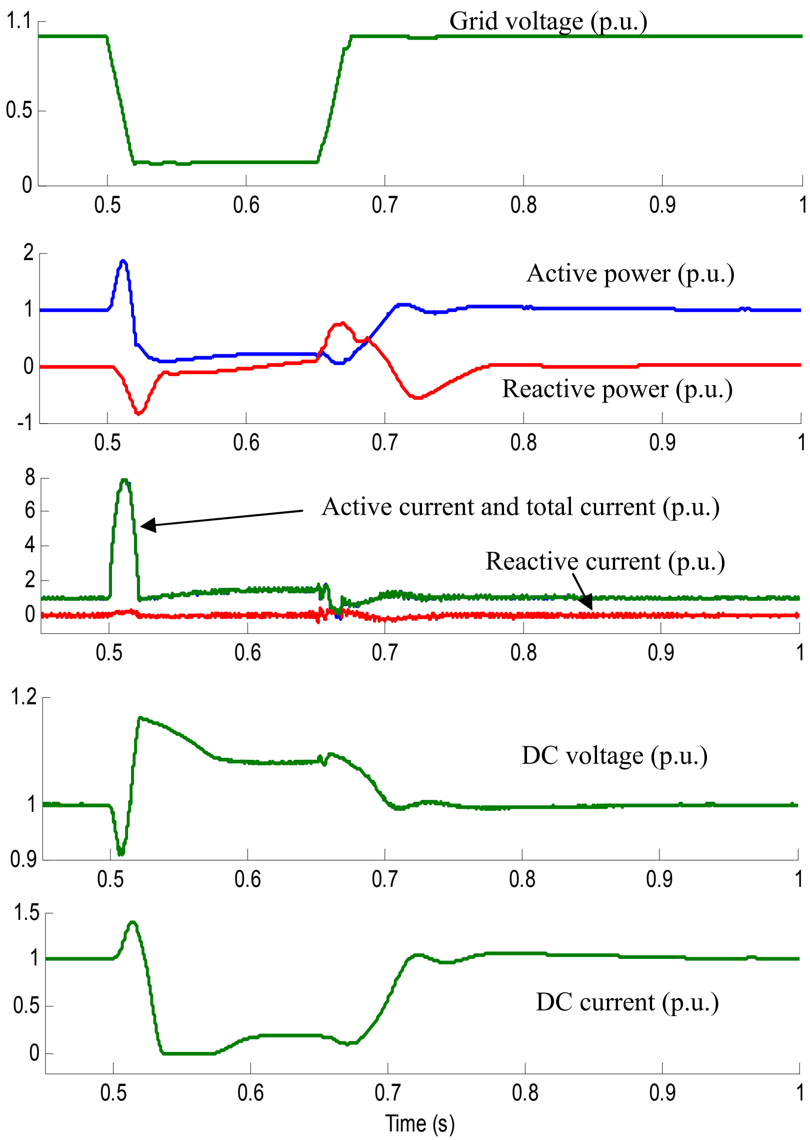


Fig. 5.8 FCGS LVRT with standard power electronic converter

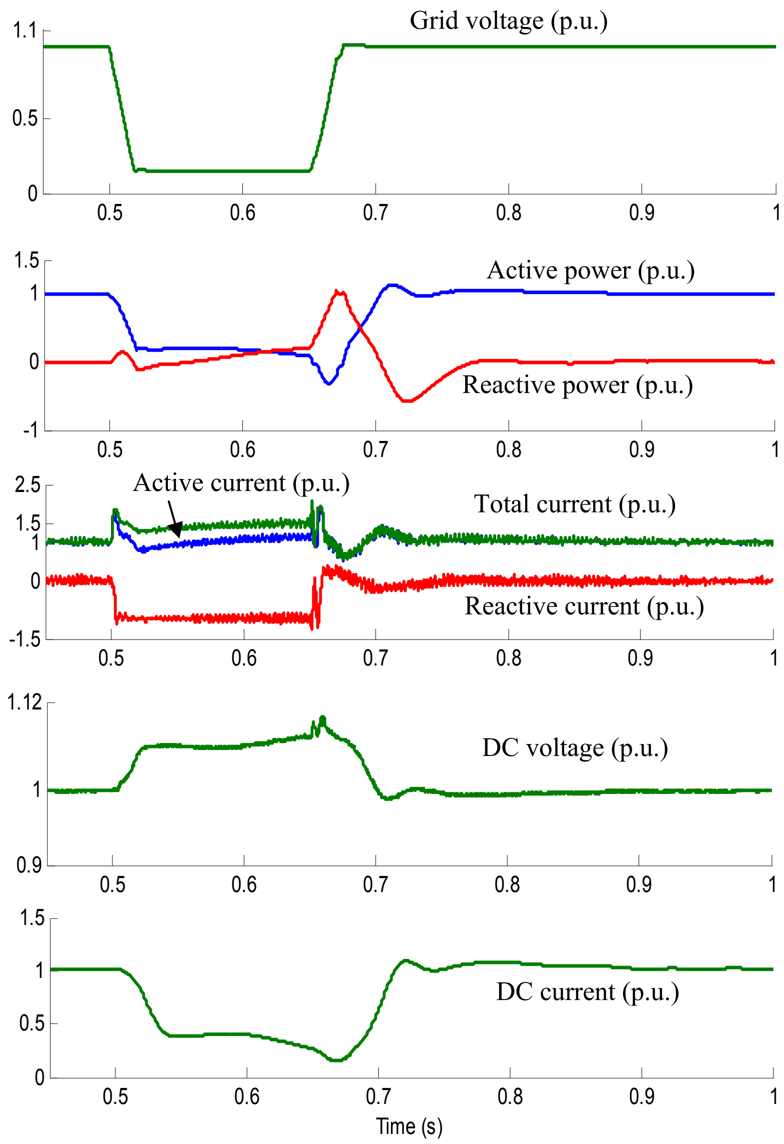


Fig. 5.9 FCGS LVRT with modified power electronic converter

5. 5 Comparison between MTGS and FCGS

MTGS and FCGS are powered by different sources but employed almost similar power electronic converter and controller. In this section, the output from MTGS and FCGS is compared. The comparison on active-reactive power, active-reactive current and total current is depicted in . It can be seen during the low voltage event and up to 350 ms after the fault is cleared, the output from two DG are almost similar. This indicates that during low voltage event and short duration after, the responses of MTGS and FCGS are influenced by their converter control.

After time is adjusted to t = 1.0 s however, the output of MTGS and FCGS is different. For FCGS the output is immediately restored to prefault value. But for MTGS the output drops again slightly before steadily settling to prefault value. This drop in MTGS output is clearly due to the swing of rotational shaft in micro turbine generator, as can be seen from Fig. 5.6.

5. 6 Comparison between FCGS and simplified model for DG

In Chapter 4 under modeling of distributed generation, it was mentioned that many researchers after taking the assumption that due to DC-voltage controller which tries to hold DC voltage constant, the model of DG is developed by only modeling the voltage source converter fed by constant DC voltage source. This approach is also justified due to large capacitance available inside the DC circuit. This simplification is investigated to see if it is also applied for severe low voltage ride-through study. The layout of the model is depicted in Fig. 5.10. Inrush current limiting circuit still needs to be included because without this protection circuit, severe inrush current will develop during LVRT.

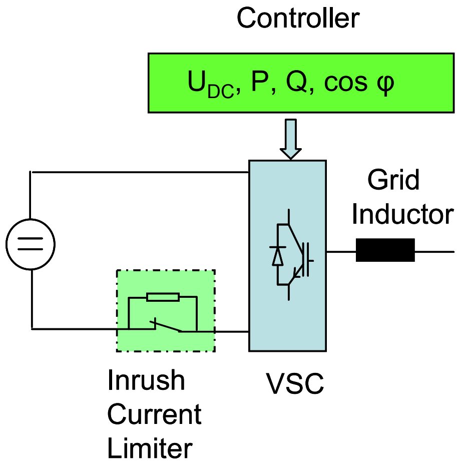


Fig. 5.10 VSC fed by constant DC source

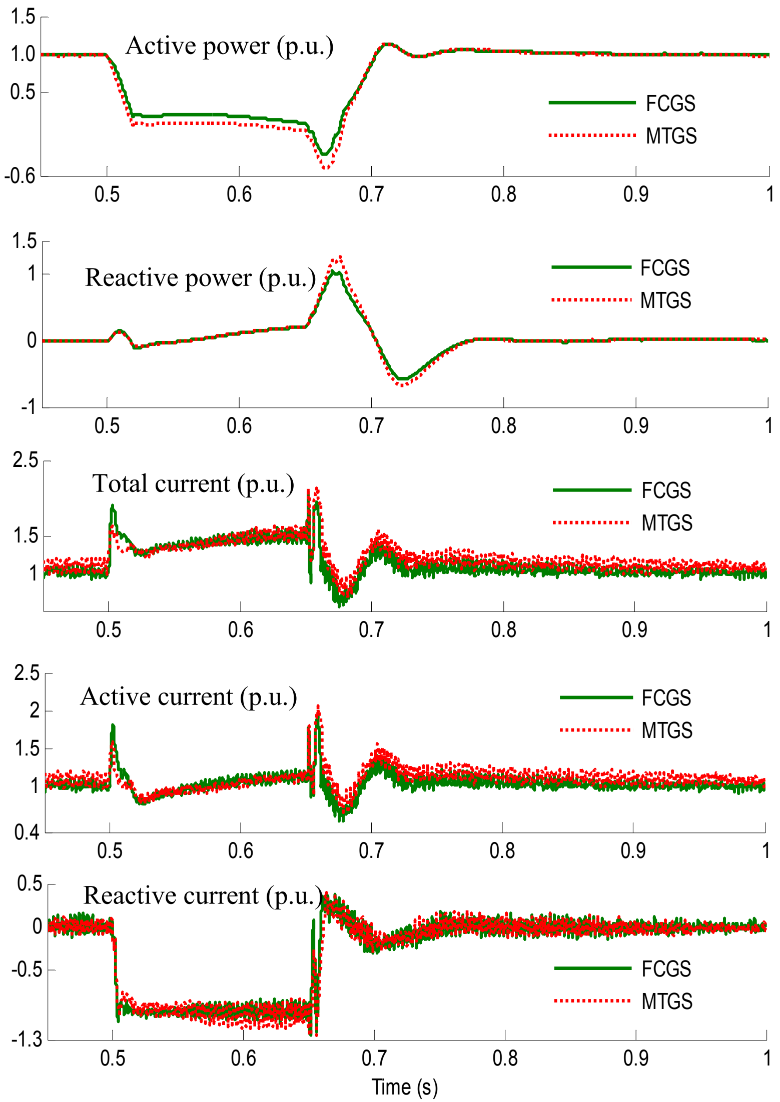


Fig. 5.11 MTGS vs FCGS

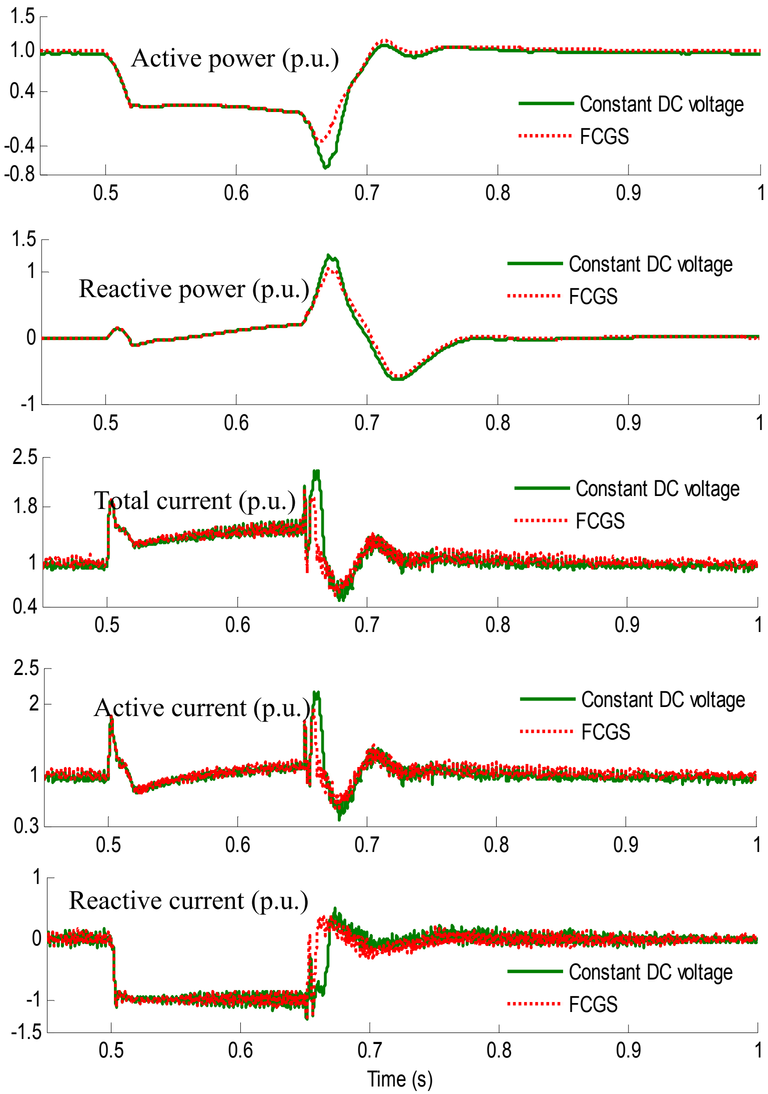


Fig. 5.12 Full model of FCGS vs general model

The simulation result is depicted in which compares the output of the model with full model of FCGS. It can be seen that the simplified model could give almost similar results in comparison to full model.

5. 7 Conclusion

This chapter presents an investigation study of the capability of MTGS and FCGS in adhering to new expected grid codes and respective simulation results have been presented. All the simulation is performed inside Simulink/SimPowerSystem environment. During LVRT, MTGS and FCGS have to operate beyond their rated value for a short moment and this causes stress on their hardware components. This overstress can be limited within permissible overload operating limit with modified power electronic converter presented. Both MTGS and FCGS are shown capable of supporting the grid with capacitive reactive current as required by the new grid code with the modified power electronic converter controller. The question whether MTGS and FCGS which are installed in the power system are capable of meeting the new grid code depends on its design and embraced technology. As a digital controller is programmable and DC protection devices are already equipped or easily added if absent, LVRT with the simulated magnitude and necessity to inject negative reactive current during this critical period can be managed by both MTGS and FCGS. The chapter ends with a comparison of output of FCGS with the general model of converter fed by constant DC voltage source. The similarity can be observed in the output and it is concluded that this simplified model can also be used to represent DG coupled to the grid through PEC.

Chapter 6

Grid Support with DG

6. 1 Introduction

Significant number of DG units will be integrated into existing power system network to replace generation capacity currently provided by large scale centrally located power plants. As some of these traditional power plants are also supporting the network by providing ancillary services, this additional task is also expected to be replaced by DG. Of most important are reactive supply to maintain the voltage and generation-load balancing for maintaining the power system frequency. This chapter will explore the capability of DG units in supporting voltage and stabilising the frequency of the grid which they are connected to. For the voltage support, DG contribution during steady state operation and temporary fault event is simulated. For frequency support, contribution of DG in stabilising frequency following sudden increase in load demand is demonstrated.

6. 2. Voltage support of DG during steady state operation

In the conventional power system network, conventional generator is normally connected to HV network whereas the load is connected far away to the MV or LV distribution network. In the distribution network as shown in Fig. 6.1 power is flowing from MV level to the LV level through line impedances. Due to this line impedance, voltage decreases from substation to the end of the feeder. Transformer at substation which is equipped with on load tap changer is normally used to compensate this voltage drop. Distribution transformer which steps down the voltage from MV level to LV level is normally equipped with a manual off load tap changer.

Voltage inside distribution network will rise during light load condition. But the automatic tap changer on the substation transformer brings the voltage within an acceptable range. However, when there is more than one feeder connected to the substation, it may be difficult to keep all the voltages in all feeders within acceptable range. Official voltage limit for 10 kV distribution network is mostly ± 10 % but in practice the range is smaller than ±5%.

Addition of DG to the distribution network will affect the voltage profile predominantly at the connection node. DG coupled to the grid through PEC, however, has the capability to inject capacitive reactive as well as inductive reactive power. Manipulating these capabilities, DG itself can be used to control voltage fluctuation inside the LV network.

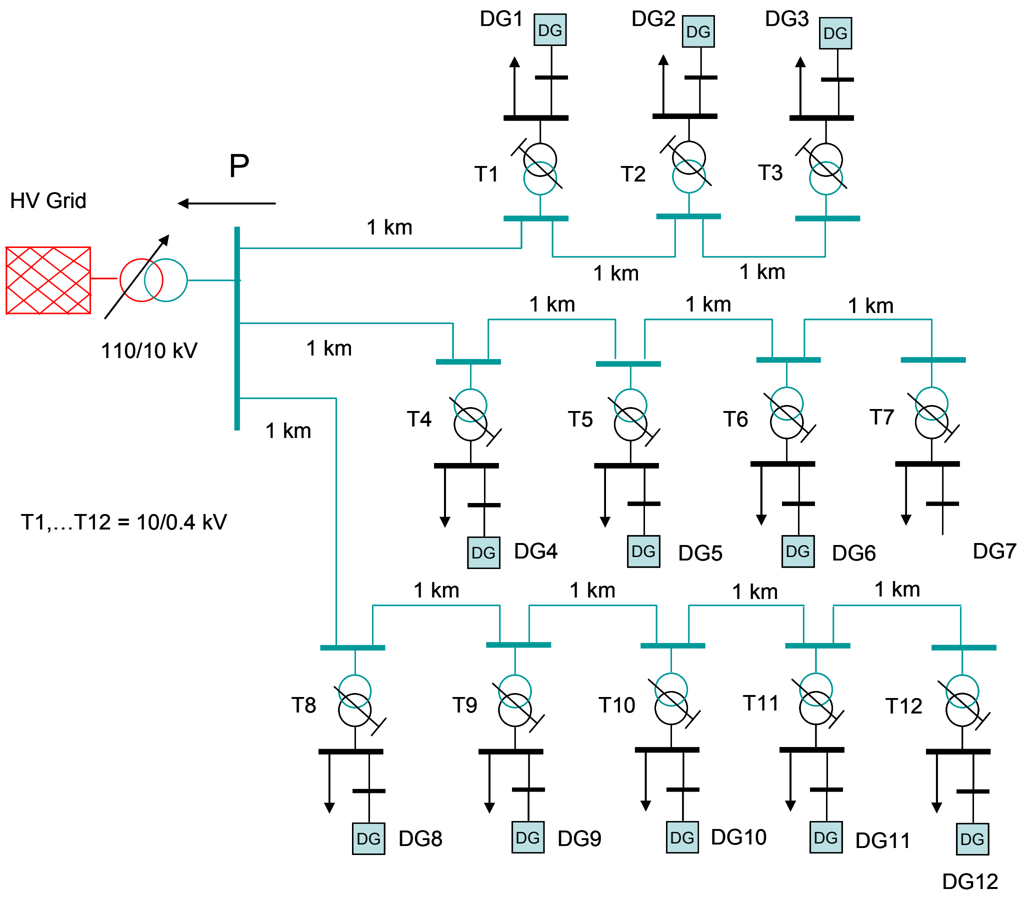


Fig. 6.1 Typical distribution network with DG [66]

6.2.2 Reactive power from DG

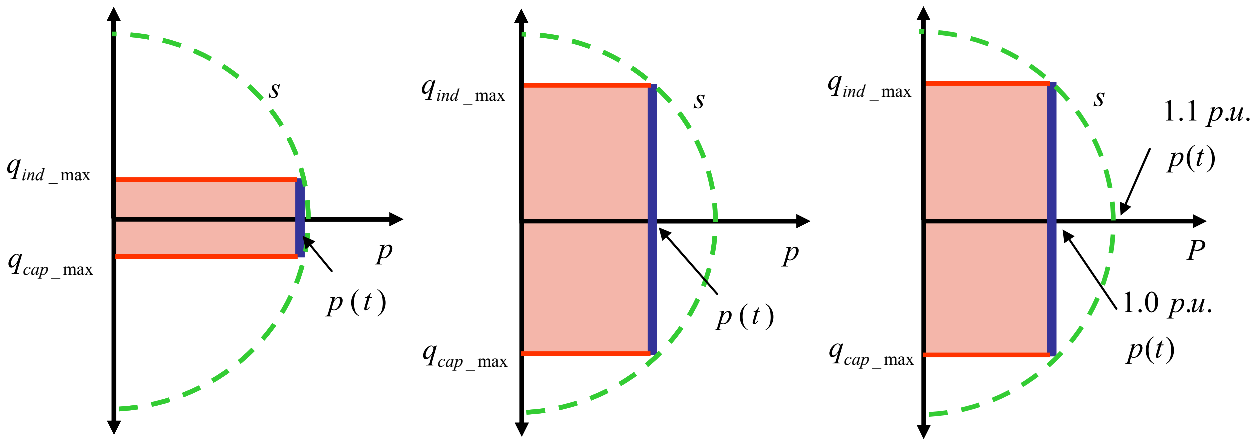
The main purpose of installing DG as onsite power generation is to supply active power to the electrical grid. DG owner or distribution network operator provides an active power reference based on technical-economic criteria production plan with the purpose of gaining maximum profitability. In some cases this plan cannot be adhered to if the generation will lead to excursion of voltage beyond its specified limit. In this case, a DG has to provide capacitive reactive power to lift up the voltage if the voltage exits the lower boundary or inject inductive reactive power if the voltage rises beyond its higher boundary.

The injection of reactive power to the grid means a reduction in active power because the maximum output from DG is limited by its rating. Relation of active-reactive power on specific DG unit is given by

$$q_{DG} = \sqrt{s_{DG}^2 - p_{DG}^2} \tag{6. 1}$$

This equation governs the reactive power availability which could be extracted from certain DG units. Graphically this equation can be depicted as shown in Fig. 6.2. Fig. 6.2(a) and Fig. 6.2(b) illustrate reactive capability if DG is not oversized. In this case, the amount of reactive power depends on the active power generated. For example, if DG unit is supplying active power at 100% of its rating, there is no reactive power available to be extracted. If the active power generation is lowered, more reactive power is available. In certain cases, DG is intentionally oversized for 110 %. By doing this even if DG is supplying full rated active power, there is still reactive power available to be extracted as depicted in Fig. 6.2(c).

When DG unit is not oversized and reactive power is needed, active power then has to be curtailed. This seems like a disadvantage because the DG owner will gain less income from reduction of active power supply. But if this reduction is complemented with some strategies such as providing loss opportunity cost where the owner is paid for the reduction of active power or reactive power supply is also paid, this will not be a problem.



(a) (b) (c)

Fig. 6.2 DG reactive power supply capability

6.2.3 Voltage regulation by DG reactive power control

In manipulating the reactive power from DG, reactive reference can be determined by distribution system operator remotely or locally using voltage/reactive power droop. This droop characteristic can be used to determine reactive power required from each DG unit to prevent the large reactive power circulation that may happen between DG units due to small mismatches in their voltage reference. The basic principle of controlling voltage using voltage/reactive power droop is illustrated in Fig. 6.3 [69].

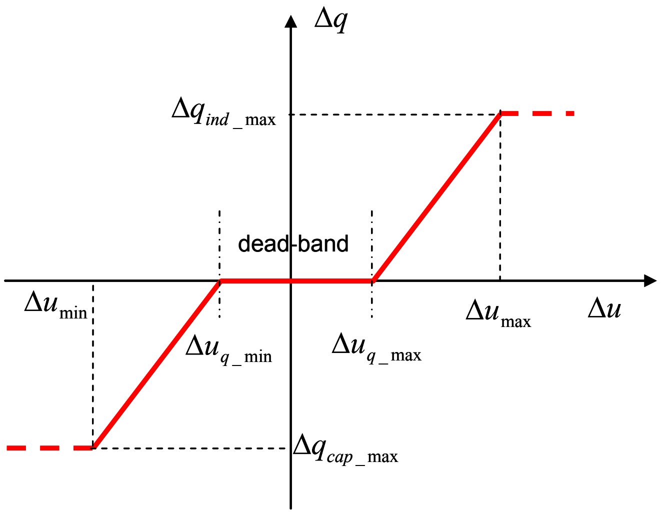


Fig. 6.3 Voltage/reactive power droop characteristic [69]

The important parameters available in the figure are listed below:

Δq_{ind_max}	is the maximum inductive reactive power available
Δq_{cap_max}	is the maximum capacitive reactive power available
Δu_{min}	is the minimum voltage magnitude allowed
Δu_{max}	is the maximum voltage magnitude allowed
Δu_{q_min}	is the minimum voltage for capacitive reactive power
Δu_{q_max}	is the maximum voltage for inductive reactive power

DG reactive power boundary can be fixed and subjected to available reactive power that can be extracted from DG, as discussed in previous subsection section. For the voltage/reactive power droop, it can be calculated as

$$k_q = \frac{\Delta q}{\Delta u} \tag{6. 2}$$

The ability of DG in performing voltage regulation is demonstrated here through time domain simulation. To show the real contribution clearly, one section of the network inside distribution network shown in Fig. 6.1 is modeled. In this small network there are two DG interfaced to the 0.4 kV bus through PEC. DG penetration here is 110 % of the maximum local load. Each DG is equipped with line side voltage controller introduced in Chapter 3. For studying voltage regulation however AC voltage controller loop is modified to include the voltage/reactive power droop. This modification is illustrated in Fig. 6.4. It should be kept in mind that this control loop is not the same as the fast voltage control loop for LVRT illustrated in Fig. 5.3. The purpose of this additional control loop is for voltage regulation in steady state operation.

As described before, this additional reactive power for voltage regulation is converted to the corresponding reactive current is to be added to the already supplied reactive current by converter. For this study, however, there is no initial reactive power initially generated by DG. Additional reactive power to be supplied will result in additional larger current magnitude so the magnitude of total current is still limited to 1.0 p.u. value.

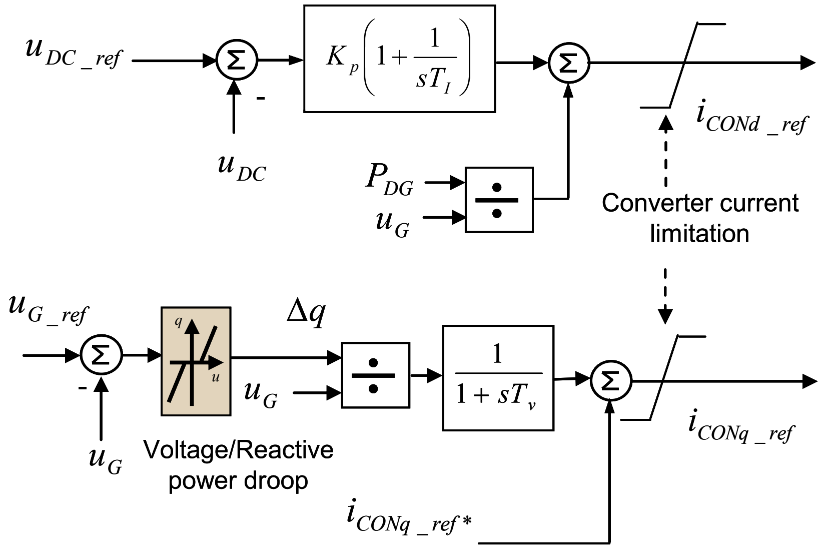


Fig. 6.4 AC voltage controller with voltage/reactive power droop

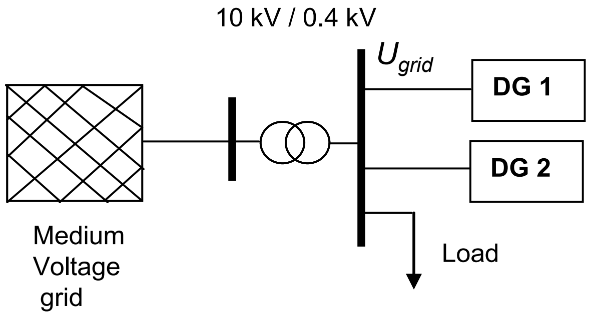


Fig. 6.5 Test network for voltage support study

The simulation study is performed in Matlab/Simulink environment. Medium voltage grid is modeled as a variable voltage source in which the magnitude of the voltage can be stepped up and down to simulate changes of voltage level. The voltage inside the network is initially inside allowable limit of ± 5 percent from nominal voltage. Beginning at t = 2.0 s the voltage inside the network exits lower boundary line. At t = 5.0 s it increases and returns inside its allowable range. Beginning at t = 0.8 s, the voltage rises beyond its upper limit. Fig. 6.6 illustrates the differences between the case when DGs are performing voltage regulation and without. The green line represents simulation results without performing voltage regulation while the red line represents results with the voltage regulation in action.

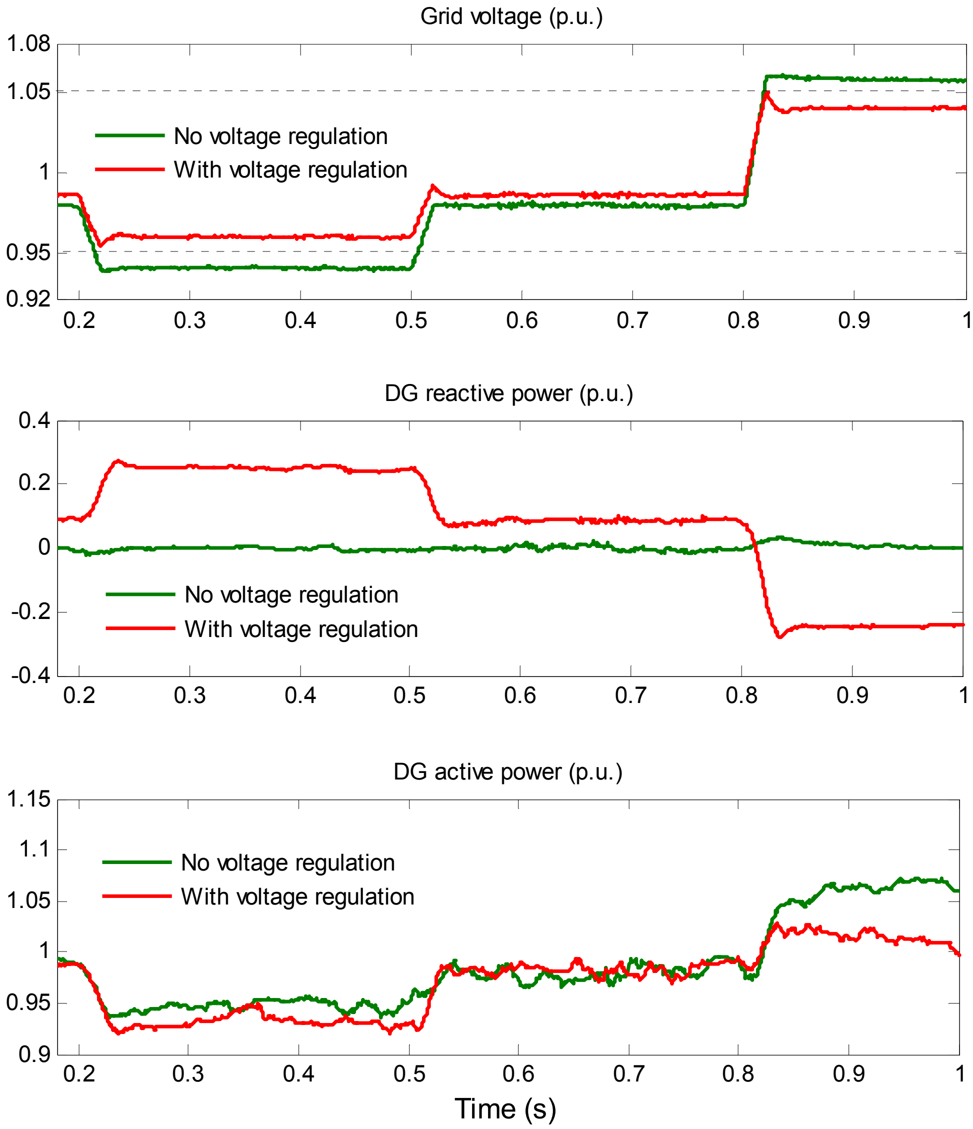


Fig. 6.6 Network voltage, DG reactive power and DG active power

With the voltage regulation from DGs, grid voltage is kept inside its allowable range throughout the simulation. As the voltage regulation is done by controlling reactive power, reactive power output of DG is also depicted. It can be seen that capacitive reactive power is injected during low voltage event while during high voltage event inductive reactive power is supplied. The generation of reactive power however as previously mentioned has to be done with the curtailment on active power. Fig. 6.6 also shows the active power supplied to the grid at the respective time. It can be seen during the low voltage event the injection of reactive power results in reduction of active power. During high voltage event, however, the active power increases beyond DG rated value for the DG without voltage regulation. This increase in active power generation is due to higher voltage at the grid connection. The active current is at that time still 1.0 p.u. but due to higher voltage the active power injected to the grid is above the nominal value. Active power generation with voltage regulation is however seen close to DG full rated power at the respective period.

6. 3 Voltage support during critical time

In the preceding section the discussion and studies performed are for steady state operation. Power system is continuously subjected to various types of temporary disturbances such as short circuit. These short circuit events will result in voltage dips at the point where DG is coupled to the grid. As mentioned in Chapter 2, we are assuming in this thesis the grid codes requirement where DG must provide the reactive support to the grid during critical time.

In Chapter 5, fault ride-through capability was performed where DG has to remain connected to the grid during fault and at the same time providing reactive support. Reactive support characteristic demanded from DG has already been mentioned in Section 2.6.2 earlier. This requirement is published for DG connected to medium voltage but it is assumed it will also apply for DG connected to LV bus. The studies in Chapter 5 however focus on the DG unit. In this section investigation will be carried out on how significantly the reactive support provides supporting network voltage during fault. In the original standard as is depicted in Fig. 2.9, the gain is 2.0 but an investigation will be carried out on the effect when the gain is increased to 3.0, 4.0 and 5.0. For the purpose of comparison, the cases when DG is not providing reactive support and DG is set to temporarily cease its power output are also simulated.

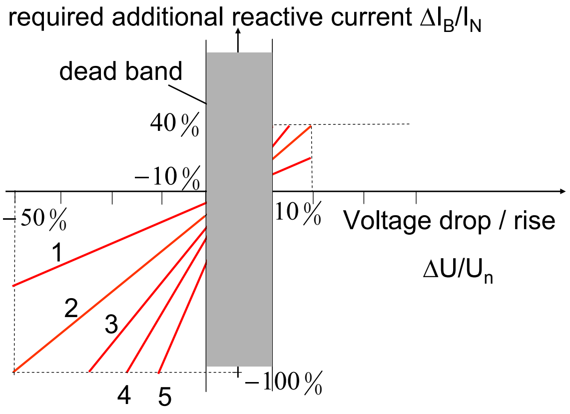


Fig. 6.7 Reactive current characteristic

The whole network connected with DG units as shown in Fig. 6.1 is used in this investigation. Similar to the voltage regulation study performed in previous subsection, Matlab/Simulink [70] software is used. Disturbance introduced here to simulate temporary low voltage event is the changing voltage magnitude inside HV grid which is modeled as a variable voltage source. The network is operating at voltage close to 1.0 p.u. of the rated voltage. At $t = 0.2$ s, voltage magnitude is temporarily stepped down for 150 ms to lower the voltage throughout the network to about 0.5 p.u. For voltage contribution evaluation, the voltage at the secondary side of the transformer 110/10 kV at the main substation is compared. The voltage comparison is depicted in Fig. 6.8 for different values of reactive current gain.

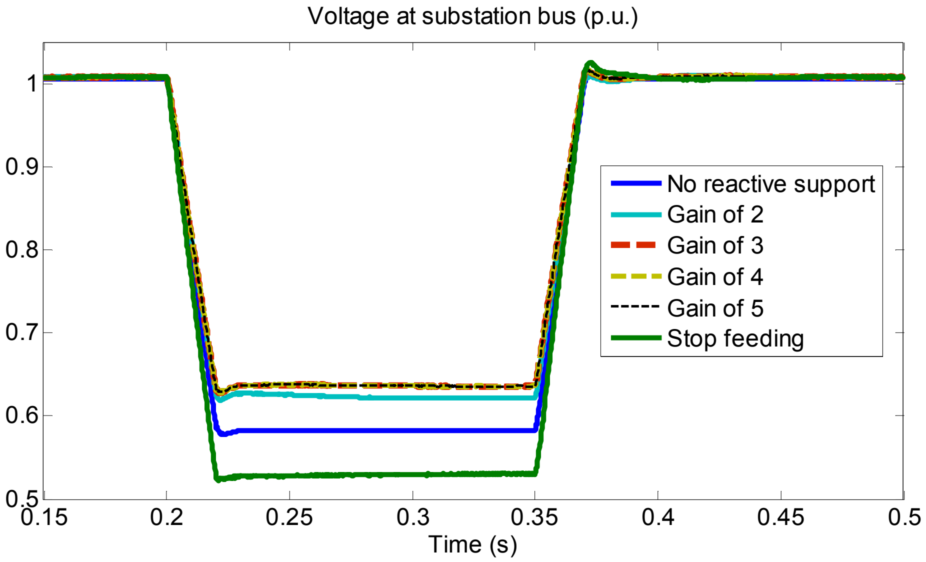


Fig. 6.8 Voltage magnitude at main substation during fault

The blue line represents the voltage during fault if DG is not providing reactive support. Cyan line is the voltage if the reactive current with the gain of 2 is injected. With the gain of 2, the voltage could be increased to about 4 %. By increasing the gain to 3 about 6 % increases can be seen. Further increase in current gain however does not make any difference because even with higher current magnitude, the maximum reactive current is limited to 100% of the nominal current. It can also be seen that if DG is set to stop feeding their power during this critical time, the dip of voltage is more severe.

Even if the effect of voltage support from DG only results in less than 10 % of voltage increase, the benefit will be quite significant. Most of the equipment is designed to withstand the voltage tolerance defined in CBEMA/ITI curve [37], as depicted in Fig. 6.9. This curve is originally published for computer industry but it is adopted by many manufacturers in designing their appliances. The curve gives the tolerance of voltage magnitude which should be withstood by appliances in their operation. By looking to the specification in the curve, if the voltage magnitude for 150 ms voltage dip is below 70 % of the nominal value, the appliances such as adjustable speed drives will stop functioning and will be disconnected [68,71]. This loss of load will create a significant imbalance immediately after the fault is cleared which could prolong the time for power system restoration. If the voltage dip is just below the boundary line, 4 to 6 % increase is already considered a significant help to the power system.

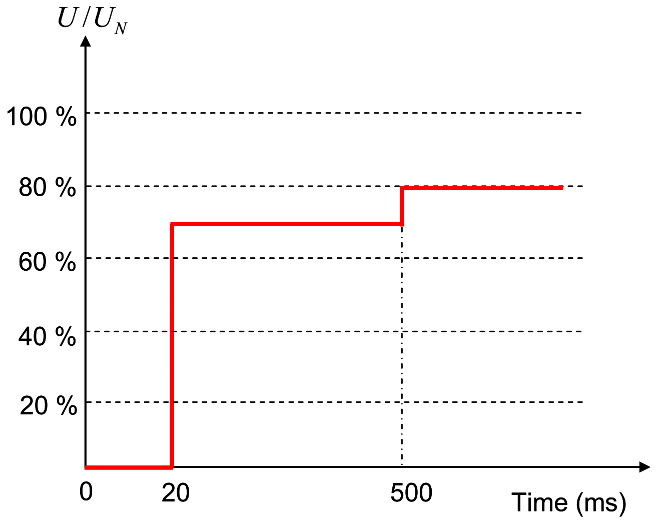


Fig. 6.9 CBEMA/ ITI curve [37]

6. 4. Frequency control contribution from DG

In a power system due to no electricity storage the generation and consumption at any time must be balanced. The imbalance will result in frequency excursion. There is always a small variation in the power balance due to variations in generation and load. But due to large inertia of the synchronous generator based power plant, the frequency fluctuation is kept small. Frequency should be maintained as constant as possible within acceptable limit for satisfactory operation of electrical power system. This limit varies between countries, with some countries having variation of ± 2 from nominal frequency. In Germany the frequency tolerance is very tight with the frequency tolerance being only 200 mHz of the nominal frequency.

6.3.1 Frequency control of a power system

In conventional power system the response of a power system with synchronous generators (SG) to a change of power balance can be divided to three stages. These three stages are illustrated in Fig. 6.10.

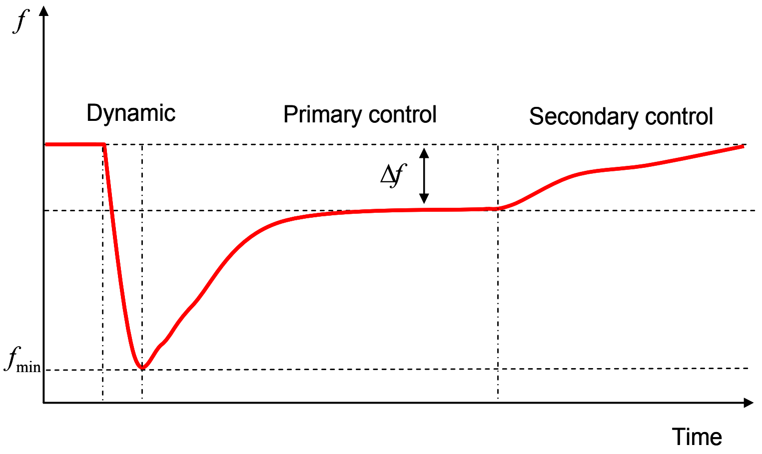


Fig. 6.10 Typical power system frequency response

The first stage is the duration before the frequency controller is not yet activated. In this short duration SG absorbs or releases their kinetic energy resulting in changing of frequency. This response is called inertia response and is determined by equation of movement of the power system. In the second stage, the controller is activated after frequency excursion reaches a certain limit. This second stage is called primary frequency control and during this period, prime mover input is changed. After the power balance is stored from primary frequency control action the power system settles at a frequency below its nominal frequency. Secondary frequency control comes into action to reduce this steady state frequency error and brings back the power system frequency to its nominal value.

6.3.2 Contribution of DG units to frequency control

Until now DG connected to LV network is prohibited to participate in frequency stabilisation. This restriction is expected to be lifted in the future when DG penetration is large. With large penetration, some conventional power plants could be replaced by DG so the task of frequency stabilisation previously done by conventional power plants must also be replaced by DG. The challenge is that most of the promising DGs are interfaced to the electrical network through power electronic converters. These DGs are considered as inertialess generation units. As mentioned previously the inertia of the generation units is important to keep the frequency fluctuation small.

6.3.3 Contribution to inertia response

In order to contribute to inertia response DG must have inertia but DG powered by micro turbine and fuel cell interface to grid through PEC and sometimes these two DGs are considered as inertialess. DG unit such as MTGS, however, has inertia from its rotating mass but it is hidden behind its PEC. This inertia, however, can be made available by implementing additional control loop in its system controller. The power that can be absorbed or released is according to [72]

$$P_{ine} = 2H_{DG}S_{DG}\omega_G \frac{d\omega_G}{dt} \qquad (6.\ 3)$$

where H_{DG} is inertia constant of DG, S_{DG} is nominal apparent power of DG and ω_G is the grid frequency. The value of inertia constant for MTGS retrieved from the literature is summarised in Appendix A.4.

6.3.4 Contribution primary frequency control

When DG unit has to participate in frequency control it must be able to increase or decrease its active power generation. For DG units powered by renewable energy sources this is generally not possible because they are normally operated at maximum available power. DG units such as MTGS and FCGS however have potential to be used in frequency control. As long as they are not running at full power capacity they can participate in primary frequency control. The question is only how fast active power can be changed. Some values found in various literatures are listed in Appendix A.5 for MTGS and Appendix A.6 for FCGS.

6.3.5 Case study of frequency support with DG

Even though it is possible to extract P_{ine} from DG it is expected no significant contribution will be seen in the power system due to very small inertia constant of DG so it will not be demonstrated here. DG operation with conventional SG inside a small portion of distribution network is the best way to show the contribution of DG in performing frequency control. Operating part of power system in a small grid is likely the direction of power system in the future. This small network is called Micro Grid [31] and the network is built as illustrated in Fig. 6.11. The network comprises one DG coupled to the grid through PEC and one conventional SG. The sharing of the generation capacity of this network is 60% from SG and 40% from DG. In this small network instead of controlling frequency in three stages as performed in the conventional power system, frequency control is performed only in two stages. DG here only contributes to primary frequency control by providing temporarily additional active power to help frequency stabilise. When the frequency returns to predisturbance value, DG stops providing additional active power.

The respective additional active power given by frequency control loop is to be added to the reference active current during frequency stabilisation considering frequency droop characteristic. This additional loop as shown in Fig. 6.12 is added to the standard DG active current calculation. The additional active power is calculated by adding two parts. The first part is the scaled frequency error multiplied by gain of k_f which is given by

$$k_f = \frac{\Delta p}{\Delta \omega} \tag{6. 5}$$

with Δp and $\Delta \omega$ being the values extracted from the frequency droop characteristic shown in Fig. 6.12. The second part is given by the derivative controller. These two are added together resulting in additional active power to be fed by DG.

For comparison three cases are simulated.

- In the first case, DG is operating with standard PQ controller delivering constant active power while the task of frequency regulation is performed totally by SG.
- In the second case the DG is equipped with continuous frequency control loop (frequency control 1).
- In the third case dead band is included inside frequency control loop (frequency control 2).

For the simulation case, initially SG is delivering 0.65 p.u. of its active power while DG is constantly generating 0.8 p.u. of its active power. At time t = 25 s, additional load is switched on resulting unbalance between the load and generation. The simulation result showing the frequency and power output from SG and DG is depicted in Fig. 6.14.

With constant power control, DG does not respond to the frequency changes. It constantly delivers its reference active power, leaving SG to perform the generation-load balancing. The frequency as seen in Fig. 6.14 finally returns to nominal value after 15 sec. In the second simulation case, DG changes its active power output to help balance the generation-load responding to the changes of frequency. When frequency returns to its nominal value, DG active power returns to predisturbance value. It is clearly seen that with DG participation, frequency deviation is significantly reduced and frequency restoration time is smaller. In the third case, frequency deviation and restoration time are smaller compared to the first case but not as significant as evident in the second case.

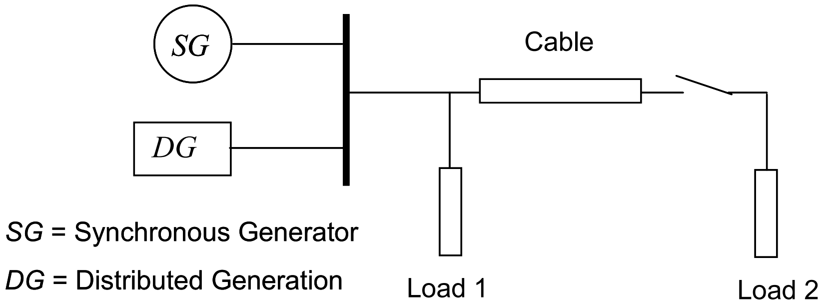


Fig. 6.11 Test network for frequency stabilisation study

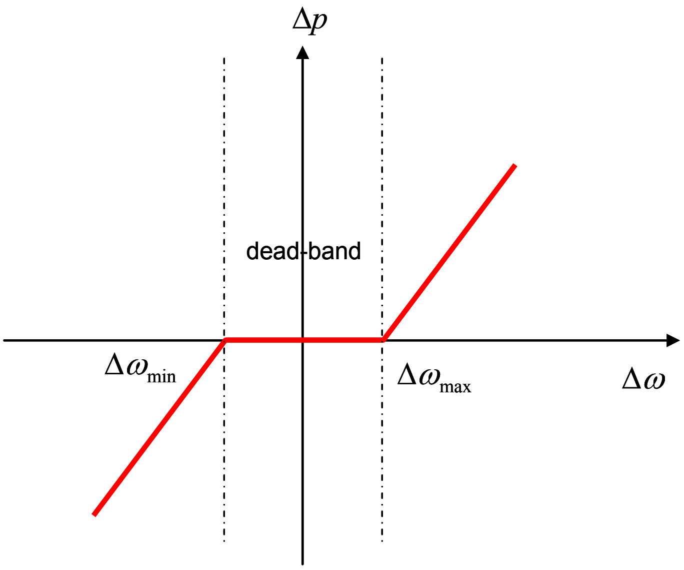


Fig. 6.12 Frequency droop characteristic for DG frequency control

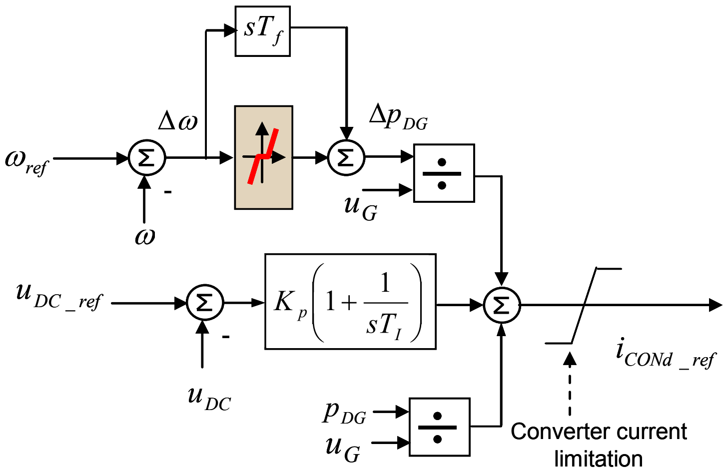


Fig. 6.13 Frequency control loop for case 2 and case 3

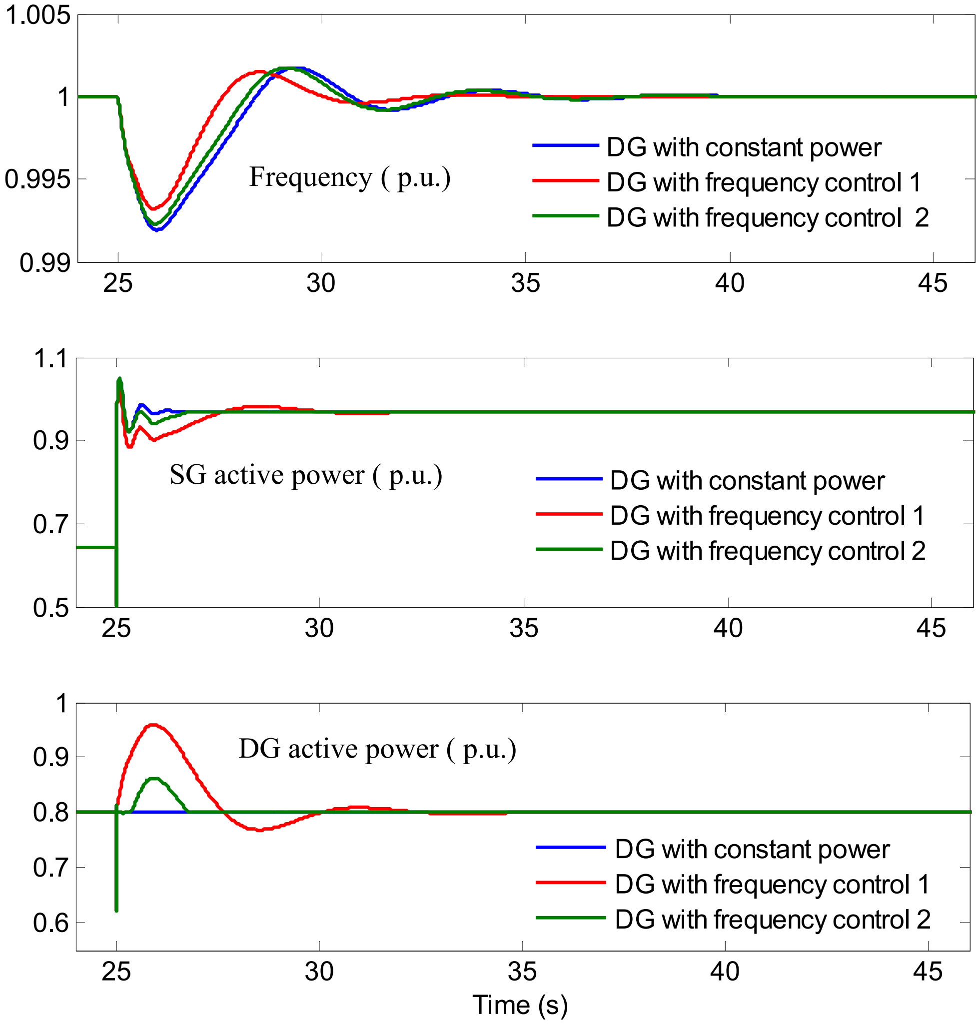


Fig. 6.14 Simulation results for frequency stabilisation study

6. 6 Conclusion

This chapter explores the contribution of DG in supporting voltage and frequency inside distribution network. It has been shown through simulation that voltage profiles in the network can be improved by allowing DG to participate in voltage regulation. During an emergency condition, reactive support from DG has also been shown to be able to increase the voltage. For the frequency stabilisation, the effectiveness of different control strategies is compared. Continuous frequency control is evidently more effective compared to the controller with deadband range. Clearly the studies indicate that DG coupled to the grid through power electronic converter has great potential to positively contribute to power system voltage regulation and frequency stabilisation. The effectiveness is however subjected to control strategy embedded in the DG controller.

Chapter 7

Stability of Power System with Large Penetration of Distributed Generation

7. 1 Introduction

This chapter analyses the most important type of power system stability with massive penetration of DG in a power system operating parallel with a large RES power plant. The study is performed in a hypothetical power system network envisioned in the future which contains a large number of DG. Network's stability when subjected to disturbances is compared with different levels of DG penetration.

7. 2 Futuristic power systems

Power system operation and control are shifting from conventional grid to Smart Grid operation. In achieving Smart Grid concept, a large number of distributed generation units are required in the distribution network. DG units are expected to be involved in demand participation, providing ancillary services such as regulating the network voltage and supporting the network during critical time due to fault or sudden changes of load. In order to positively supporting the grid in the ways mentioned previously, DG sources must be reliable, dispatchable and meeting various other operating criteria. These needed characteristics could be provided with DG interfaced to the electrical grid through power electronic converter. It is envisioned that future power systems will have a large number of power electronic based DG connected to LV network as illustrated in Fig. 7.1. With this large number of penetration, some conventional power plants will be dismantled and their tasks will be shouldered by DG and RES [5-7].

The sharing of generation among conventional power plant, large RES power plant and DG is in fact already realised in many European countries. In Germany for example, by the end of 2007, 22.2 GW of wind turbines and 3.8 GW of photovoltaic systems had been installed. Combining with other energy sources including hydropower and biomass plant a total of 34 GW RES has been installed [73]. This magnitude of penetration is considered significant comparing to the Germany load demand of 40-80 GW. This DG and RES can constitute more than 50% of the total power generation when the weather condition is optimum.

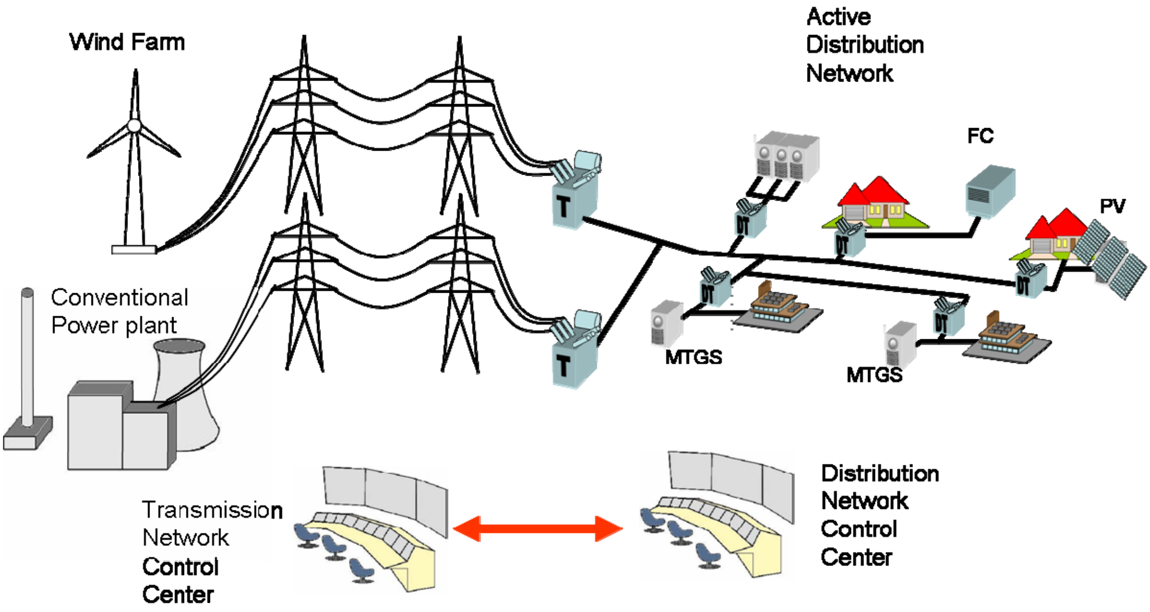


Fig. 7.1 Futuristic power system [6]

7. 3 Power system stability studies with DG and RES

With this large number penetration, some conventional power plants will be dismantled and the supplied power will be replaced by DG and RES. Different characteristics of DG and RES (discussed in Chapter 3) in comparison to conventional power plant, created a lot of concern on power system network operation and control. This concern had sparked research on the topic of stability of a power system network with the penetration of DG [74-77]. It was concluded from those research works that DG penetration improves the stability of power system if they are properly sized and located. In these studies, the old grid code is considered where DG unit will be disconnected if the voltage at the point of connection goes below 80 % [75] or 85% [74,76,77]. The disconnection, however, creates another disturbance to the network having already gone through a critical situation. If DG penetration is significant as expected in future power system which is termed Smart Grid, there is substantial loss of active power supply inside the network and this strategy will prolong the restoration of power system to equilibrium operation.

Due to the substantial penetration of DG and RES in recent years, new requirements are codified as grid codes in Germany require all generators connected to HV [25]and MV [26] level to remain connected to the network up to 150 ms even if the voltage at the point of connection reaches zero. This applies for both conventional power plant and also generation unit interfaces to the grid through PEC. During this fault ride-through, the generation units coupled to the grid through PEC also need to provide a network a reactive support with a specific characteristic [26]. For generation connected to LV network this ride-through requirement has not yet been imposed but it is expected in the future.

Even though the PEC based DG considered is 100 % in [75] while only a proportion in [74,76,77], the short circuit current limiting capability and injection of reactive current of the PEC based DG was not considered in those study. During a disturbance, current output of the PEC based DG could be limited with the current limiting circuit. This magnitude of maximum current depends on the withstand capability of the semiconductor devices against temperature and the value is normally 1.5 p.u. of the converter rating. Decoupling control employed in the converter also makes it possible for the reactive current to be controlled independently to meet the requirement imposed by new grid codes.

Different characteristics mentioned above indicate the need for further studies of impact on power system with a large number of DG integration. A more accurate model of DG should be used and this is possible with the capability of current simulation software and more advanced personal computer technology available today. In this chapter, stability of power system with substantial penetration of DG is assessed. To represent the present situation a wind farm is considered in the study. New German grid codes requirement are considered for conventional power plant, wind farm and DG units respectively. The most essential stability classes will be analysed.

7. 4 Generator fault tolerance and grid codes

In a large interconnected power system network, each generation unit must participate in maintaining the security and reliability of the power system which it is connected to. Each unit must have a capability to recover voltage and remain in synchronism with the power system after a disturbance. In a future grid in addition to this capability, each generation unit must also have a capability to ride-through a fault. This fault ride-through (FRT) requirement is depicted in Fig. 7.2 for synchronous generator [25]. As depicted in the Fig., the unit must remain connected to the grid even if the voltage at the point of connection reaches zero for up to 150 ms.

For non-traditional generator which includes generation units interface to the grid through PEC, the requirements are different and are depicted in Fig. 2.7 for the unit connected to HV network and in Fig. 2.8 if it is connected to MV voltage level. But the similarity is in the FRT requirement for the first 150 ms after the occurrence of fault. PEC based generation must also remain connected to the grid even when the voltage at the point of connection reaches zero value for up to 150 ms.

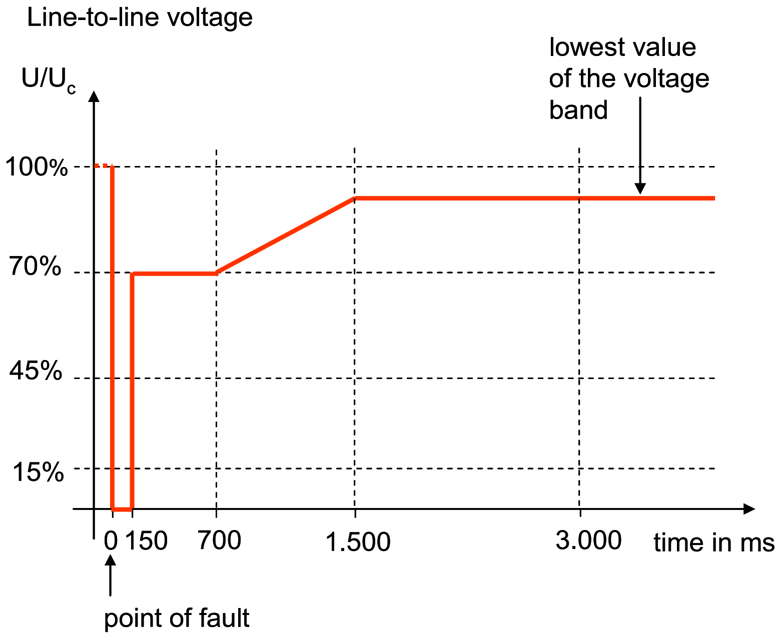


Fig. 7.2 HV FRT requirement for SG [25]

For generators coupled to the power system network using PEC additional requirements are imposed. During the FRT, the generator is demanded to inject reactive current with the gain of two as depicted in Fig. 2.9. This reactive support is supposed to be available within 20 ms after a fault was detected and supposed to be added to the actual reactive current from steady state operation. When the voltage has already returned into the deadband range, this reactive support must still be continually provided for further 500 ms. If the voltage however rises above 110%, an inductive reactive current in opposition to capacitive is demanded to reduce the grid voltage.

In Germany, DG with rated capacities from 100 kVA up to 10 MVA is directly connected to the MV network (10kV to 35 kV). These DG units include large PV plants, CHP units and single or several wind turbines. For these generators grid code for medium voltage level depicted in Fig. 2.8 applies. For the generation unit connected to LV, FRT is still not required but in this study, the requirements as depicted in Fig. 2.8 and Fig. 2.9 are assumed.

7. 5 Power system description

Power system network considered is similar to the network used in [75]. This network is a reduced network which is simplified from 16 machines power system network, PST16 [78]. This simplified network as depicted in Fig. 7.3 comprises two HV levels 380 kV and 110 kV and are fed by two conventional power plants connected through step up transformer to 380 kV bus. The area which is circled and colored in green is where the distribution network with DG is connected. For the purpose of investigating the influence of huge DG penetration, six typical distribution networks illustrated in Fig. 6.1 are connected to the 110 kV busses in this area.

7.3.1 Synchronous generator

Synchronous generator is modeled as fifth order model with the rated voltage of 15.75 kV. Typical parameters of thermal units are used. For speed governors and excitation systems, standard IEEE regulators [52] are used.

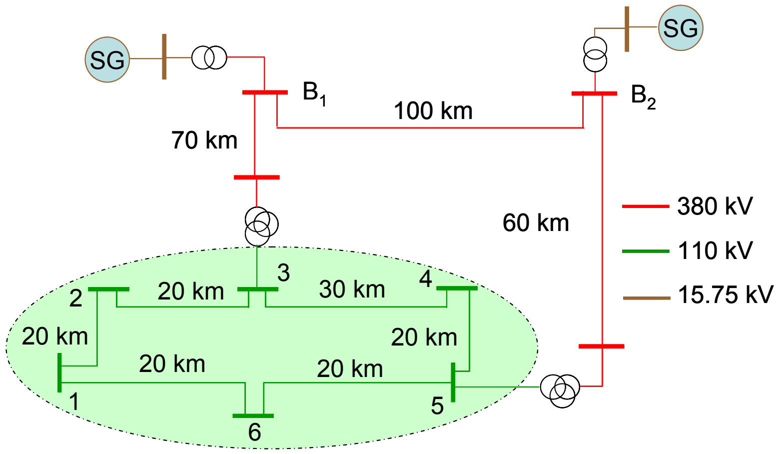


Fig. 7.3 Test power system network [75]

7.3.2 Distributed generation

In achieving the Smart Grid concept, DG units are expected to be involved in demand participation, providing ancillary services such as regulating the network voltage and supporting the network during critical time due to fault or sudden changes of load. In order to positively supporting the grid in the ways mentioned previously, DG sources must be reliable, dispatchable and meeting various other operating criteria. DG technologies that suit this requirement are DG coupled to the grid through PEC. For this type of DG, there is no direct coupling between grid and DG sources. The dynamic of the DG is dominantly influenced by its converter and this is already justified in the earlier chapter of this thesis. For that reason MTGS dynamic model introduced in Chapter 4 is used to represent this type of DG. MTGS is chosen as it is one of the most promising DG technologies to be employed in realising future Smart Grid. Layout of the MTGS model utilised in the study has already been depicted in the previous Chapter in Fig. 5.1 so it will not be shown here.

This dynamic model is tuned to follow the requirements of the grid code discussed in Chapter 3 and this DG technology has been shown capable in meeting new grid code requirements as demonstrated in Chapter 5 and reference [79]. The way DG model is connected into the distribution network is as depicted in Fig. 6.1. In this distribution network, DG is connected to the LV level on the secondary side of distribution transformer. Six similar distribution networks are connected to the 110 kV busses in test power system network depicted in Fig. 7.3.

7.3.3 Wind farm

In Germany, by the end of 2007, 22.2 GW of wind turbine had been installed [73] and comparing to German load demand of 40-80 GW this amount is considered significant. With this magnitude of penetration, performing stability study without considering wind turbine is considered unrealistic. In Germany, a few wind turbines operated as a wind farm with rated capacities from 10 to 200 MW is fed directly into the 110 kV level. Typical layout of wind farm is shown in Fig. 7.4. In this study, 25 MW wind farm comprises five 5 MW DFIG wind turbine as introduced in reference [80] is considered and connected to node 2. DFIG is considered as nearly all modern large wind turbines are based on this technology. Compared to the wind turbine using PMSM interface to the grid through full size converter, this DFIG technology posseses an advantage in using smaller and cheaper converters but still posseses reactive power controllability. The layout of DFIG wind turbine is shown in Fig. 7.5.

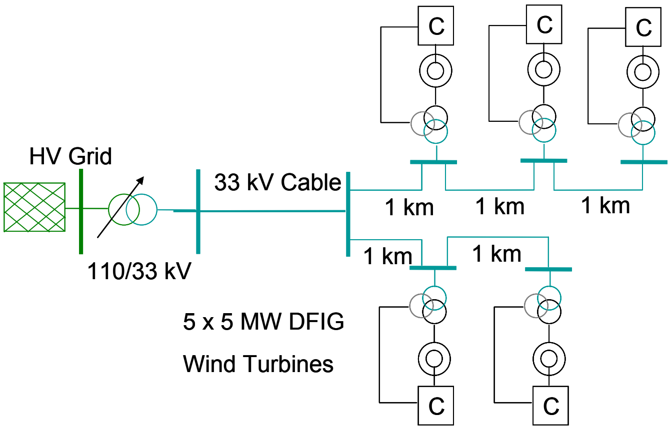


Fig. 7.4 Layout of the wind farm [80]

7. 6 Response of generation units to fault

SG, DFIG wind turbine and MTGS due to difference in technology respond differently when the voltage at their connection node reduces sharply due to fault inside the grid. Fig. 7.6, Fig. 7.7 and Fig. 7.8 respectively depicts the response of the SG, DFIG wind farm and MTGS when power system network in Fig. 7.3 is subjected to temporary self-clearance three phase fault at bus B_2 for 150 ms. During the fault and after the fault no component inside the network is disconnected. During the event of voltage dip at the point of connection, all generators are seen to inject lower active power. This is due to rated power which cannot be transferred to the grid due to a drop in the grid voltage. For SG, this behaviour is common and is well understood. For DFIG windfarm and MTGS, it can be observed there is a large increase in reactive power generation during this low voltage event. This is to comply with the requirement of new grid codes to inject reactive power. During this time the priority is given to reactive component with the curtailment of active power. After the fault is cleared, all generators return to their prefault operating point. The duration and dynamic of the generators in restoring the output to prefault value are quite different.

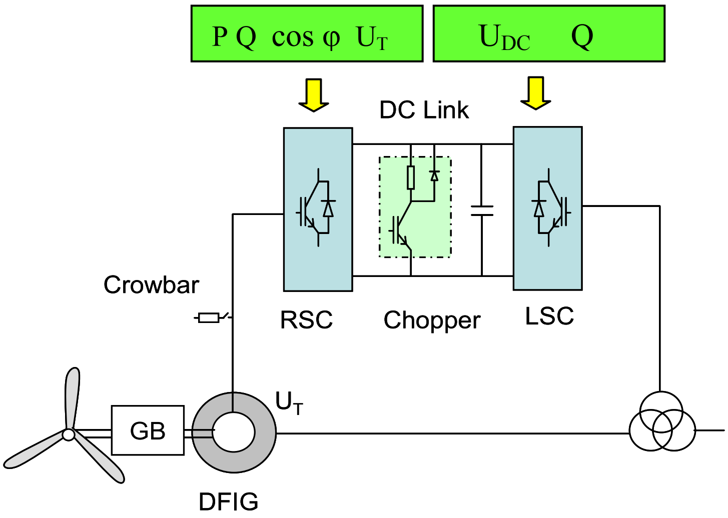


Fig. 7.5 Layout of the DFIG wind turbine [80]

For SG, there is a power surge then followed by the oscillation of active power which damps out approximately in 4 seconds. For DFIG wind farm, there is no oscillation of active power seen with time taken to restore to prefault condition less than 1 second. For MTGS the power is restored almost immediately. This is due inertialess nature of this DG technology with combination of advanced control employed in its PEC.

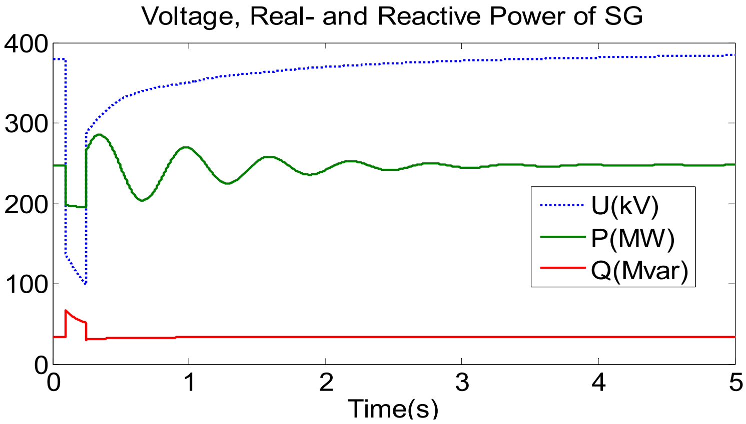


Fig. 7.6 Voltage and real-reactive power of SG

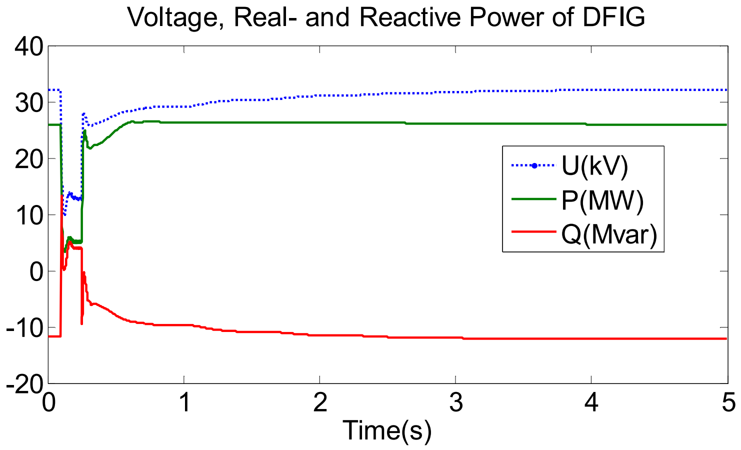


Fig. 7.7 Voltage and real-reactive power of DFIG wind farm

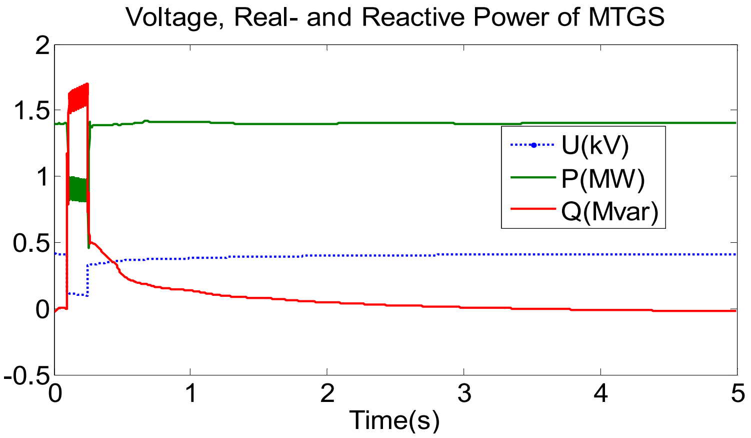


Fig. 7.8 Voltage and real-reactive power of MTGS

7. 7 Transient stability

Transient stability is defined as a capability of the power system to remain in synchronism after subjected to a severe transient disturbance such as short circuit or loss of large loads or generations [52]. It is also referred as first swing stability. Initial operating condition of the system, as well as the type, severity of the location will affect this transient stability. After a disturbance, the power system oscillates together and depending on the system damping, the oscillation will damp out in a certain period of time.

7.5.1 Transient stability with DG

To access the transient stability, a few cases are investigated. In the first simulation setup, no wind farm is considered. In the first case (case 1), power system is operated without DG. Case 2 considers maximum penetration by DG without many changes necessary on the existing infrastructures and control devices inside a network. DG penetration in Case 2 is 40 %. In a future power system network under Smart Grid, distribution network is expected to be an active network where it is not only importing active power but also exporting active power when required. This requires penetration of larger than 40 % of DG. This amount of penetration makes it possible to operate the whole distribution network as a cell or some portion of the network as a Micro Grid which are two concepts of DG control under Smart Grid concept. This envisioned operation is considered under Case 3 and Case 4. Summary of the cases simulated is tabulated in Table 7.1.

Most widely used method in assessing transient stability is the time domain simulation method which is adopted in this study. The excursion of power angle between synchronous generators is used to evaluate the transient stability. Fig. 7.9 depicts the change of the power angle of the synchronous generator following a fault which occurs at bus B_2. The fault is assumed as a self cleared fault of 150 ms. 150 ms is chosen as the grid code considered in the study requires all generation units to remain connected for the disturbance occurring up to 150 ms. It is also assumed no parts of the network are disconnected during the fault.

Table 7.1 Simulated cases of DG penetration

Cases	Description
Case 1	DG Penetration is 0 %
Case 2	DG Penetration is 40 %
Case 3	DG Penetration is 80 %
Case 4	DG Penetration is 110 %

From the observation of the first swing, addition of DG units reduces the magnitude of the maximum angle deviation. This reduction seems proportional with the penetration level. This indicates that addition of DG improves power system transient stability. This is consistent with the result presented in [75].

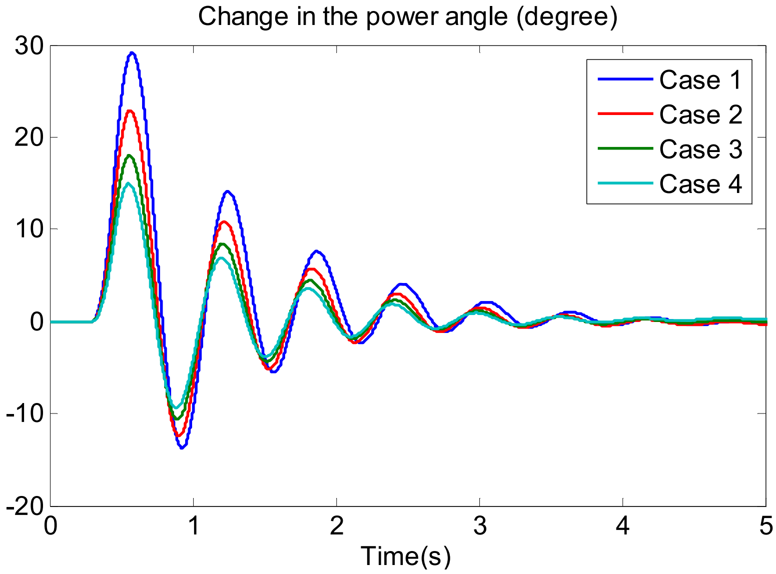


Fig. 7.9 Change of power angle against DG penetration

7.5.2 Transient stability with wind farm and DG

In the second simulation setup, 25 MW wind farm is considered. For the base case again the power system network only fed by conventional generator is simulated as Case 1. Power system with wind farm but without DG is considered in Case 2. In Case 3 power system is fed by conventional synchronous generator and wind farm with 40 % penetration level of DG. Penetration of DG of 110 % is simulated in Case 4. All simulated cases are summarised in Table 7.2.

Table 7.2 Simulated cases of wind farm and DG penetration

Cases	Description
Case 1	No Wind farm and no DG
Case 2	25 MW Wind farm with 0 % DG
Case 3	25 MW Wind Farm with 40 % DG
Case 4	25 MW Wind Farm with 110 % DG

First swing of the rotor angle is again observed from the simulation results depicted in Fig. 7.10. The addition of wind farm with DG units reduces the magnitude of maximum angle deviation. This reduction in power angle is as previously without windfarm proportional to the penetration level of DG. This indicates that combination of DG and wind farm does not lead power system to instability.

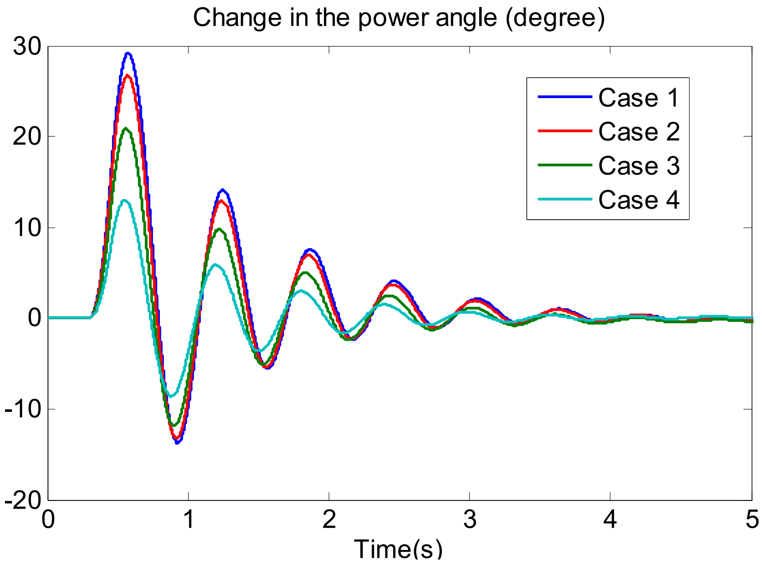


Fig. 7.10 Change of power angle against DG penetration considering RES

7.5.3 Transient stability with and without wind farm

In Fig. 7.11 the deviation of power angle is compared for the same DG penetration level. It is clearly seen that power system network is more transiently stable with the combination of wind farm and DG as opposed to only DG. This clearly indicates that the network has more capability to withstand larger disturbance with the inclusion of DG and windfarm.

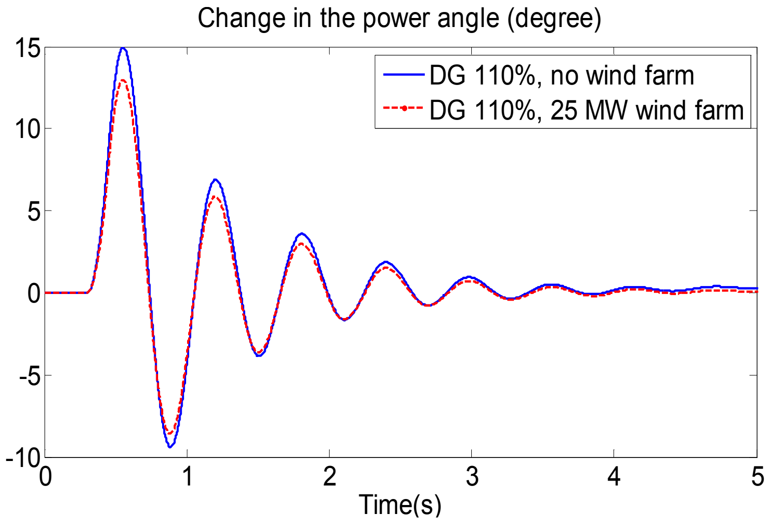


Fig. 7.11 Change of power angle with and without wind farm

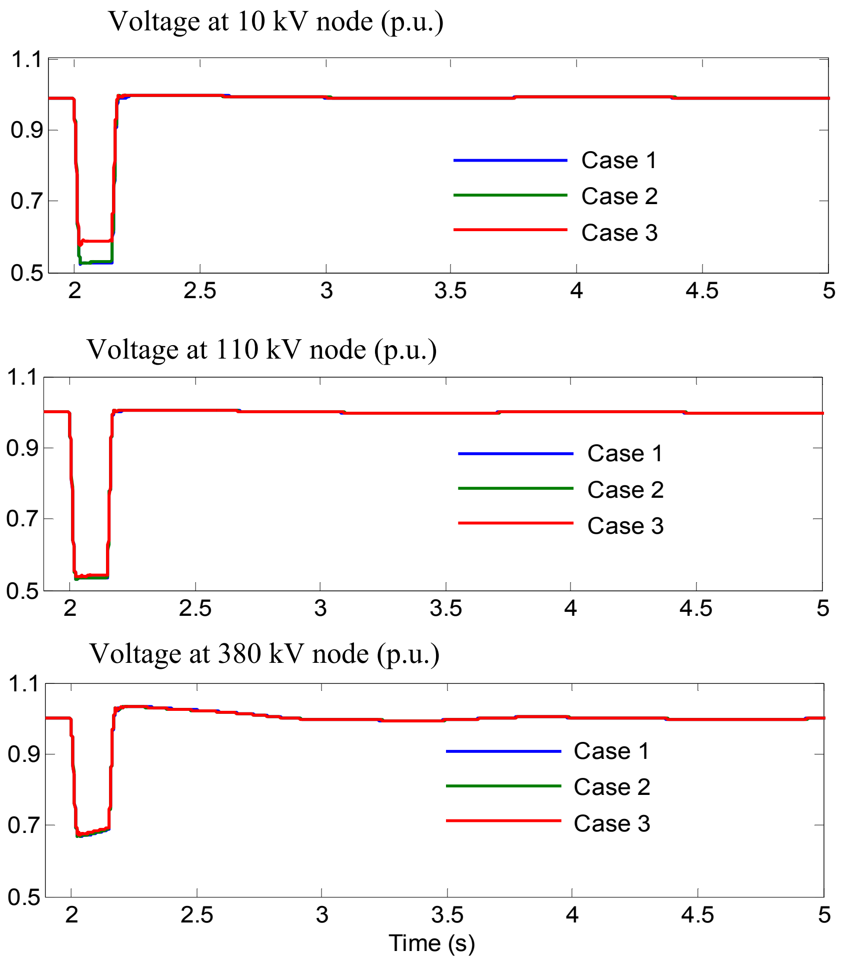
7. 8 Voltage stability

Another critical type of stability problem is voltage stability. Voltage stability covers a wide range of phenomena. It is sometime referred as load stability in some literatures. It is a sense of the ability of power system to maintain the voltage at all nodes within acceptable limit following the disturbance. Voltage instability mainly involves load and the means of voltage control. After power system disturbance, dynamic load has a tendency to restore its power after disturbance by adjusting its operating slips. This action will draw more reactive power from the network leading to further voltage drop in the network. If this required reactive power is beyond the capacity of the generation units and transmission system, voltage instability will take place [52].

A power system at a given operating point is considered voltage stable if after being subjected to disturbance the voltage at all nodes approach the post disturbance equilibrium values. To ascertain voltage stability the generator voltage and a voltage near load area following the faults are compared for various cases. Three cases are compared. For all the cases DG penetration is 80 % operating in parallel with the wind farm.

- Case 1: In the first case DG is disconnected when the voltage reduces below 0.9 p.u. of the effective value and is reconnected 500 ms after the fault is cleared. In this first case, there is no reactive support given by DG.
- Case 2: In the second case, DG is set to deliver constant active power and remain connected to the grid. During LVRT, DG injecting only active power with no reactive support is provided to the grid.
- Case 3: In the third case, DG is set to follow the grid code requirement introduced in Fig. 2.9. After the voltage level drops below 0.9 p.u., reactive support is given to the grid and continues for another 500 ms after the fault is cleared.

This power system voltage at the node close to synchronous generator (node B_1), 110 kV level near consumption area (node 5) and LV node inside distribution at DG connection node are compared in Fig. 7.12 for all three cases. From the figure there are no significant changes on voltage dynamics for three different cases seen at HV level. Close to the point where DG is connected, some improvement is evident especially at the voltage level during the fault. To clearly see the difference, voltage during the fault and immediately after the fault is zoomed in to see clearly the contribution of DG during and after the fault as illustrated in Fig. 7.13. It is seen that DG increases voltage magnitude for about 6 % even without providing reactive support. In helping voltage recovery, DG is seen to help the voltage recover after the fault. It is however surprising that the voltage dynamics of the power system does not have substantial difference with the reactive power injected from the DG compared to the case where DG is only providing active power. It is however realized that by allowing DG to continuously remain connected and injecting its power, power system is more voltage stable when subjected to faults.

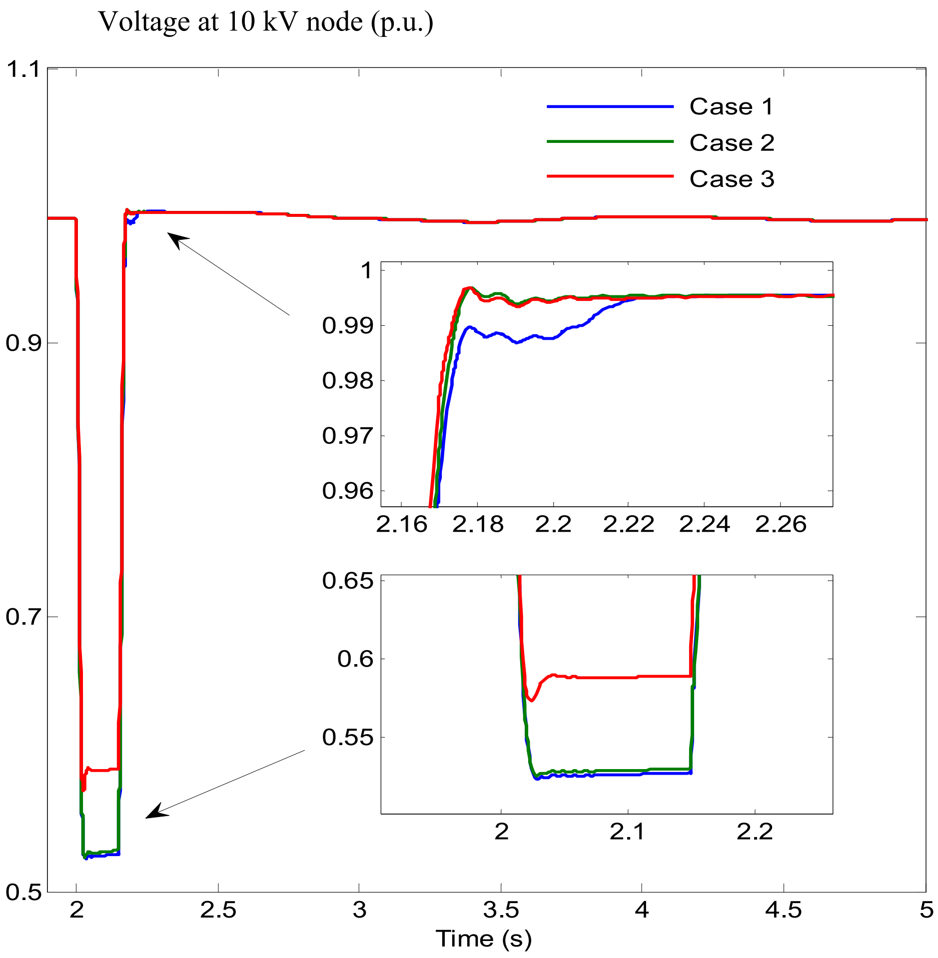


Voltage at 10 kV node (p.u.)

Voltage at 110 kV node (p.u.)

Voltage at 380 kV node (p.u.)

Fig. 7.12 Voltage magnitude at various nodes



Voltage at 10 kV node (p.u.)

Fig. 7.13 Voltage at 10 kV node

7. 9 Conclusion

This chapter investigates the influence of DG on two most vital stabilities issues. The study considers the massive penetration of DG operating in parallel with a wind farm. All generations inside power system under study is set to operate according to Germany’s new grid code. The inclusion of wind farm inside the power system network is considered as it represents the current scenario in power system industry. The study indicates transient stability is greatly improved with larger penetration of DG. For voltage stability improvement however the greatest impact is seen inside a distribution network with a small enhancement seen inside the HV network. But the concern on stability of power system network with the addition a large amount of DG inside LV network is however answered. This large penetration will not lead the power system network into instability when it is subjected to large disturbance but in fact increases the power system ability to withstand larger disturbances.

Chapter 8

Predictive Var Management of Distributed Generation

8. 1 Introduction

This chapter presents and describes a smart predictive technique for managing reactive power from a number of DG units connected to LV buses in a distribution network. The technique applies an optimisation process in the first stage and in the second stage the procedure is generalised using artificial neural network (ANN). The ANN is trained to replace the role of optimisation process which is repetitive in nature and time consuming. The technique can speed up the time while scarifying a little accuracy. The objective is to develop an intelligent management tool that can be used to manage reactive power from a group of DG units for online management. This technique predicts the optimal reactive power for the next time step that needs to be supplied by each DG unit with the objective of minimising active power losses and keeping the voltage profile within the required limit.

8. 2 Reactive power management in distribution network

Future electricity network under Smart Grid concept must have an efficient management that will minimise line losses [7]. Integrating DG inside distribution network already reduces power losses because some portion of the required load current from upstream is substantially reduced, which results in lower losses through line resistance. Further reduction of losses can be achieved by intelligently managing reactive power from the installed DG [81].

Methods for managing reactive power from DG units in [82] coordinate reactive power from DG units locally with local voltage controller due to poor communication infrastructure in the distribution network. There is no coordination among DG units and voltage control devices are located remotely. However, under the concept of Smart Grid [6], with the existence of good communication facilities, DG units are suggested to be coordinated centrally with other voltage control devices [83]. Evolutionary optimisation technique is used in [86] to determine the optimal reactive power from DGs while coordinating the operating points of each individual voltage controller. However, optimisation is computationally expensive and this will limit the proposed technique for real time online application as required in a Smart Grid concept. In addition, complete system information is needed in carrying out such optimisation simulation.

The next section of this chapter will first envision future distribution network operation and control issues. Optimal reactive power as well as method in finding its optimal value will then be discussed and finally development of the controller is described and the performance of the controller is tested.

8. 3 Future distribution network

As depicted in Fig. 8.1, future distribution network is a Smart Grid which will be integrated with advance communication facilities which link all DGs, sensors and actuators with network control center. This integration will enable efficient decisions on how to operate the network in real time. It is envisaged that all voltage controller and DG inside distribution network will be coordinately controlled remotely by one control center as illustrated in Fig. 8.2. Network will be scanned by data acquisition device and the information be used to determine the optimal operation of all DGs and voltage controllers and optimal set-point will be adjusted remotely through communication link. In a day, assuming the network is scanned every 15 minutes, for twenty-four hours operation, the network is scanned for 96 times.

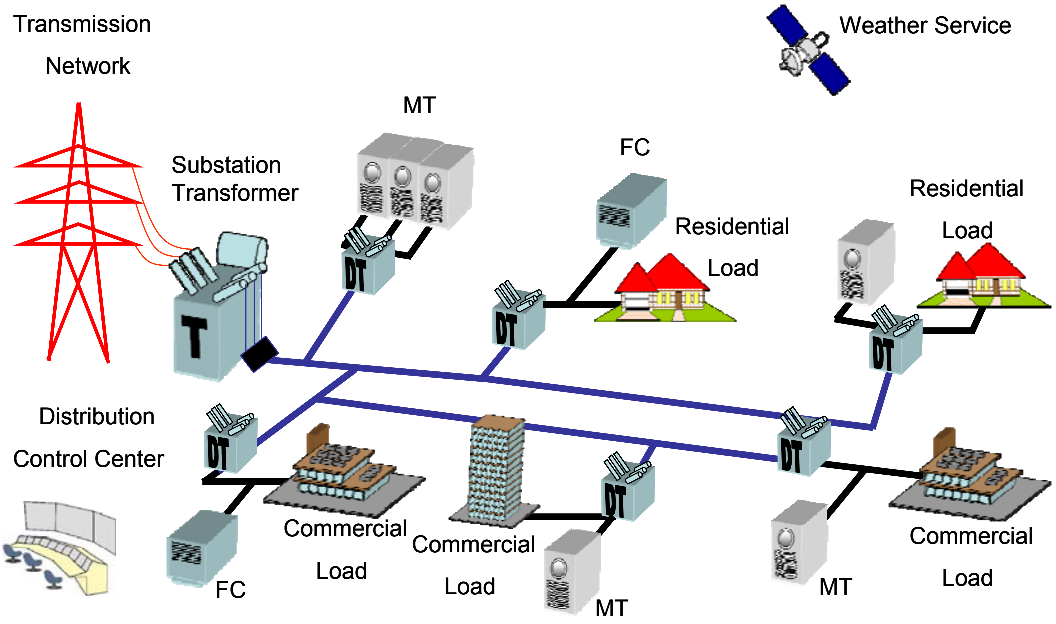


Fig. 8.1 Future distribution network [5]

In future electricity network is termed as smart, with information about system profiles expected to be available every 15 minutes. It is therefore suggested that instead of using one day ahead dispatch planning [84-85], it is performed every 15 minutes to determine the next 15 minutes power to be dispatched for each DG based on the projected forecast and real time data. In the future, with advance weather information services provided by satellite continuously, load forecast could be calculated in real time. With this approach any sudden changes in the weather condition can be considered in the management to make sure power system is operated optimally. Reactive power set-point given by optimisation process can be sent remotely by network operator manually or automatically.

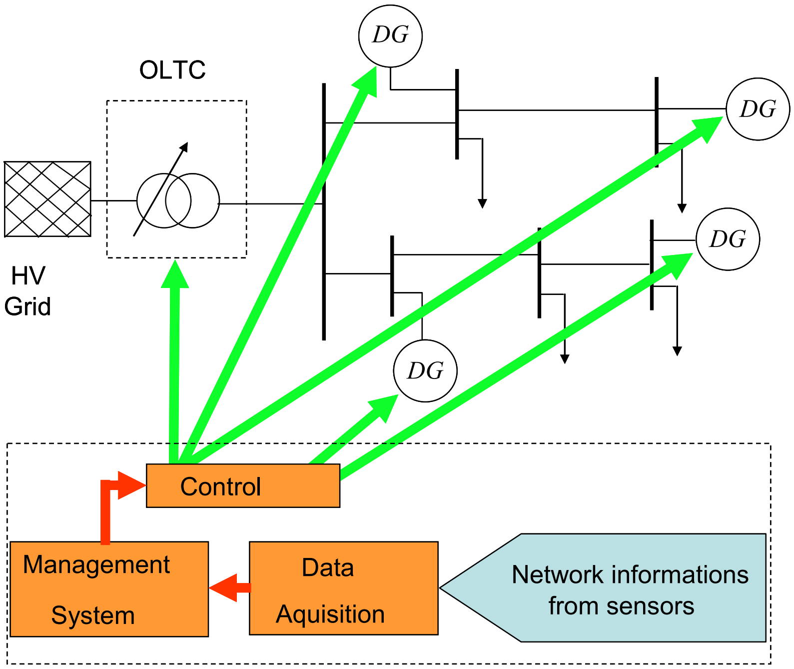


Fig. 8.2 Management approach of future distribution network

8. 4 Optimal reactive power from DG

Reactive power availability from each DG is already discussed in Section 6. 2 but the question is how much reactive power should be delivered from each DG. The other question due to reactive power from DG is to regulate distribution network voltage, how the voltage control is performed. Considering there is advanced communication link in the future grid, voltage control is suggested to be performed by coordinating the OLTC on substation transformer and available DG reactive power.

For determining optimal reactive power from DG and OLTC position, this optimisation problem can be solved by utilising optimisation algorithm. In performing optimisation process, objective function and constraints must be defined. For the objective function it is recommended that minimising active power losses is set as an objective function. The constraints are the allowable voltage range and available OLTC tap changer position. Decision variables here are DG reactive power and OLTC taps.

In mathematical equation the problem can be written as

$$\text{Min} \qquad \text{Ploss}\,(\mathbf{x})$$

Subject to

Transformer tap setting limits

$$a^{\min} \le a \le a^{\max} \tag{8. 1}$$

All bus voltage limits

$$u_i^{\min} \le u_i \le u_i^{\max} \qquad \forall i \in N_B \tag{8. 2}$$

DG reactive power limits

$$Q_{DG\_i}^{\min} \le Q_{DG\_i} \le Q_{DG\_i}^{\max} \qquad \forall i \in N_{DG} \tag{8. 3}$$

where N_B is the number of buses and N_{DG} is the number of DG units. Vector **x** contains control variables (8.1) and (8.3). The transformer tap setting is treated as a discrete decision variable while the DG reactive power limit is treated as a continuous decision variable. DG reactive power and transformer tap setting are treated as decision variables to be optimised with the objective of finding minimum power losses subjected to the constraints described in Eqn. (8.1), (8.2) and (8.3). But to solve the optimisation problem described before optimisation algorithm is required. There are many optimisation algorithms available but in this thesis, particle swarm optimisation (PSO) is utilised.

8. 5 Particle swarm optimisation

PSO is a population based search algorithm used to find the global optimal solution by a process motivated by social behaviour of swarms such as fish and birds searching for food. Algorithm is initialised by a population of random potential solutions called particles and a group of particles is called a swarm. Each particle in the swarm moves in over the search space with a certain velocity. This velocity is influenced by both particles' own flying experience and its neighbour flying experiences. PSO mentioned here requires parameter tuning which is difficult for someone who doesn't have experience working with optimisation algorithm. There is research going on developing optimisation tool which acts as a black box, meaning the user gives the input and will get the output. Tuning of parameters will be performed automatically by the algorithm. One of these algorithms is adaptive particle swarm optimisation (APSO) [87].

APSO is an extension of PSO which is free from parameter tuning. This parameter free stochastic optimisation algorithm has been shown capable of solving many power system optimisation problems which are nonlinear and discontinuous in nature [88]. For this algorithm only search space, objective function and stopping criterion need to be defined. In this algorithm, 'Tribes' comprises a group of particles moving together in search space to find local minimum. There are linkages amongst tribes where they exchange the information on their local minimum and decide global minimum. The tribes which contain more good particles compared to bad particles will be considered as good tribes while they are considered as bad tribes if otherwise. Each bad tribe will generate a new particle simultaneously and these new particles will form new tribes. This adaptation continues until certain requirements are met.

The distribution network shown in Fig. 6.1 is modeled in the power flow program winlf8 [89]. For every 15 minutes interval, historical load demand of a working day in summer [90], the load is distributed inside the network. Power flow is run using winlf incorporating Newton Rapson method while APSO is used to solve the optimisation problem. APSO is integrated inside winlf8 in such a way that addition of decision variables can be done easily.

8. 6 Distribution network power losses

Future distribution grid needs to be efficient where losses are reduced to a minimum value. Active power losses occur in the process of transporting electrical power, due to line resistance. An active power loss in the line depends on the magnitude of the current flows through the line and resistance of the line. Subjected to the number of lines available in the network, total active power losses is given by

$$P_{total}^{loss} = \sum_{ij} 3I_{ij}^2 R_{ij} \qquad \forall ij \in N_L \tag{8. 4}$$

where N_L is the number of the lines available in the network. In AC distribution circuit, due to electric and magnetic fields produced by the flow of time varying current, inductance and capacitance can be significant. When current flows through these two components, reactive power which transmits no energy is produced. Reactive current flow in the line contributes to extra power losses in addition to active power losses mentioned previously.

Integration of DG already reduced active power losses because some portion of power from upstream is already reduced. Losses reduction can be further reduced by controlling the voltage profiles in the network. In conventional practice, capacitor banks are added in the distribution network to control the flow of this reactive power. These capacitor banks can be switched in and out using voltage regulating relay to deliver reactive power in steps. The switching is however lowered power quality delivered to the customer as it leads to step changes in bus bar voltage. Even though this power quality problem can be reduced by switching smaller amount of capacitance at each step, this action however increases maintenance cost of switch gear and complexity of control equipment. Reactive power however can be controlled continuously using DG coupled to grid through PEC and the previously discussed power quality problem can be mitigated.

As DG is capable of providing reactive current, coordinating DG with other voltage controller devices in the network for voltage control is a strategy that can be applied. Loss reduction in distribution level will also reduce the losses in transmission network. This will lead to a reduction of fossil fuel combustion, air pollutant and green house gases. The need for providing spinning reserves can also be reduced.

8. 7 Optimal reactive power simulation results

For the distribution network depicted earlier, the voltage profile is compared between when DG is only generating active power and with the case when DG is delivering optimal reactive power. Without reactive power from the DGs, voltage regulation is performed entirely by transformer equipped with OLTC at the main substation. With the load curve of one day in summer season the voltage profile for every 15 minutes interval is calculated.

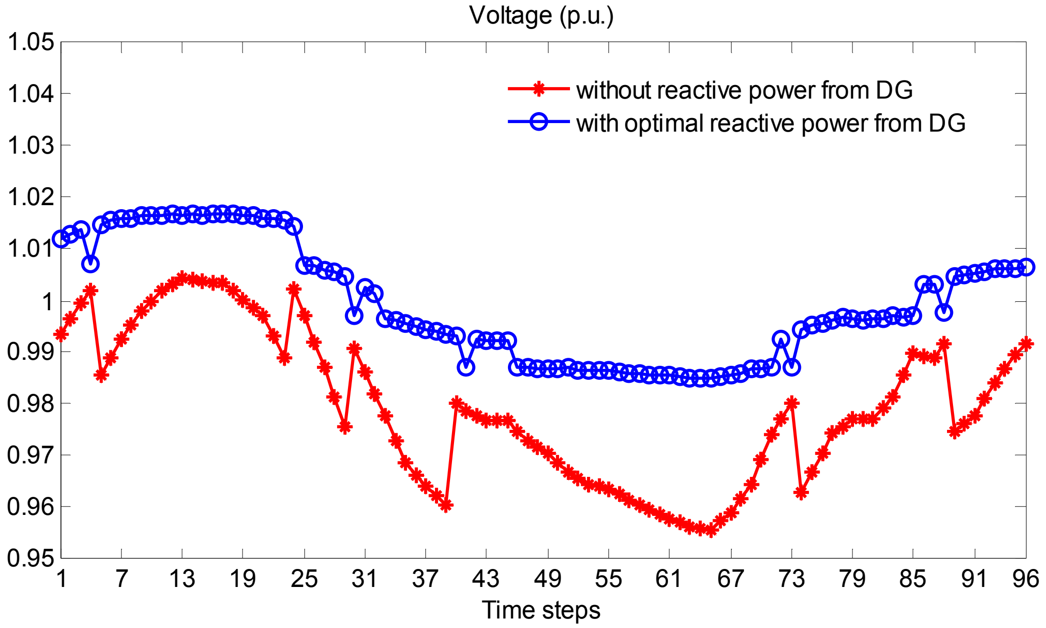


Fig. 8.3 Voltage at secondary side of transformer T12

Customer oriented system is used in the simulation where negative reactive power is capacitive while positive value is inductive. From the results displayed in Fig. 8.4, it can be seen that to meet the active power loss minimisation objective in some time steps, DG 12 needs to supply capacitive reactive power to the network while DG 4 needs to inject inductive reactive component. These requirements are dictated by the location of the DG units in the network. For example the farthest location in the network is where DG 12 is located. This location experiences the lowest voltage profile compared to the other locations.

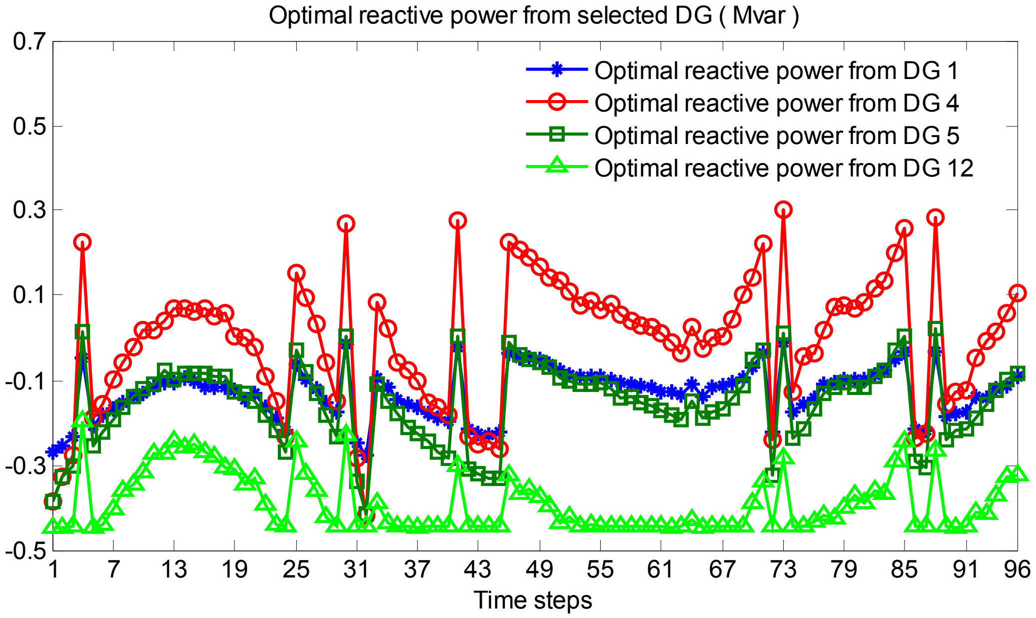


Fig. 8.4 Reactive power reference of 4 selected DG

The coordination of voltage control as previously mentioned is done by coordinating DG reactive power and transformer tap changer position. Fig. 8.5 shows the voltage correction achieved by tap changes which represent the change of tap position. Comparing the cases considered, with optimal operation, changes of tap is reduced from 15 to only 6 times. This is indication that this approach is effective as normally allowed tap changes of transformer in one day operation should be limited to below 10 times.

As the main objective is to centrally manage a group of DG units to reduce the active power losses, the comparison of active power losses with and without reactive power supply coming from DG is depicted in Fig. 8.6. In most of the time steps shown in the figure, at least 0.05 MW of active power losses are reduced when reactive power form DG is centrally managed. In some time steps, it can be seen that up to 0.1 MW of loss reduction is achievable. If all losses are accumulated, a substantial amount of reduction in active power losses could be achieved in one day operation. It also has to be kept in mind that this loss reduction in distribution network will also reduce the losses in the transmission network as well. If all distribution networks connected to transmission grid manage DG reactive power effectively, a substantial amount of losses could be reduced in the whole power system.

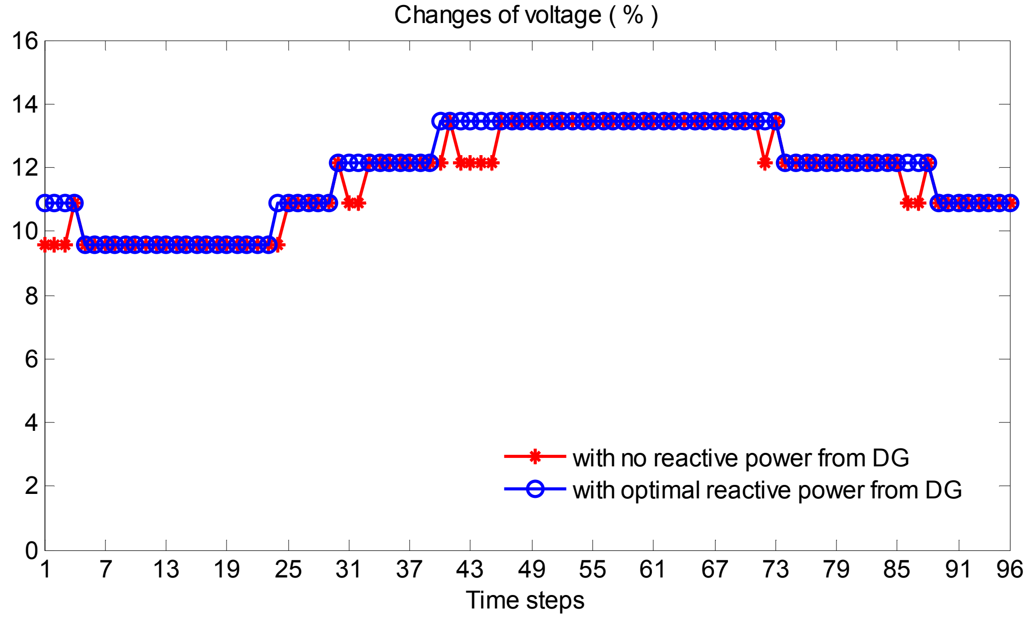


Fig. 8.5 Correction voltage by OLTC

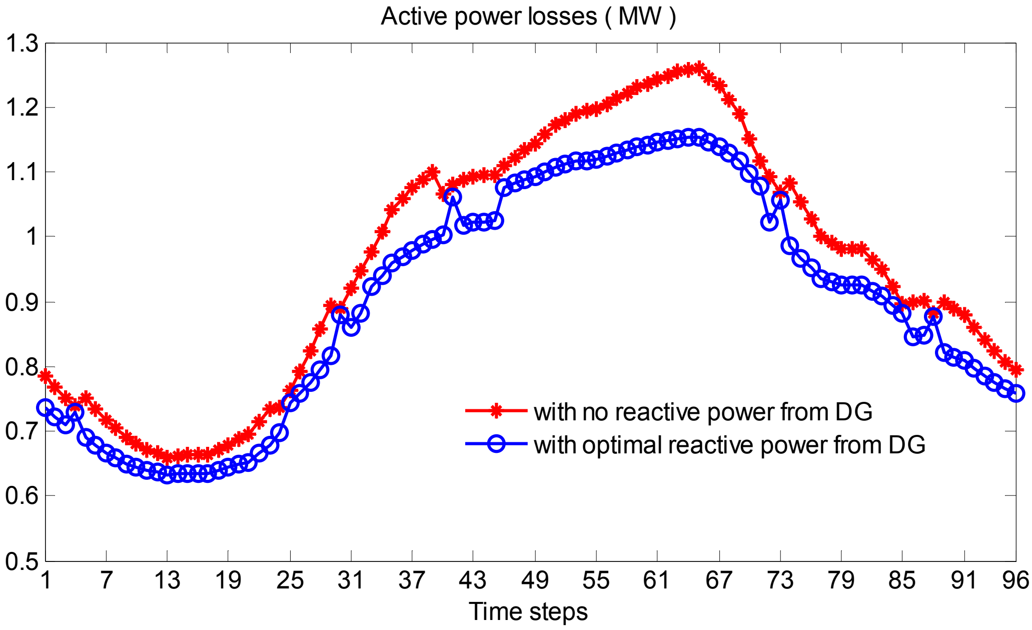


Fig. 8.6 Comparison of active power losses

8. 8 Predictive DG optimal var using ANN

Optimisation process for coordinating DG var and OLTC for voltage control with the objective to reduce power losses discussed in the preceding section is timely expensive and requires complete information of the network. This approach is therefore unattractive for online application management envisions in Smart Grid. To overcome the repetitive task of optimisation algorithm, ANN was introduced in [91] to replace the optimisation task which manages the DG unit operation. The objective was to reduce operational cost of DG unit subjected to fuel and electricity tariff. The ANN was trained using database extracted from genetic algorithm optimisation process and the results given by ANN were shown to be comparable with the results given by genetic algorithm. However, in the study, the ANN implementation was only for one DG unit. In next sections to follow, an intelligent predictive management technique for a group of DG units which is suitable for online application is presented. An ANN is trained to replace the task of optimisation process and it is used to predict the next time step optimal output of reactive power from a group of DG units. The management objective is to minimise power losses while maintaining voltage profile throughout the distribution network within the required limits. This fast and promising technique eliminates repetitive and time consuming process of optimisation simulation which has to be performed everytime the network loading condition changes.

8.9.1 Artificial neural network

Artificial neural network is algorithm composed of simple elements operating in parallel taking the inspiration from biological human brain. This is because in nature connection between these elements largely determine the network function. ANN can be trained to perform particular function by adjusting the values between the interconnection. Typically ANN is trained so that particular input leads to a specific target output. Fig. 8.7 depicts the process of training the ANN. The network is adjusted based on a comparison between output and target, until the network output matches the target. If properly trained, neural network can be used to solve problems that are difficult for conventional computer or human being [92].

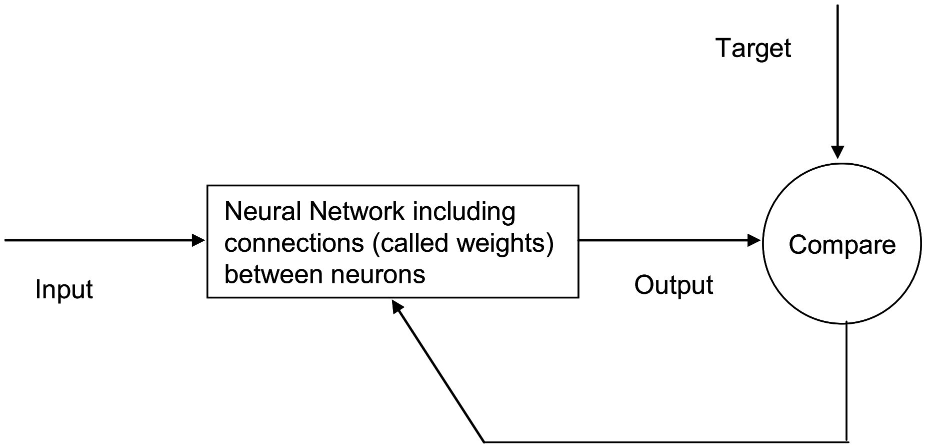


Fig. 8.7 Artificial neural network training process

8.9.2 Feedfoward neural network

Feedfoward neural network has no feedback elements and contains no delays. In feedfoward network as shown in Fig. 8.8, the neurons are arranged in a feedforward manner, in the form of layers. Each neuron receives an input from the external environment or preceding layers. Neurons are not allowed to have feedback connection or connections from neurons with the same layer. The output of this network is calculated directly from the input through feedfoward connections [92].

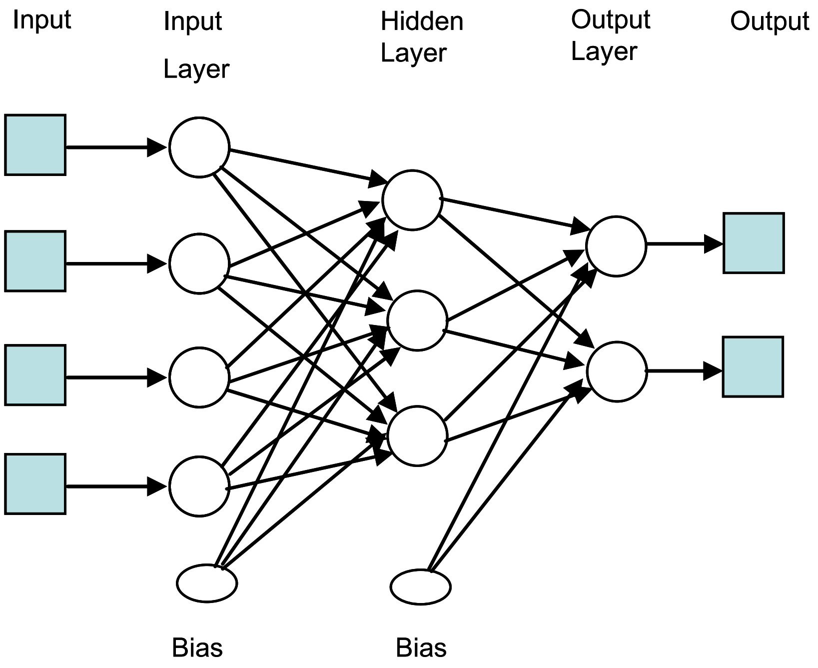


Fig. 8.8 Feedfoward ANN structure

8.9.3 Backpropagation ANN

Back propagation is the generalisation of the Widrow-Hoff learning rule to multiple-layer networks and nonlinear differentiable transfer functions. Input vectors and corresponding target vectors are used to train the network until it can approximate functions, associate input vectors with specific output vectors, or classify input vectors in appropriate ways as being defined. Networks with biases, a sigmoid layer, and a linear output layer are capable of approximating any function with a finite number of discontinuities [92].

Standard backpropagation is a gradient descent algorithm, as in Widrow-Hoff learning rule, in which the network weights are moved along the negative of the gradient of the performance function. The term backpropagation refers to the manner in which the gradient is computed for nonlinear multilayer networks. Properly trained NN gives a reasonable output when presented with the input that it has never seen. Typically a new input leads to an output similar to the correct output for input vectors used in training that are similar to the new input being presented. This generalisation property makes it possible to train a network on a representative set of input/target pairs and get good results without training the network with all possible input/output pairs [92].

8. 9 ANN for DG var prediction

The optimisation process previously discussed can be used to develop a database to train ANN offline. For predicting DG var at one time step ahead, ANN is trained by introducing the input of:

- Active power draws by distribution network at current time step and previous h time steps
- f time steps ahead of forecasted load demand
- Active power from N number of DG

The output of ANN is a vector comprising of the optimal reactive power of each DG and tap position of main substation transformer. Implementation of the said ANN is depicted graphically in Fig. 8.9.

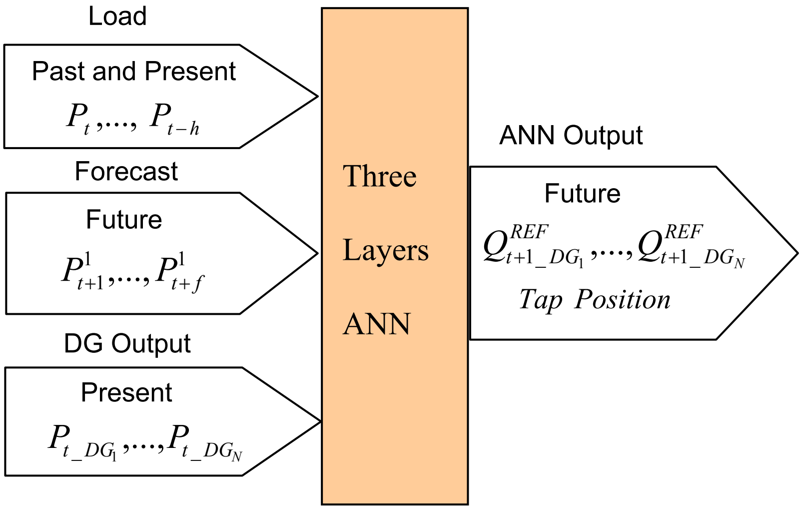


Fig. 8.9 Predictive DG vars using ANN

In the ANN controller development, h time steps of historical active power draws by distribution network, f time steps of future forecasted load demand and active power output from all DG units can be used. To make sure ANN is robust in predicting optimal reactive power, during the training process it can be introduced with three sets of input data which have forecast error of zero, five and ten percent respectively. Active power from DG can also be an input to ANN if some DG is operated at a certain power factor while some are intentionally oversized.

The performance of the ANN is evaluated in terms of maximum error (e_{max}) and RMS error (e_{rms}) which are given respectively by,

$$e_{\max} = \max\left\{\left|T_q - O_q\right|\right\}, \quad q = 1,2,\ldots,NO \tag{8. 5}$$

$$e_{rms} = \sqrt{\frac{1}{p^{\max}}\sum_{q=1}^{p^{\max}}\frac{1}{NO}\sum_{q=1}^{NO}\left[t_{qp} - o_{qp}\right]^2} \tag{8. 6}$$

where $T_q = [t_{q1}, t_{q2}, \ldots, t_{qp}{}^{max}]$ is the target vector at the q^{th} neuron of the output layer, $O_q = [o_{q1}, o_{q2}, \ldots, o_{qp}{}^{max}]$ is the output vector at the q^{th} neuron of the output layer, p^{max} is the number of patterns and NO is the number of neurons in the output layer.

8. 10 Test study on the proposed technique

The proposed online predictive technique is tested in controlling voltage and by intelligently coordinating DG vars and tap changer position. Similar test network introduced earlier in Fig. 6.1 is used. On each LV side of a distribution transformer there are aggregated DGs with rating capability of 33% of the maximum local load. With this magnitude of generation capacity all the active power supplied by DGs is consumed by local load. In this network, without DG reactive supply, the main voltage control in the network is achieved by using OLTC at the main substation.

DG technology considered in the study is again MTGS and FCGS which have reliable generation capacity. These two technologies are capable of supplying electricity and thermal power, but in this study it is assumed that they are used to generate only electrical power. All DG units are also assumed to be intentionally oversized to reduce the complexity.

In creating a database, optimisation simulation is run for each 96 time steps of distribution network operation based on the historical load demand [90]. The load is distributed at each time step. Optimal reactive power from each DG unit, transformer tap position, network power losses and other information are saved in the database. The information from the data base is then extracted to train ANN as described in Section 8. 9.

The ANN controller is tested to predict the optimal reactive power for 96 new time steps of one day operation which was not introduced during the training process. Maximum error

(e_{max}), root mean square error (e_{rms}) and standard deviation of error are calculated and tabulated in Table 8.1. The results show that the trained ANN correctly predicts all the optimal DG reactive power with small errors. Maximum prediction error is seen for DG 2 with the magnitude of 0.0804 MVar. The greatest root mean square error as can be seen is for DG 4 with the value of 0.0159 MVar. Standard deviations of error for all DG units are close to their root mean square errors.

Table 8.1 Performance of ANN in testing stage

DG No.	e_{max} (MVar)	e_{rms} (MVar)	σ (MVar)
DG 1	0.0348	0.0086	0.0085
DG 2	0.0804	0.0117	0.0118
DG 3	0.0501	0.0124	0.0125
DG 4	0.0636	0.0159	0.0160
DG 5	0.0411	0.0107	0.0107
DG 6	0.0286	0.0089	0.0089
DG 7	0.0541	0.0127	0.0127
DG 8	0.0261	0.0097	0.0098
DG 9	0.0484	0.0122	0.0123
DG 10	0.0351	0.0097	0.0098
DG 11	0.0318	0.0094	0.0094
DG 12	0.0586	0.0117	0.0117

The reactive powers predicted by ANN are compared graphically with the values obtained from the conventional optimisation technique are shown by Fig. 8.10 and Fig. 8.11 for DG 4 and DG 12 respectively. In Fig. 8.12, voltage correction provided by OLTC is shown. The value given by ANN is continuous so the values are rounded to the nearest discrete values. It can be seen that ANN manages to predict the position of the taps without any error.

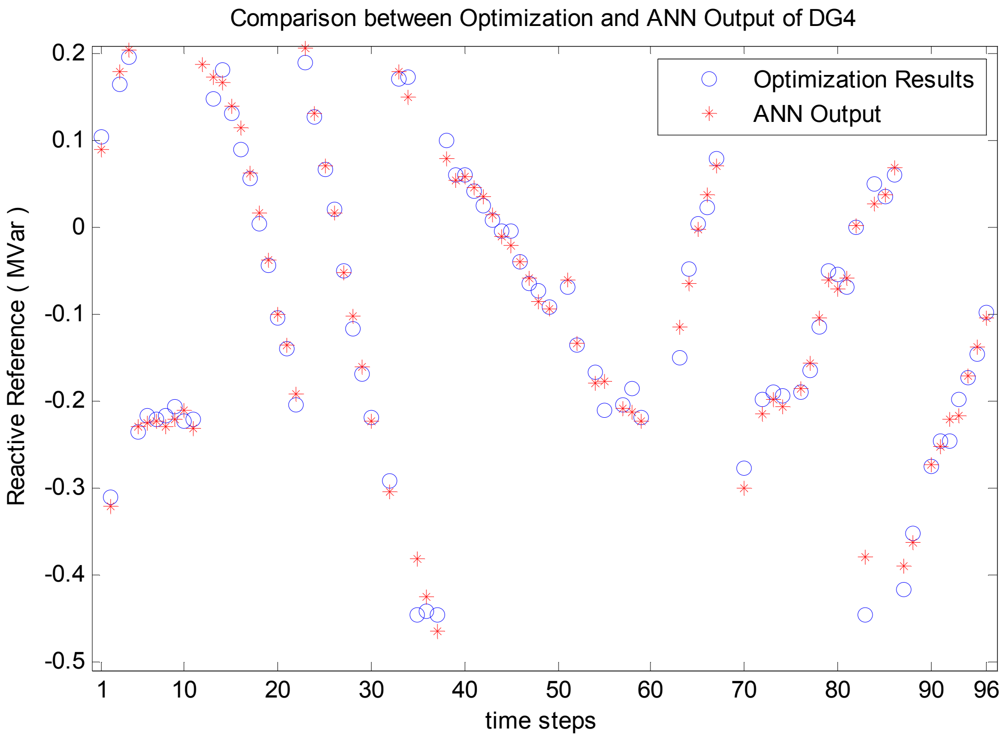


Fig. 8.10 Optimisation vs ANN output for DG 4

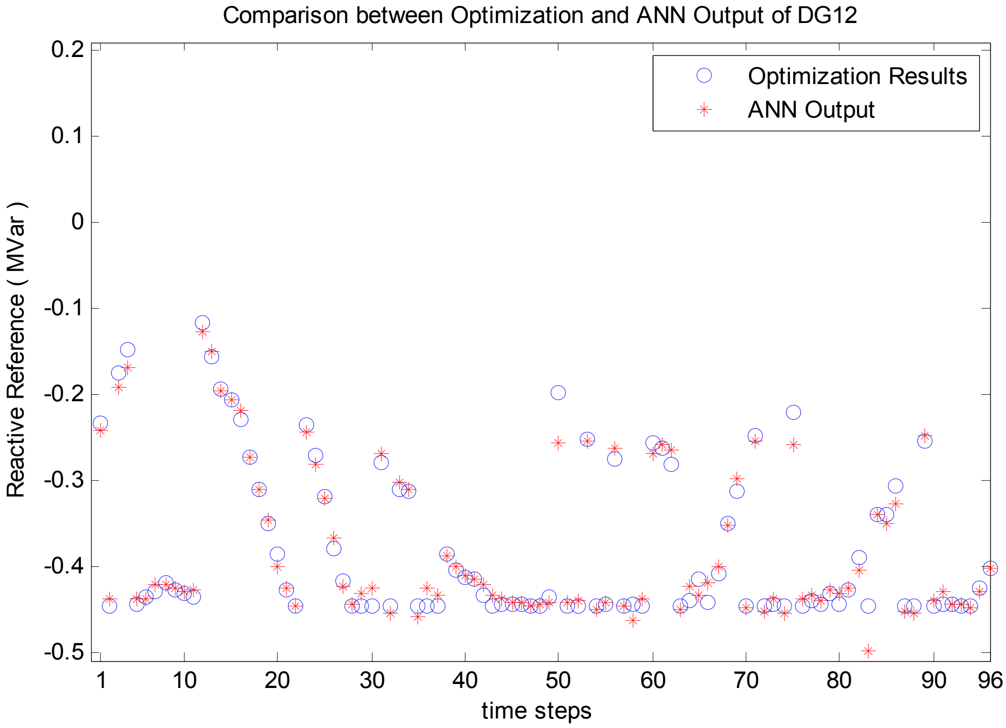


Fig. 8.11 Optimisation vs ANN output for DG 12

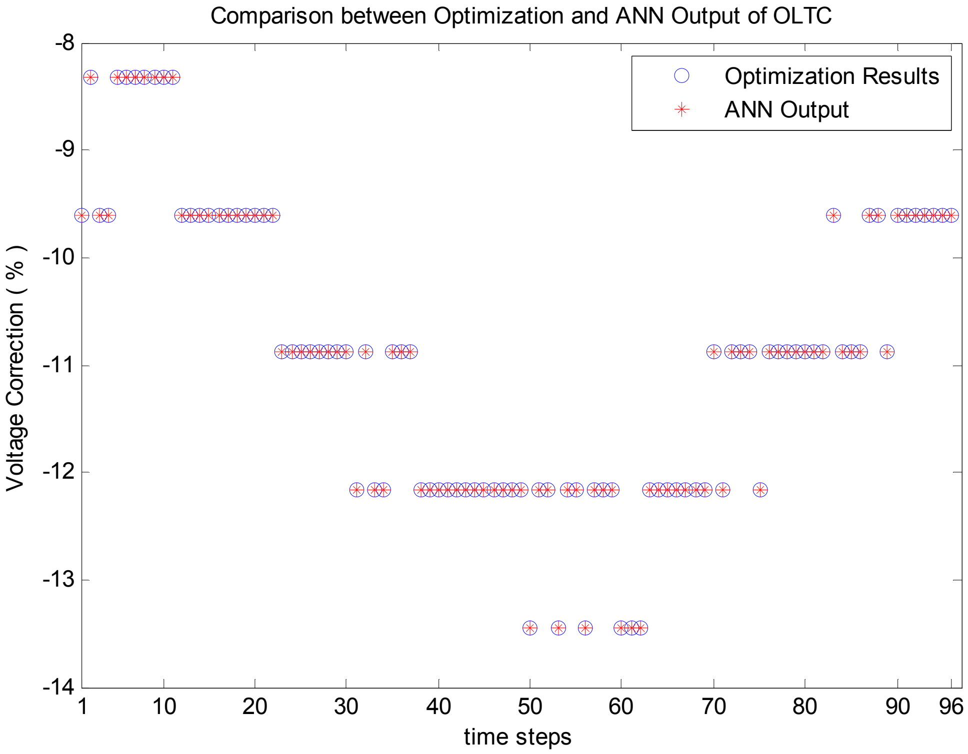


Fig. 8.12 Optimisation vs ANN output for transformer's tap

8. 11 Conclusion

In this chapter, intelligent predictive control technique for online management of reactive power from a group of DG units is presented. A group of DG units is centrally controlled using one controller which was developed using two stage intelligent techniques APSO and ANN. The database extracted from APSO optimisation is used to train an ANN to predict the next time step optimal reactive power from each DG. The ANN replaced the task of optimisation process in finding the optimal operating point of each DG available in the network. The effectiveness of the technique is demonstrated on the test distribution network containing twelve DG units. The simulation results indicate that a single ANN is effective in predicting the optimal reactive power from twelve DG units simultaneously with acceptable error and OLTC position without any error. The number of tap changes is also considered acceptable. This predictive control technique is suitable to be integrated into energy management system application under Smart Grid concept which will be applied to the Europe's electricity networks in coming years. In addition to effective management of reactive supplies from DGs, voltage control of the distribution network is performed simultaneously.

Chapter 9

Conclusion and Future Directions

9. 1 Conclusion

This thesis covers most important topics related to DG integration inside power system network. Driving motivations are thoroughly addressed and research topics performed are precisely explained. Overviews of DG's most pertinent aspects starting from their inconsistent definitions to their anticipated roles in future power system network are discussed. Many concerns on power system operation and control with large DG penetration are answered and solutions to mitigate expected operation challenges are proposed. Specifically, important research areas are addressed and covered in this thesis.

9.1.1 Modeling of distributed generation

Different types of power system studies with DG integration require different types of DG dynamic models. These models must as accurately as possible imitate the behaviour of real commercially available DG units. Various methods in modeling different DG technologies which coupled to the electrical grid through PEC are discussed under this research topic. The method started with specific detailed model which considers the switching of PED to the more flexible simplified model which considers only RMS value of the time variant electrical quantities. The performance of the developed models is compared to the performance reported in the literature and the results are comparable. Different DG technologies are also compared and the conclusion can be drawn that the behaviour of DG coupled to the grid through PEC is mostly influenced by their converter characteristic.

9.1.2 DG fault ride-through capability

Investigation study of MTGS and FCGS capability in adhering to new expected grid codes has been presented. During LVRT, with their standard power electronic converter, MTGS and FCGS have to operate beyond their operating limit which will cease their operation. The modification inside their power electronic converter hardware is proposed and with this modification, continuous operation during fault ride-through is possible. In meeting reactive support requirement, addition of control loop to the standard power electronic converter controller is required. The question whether MTGS and FCGS which have already been installed inside power system grid are capable of meeting this new grid code depends on their original design and embraced technology. As digital controller is programmable and DC protection devices are already embedded or easily added if absent, LVRT up to zero voltage and the necessity to inject negative reactive current during this critical period can be fulfilled by both MTGS and FCGS. With the necessary modifications, both MTGS and FCGS are shown capable of operating continuously during LVRT while at the same time supporting the grid with capacitive reactive current as demanded.

9.1.3 Grid support by DG

Voltage support and frequency control contribution that could be provided by DG to the power system are discussed and investigated. DG capability in performing these two most essential ancillary services is well demonstrated. Different control strategies are applied in exploring the most effective way to participate DG in voltage control and frequency stabilisation. The effectiveness of different control strategies is compared. The result of the studies clearly indicates that DG coupled to the grid through power electronic converter is capable and has great potential to positively contribute to power system voltage regulation and frequency stabilisation.

9.1.4 Influence of DG on power system stability under new grid codes

Influence of DG penetration on the most important stabilities issues was discussed and studied. The study considers a massive penetration of small scale DG in LV level with integration of wind farm in HV network. All generations inside power system under study are set to operate according to Germany’s new grid code. The inclusion of wind farm inside the power system network is considered as it represents the current scenario in power system industry. The study indicates transient stability is greatly improved with larger penetration of DG. For voltage stability however the greatest impact is seen inside distribution network with the small improvement seen inside HV network. But the concern on stability of power system network with mix of conventional and nonconventional generation units is answered. This vast penetration will not lead the power system network into instability when it is subjected to large disturbance but in fact enhances the stability. This mixed generation also increases the power system ability to withstand larger disturbances.

9.1.5 Predictive var management of distributed generation

An intelligent predictive control technique for online management of reactive power from a group of DG units is presented. A group of DG units is centrally controlled using one controller which was developed using two stage intelligent techniques APSO and ANN. The database extracted from APSO optimisation is used to train an ANN to predict the next time step of optimal reactive power from each DG unit. The ANN replaces the task of optimisation process in finding the optimal operating point of each DG available in the network. The effectiveness of the technique is demonstrated on the test distribution network containing twelve DG units. The simulation results indicate that a single ANN is effective in predicting the optimal reactive power from twelve DG units simultaneously with acceptable errors while for OLTC position the ANN successfully predicts it without any error. This predictive control technique is suitable to be integrated into energy management system application under Smart Grid concept which will be the backbone of Europe's electricity networks in coming years. In addition to effective management of reactive supplies from DGs, voltage control of the distribution network can be performed simultaneously.

9.2 Future Recommendations

The solutions and recommendations proposed in this thesis are possible options which can be taken to solve the operating challenges with enormous DG penetration. They are derived based on very reasonable assumptions and specific state of the art technologies available to date. While the technologies are continuously advancing rapidly along with introduction of new energy policies, different solutions are still to be sought. In moving forward, some possible directions are highlighted.

- Modeling of DG inside this thesis focusing on FCGS and MTGS as they are seen as the most promising technologies to be employed as DG by looking into current energy crisis and situation. With the rapid advancement in material sciences and power electronic technologies, other DG technologies such as solar and wind will also present inside future power system in significant number. Different types of dynamic models of these DG technologies should also be developed for various power system integration studies.
- Fault ride-through capability is anticipated to be necessary for DG connected to LV grid in the future. The capability of MTGS and FCGS in riding through a grid fault is shown only possible without ceasing their operation, with additional protective devices. With some of these DG technology already installed inside power system network, these additional protective devices may be a difficult option to add. Further study can be directed to explore the possibility of modifying the controller structure which can be easily programmed to each DG coupled to the grid through PEC.

- The support provided by DG in distribution network especially voltage support during steady state operation and critical operation is discussed. DG reactive power is however limited due to small sizes of DG and priority is given to active power generation. Other means of reactive power compensation coordinated with DG should be explored. For DG to participate in frequency stabilisation, more studies need to be done for example considering energy storage technologies to exploit more DG potential. The attention should also be given to the changes of grid codes which are continuously reviewed following changes of new energy policies.
- The stability concern and studies reported in this thesis mostly concentrated in power system with multi voltage level ranges from HV to LV. In the future, part of the power system will have an option to be operated in grid connected mode or in certain situation separated from the grid and be operated in an islanding mode. Cell which comprises a few voltage level and Micro Grid which typically operates only in LV level are the examples. In the islanding mode operation, these Cell and Micro Grid will be similar to a small power system which will be operated similar to bulk power system. The challenges include concern of how to stabilise the voltage, frequency and etc. within this small grid. It is suggested the stability study is directed toward this direction.
- For managing a group of DG effectively, the intelligent predictive var management of DG developed using APSO and static back propagation of neural network was proposed. However many more optimisation algorithms and different types of ANN are available. The use of these other optimisation algorithms should be explored. For ANN, there are dynamic neural networks available such as Focused Time-Delayed Neural Network, Distributed Time-Delay Neural Network and Layer recurrent network which are claimed more powerful in solving problem associated with time series data. Future study should try to investigate the potential of using these types of neural networks in this predictive technique application.

Appendices

Appendix A.2 PMSM parameters for 60 kW MTGS

Un = 550V	No. of poles = 2	$J = 0.848595\text{x}10^{-3}$ kg.m^2
Pn = 60 kW	$\Psi = 0.077685$ V.s	$L_{S\ d} = 258.2$ mH
$\omega_{\text{rated}} = 6387$ rad/s	$R_S = 0.0201\ \Omega$	$L_{S\ q} = 258.2$ mH

Appendix A.3 50 kW fuel cell parameter

Pn = 50 kW	$T_{H_2} = 3.37$ sec
T = 343 K	$T_{H_2O} = 18.418$ sec
$F = 96484600$ Ckmol^{-1}	$T_{O_2} = 6.74$ sec
$R = 8314.47$ Jkmol^{-1}K^{-1}	$T_1 = 2$ sec
$E_0 = 900$ V	$T_2 = 2$ sec
$N_0 = 900$	$CV = 2$ sec
K_r (=N$_0$/4F) = 2.33 x 10^{-6} kmols^{-1}A^{-1}	$B = 0.04777$ A^{-1}
$U = 0.8$	$C = 0.0136$ V
$k_{H_2} = 4.22$ x 10-5 kmols^{-1}atm^{-1}	$R^{\text{int}} = 0.65704\ \Omega$
$k_{H_2O} = 7.716$ x 10-6 kmols^{-1}atm^{-1}	$X = 0.05\ \Omega$
$k_{O_2} = 2.11$ x 10^{-5} kmols^{-1}atm^{-1}	$r_{h-O} = 1.168$

Appendix A.4 Kinetic energy and inertia constant of MTGS

Prated (MW)	H(s)	Source
20	10	[93]
250	8.2	[94]
450	3.9	[95]
0.25	0.822	[96]
0.4	0.74	[48]

Appendix A.5 Ramp up and ramp down speed of MTGS output power

Prated (kW)	dP/dt up (p.u./sec)	dP/dt down (p.u./sec)	Source
30	0.012	0.015	[97]
75	0.011	0.015	[97]
100	0.020	-	[98]
100	2.0	-	[99]

Appendix A.6 Ramp up and ramp down speed of FCGS output power

Prated (kW)	dP/dt up (p.u./sec)	dP/dt down (p.u./sec)	Source
5	0.04	0.09	[53]
100	0.01	-	[94]

References

[1] H. B. Puttgen, P. R. Mac Gregor, and F. C. Lambert, "Distributed generation: semantic hype or dawn of a new era?", *IEEE Power & Energy Magazine*, vol. 1, no. 1, pp. 22-29, Jan./Feb. 2003.

[2] F. A. Farret and M. G. Simoes, *Integration of Alternative Sources of Energy*, Wiley-Interscience, 2006.

[3] L. Freris and D. Infeield, *Renewable Energy in Power System*, John Wiley & Sons, 2008.

[4] M. H. Nehrir and C. Wang, *Modeling and Control of Fuel Cell*, John Wiley & Sons, 2009

[5] European Commision, 2007, Strategic research agenda for Europe's electricity networks of the future, [Online], Available: http://www. Smartgrids.eu/documents/sra/sra_finalversion.pdf

[6] European Commission (2006), European SmartGrids technology platform: vision and strategy for Europe's electricity networks of the future, [Online]. Available: http://www.smartgrids.eu/documents/vision.pdf

[7] Grid 2030 – A national vision for electricity's second 100 years. [Online]. Available: http://www.ferc.gov/EvenCalendar/Files/20050608125055-grid-2030.pdf.

[8] H. Zareipour, K. Bhattacharya and C. A. Canizares, "Distributed generation: Current status and challenges," in *Proc.2004 IEEE North American Power Symposium (NARS), Moscow, Idaho*, pp: 392-399.

[9] T. Ackermann, G. Andersson and L. Söder, "Distributed generation: a definition," *Electric Power System Research*, vol. 57, pp: 195-204, 2001.

[10] P. P. Barker and R. W. Mello, "Determining the impact of distributed generation on Power System: Part I – Radial distribution systems," in *Proc. 2000 IEEE PES Summer Meeting*, pp: 1645-1656.

[11] J. B. Campbell, T. J. King, B. Ozpineci, D. T. Rizy, L. M. Tolbert, Y. Xu and X. Yu, "Ancillery services provided from DER," Oak Ridge National Laboratory, Tennessee, Tech. Rep. ORNL/TM-2005/263, Dec. 2005.

[12] L. F. Ochoa, A. P. Feltrin and G. P. Harrison, "Evaluating distributed generation impacts with a multiobjective index, " *IEEE Transactions on Power Delivery*, vol. 21, no. 3, July 2006.

[13] P. B. Andersen, B. Poulsen, M. Decker, C. Traeholt and J. Ostergaard, "Evaluation of a generic virtual Power Plant Framework using Service Oriented Architecture, " in *Proc. 2008 2nd IEEE International Conference on Power and Energy*, pp. 1212-1217.

[14] T. K. Abdel-Galil, A. E. B Abu-Elanien, E. F. El-Sadany, A. Girgis, Y. A. R. I. Mohamed, M. A. Salama and H. M. Zeineldin, "Protection coordination planning with distributed generation," Tech. Rep., CETC Varenner, June 2007.

[15] W.Kramer, S. Chakraborty, B. Kroposki and H. Thomas, "Advanced power electronic interfaces for distributed energy systems - part 1: system and topologies," National Renewable Energy Laboratory, Golden, Colorado, Tech. Rep. NREL/TP-581-42672, Mar.2008.

[16] W. G. Scout, "Micro-turbine generators for distribution systems," *IEEE Industry Application Magazine*, May/June 1998.

[17] D. K. Nichols and K. P. Loving, "Assesment of microturbine generators," in *Proc. 2003 IEEE PES General Meeting*.

[18] A. Al-Hinai, K. Schoder and A. Feliachi, "Control of grid connected split-shaft microturbine distributed generator," in *Proc. 2003 IEEE 35th Southeastern Symposium*, pp: 84-88.

[19] Capstone Turbine Corporation, 2010 product catalog, [online]. Available http://www.capstoneturbine.com

[20] Elliot Microturbine, http://www.elliot-turbo.com/new/products_microturbines.html

[21] Turbec T100, Turbec AB, http://www.turbec.com

[22] O. Aglen, A high speed generator for microturbines, [Online], Available: http//eme.ekc.kth.se/publications/pdf/2001/ola-daressalam2001.pdf

[23] E. Ritchie, "Incentive and sustainability drive demand for small wind turbines," *Distributed Energy: The Jounal of Energy Efficiency & Realibility*, pp: 38-42, Sept/Oct 2010.

[24] M. Braun, G. Arnold and H. Laukamp, "Plugging into the zeitgeist," *IEEE Power and Energy*, vol. 7, no. 3, May/June 2009.

[25] E.ON Netz GmbH, Byayreuth, Grid Code, High and Extra high voltage. [Online]. Available: http://www.eon-netz.com/ Ressources /downloads/ ENENARHS2006eng.pdf

[26] Technische richtlinie erzeugungsanlagen am mittelspannungsnetz, BDEW Standard. [Online]. Available :http://www.energiedienst.de/site/DE/netze/img/Pdf_02_netzanschluss/Technische_Richtlinien/BDEW_RL_EA-am-MS-Netz_Juni_2008.pdf

[27] E. Santacana, G. Rackliffe, L. Tang and X. Feng, "Getting Smart," *IEEE Power and Energy*, vol. 8, no. 2, pp: 41-48, March/April 2010.

[28] B. Awad, J. Wu and N. Jenkins, Control of distributed generation, *Elektronik & Informationstechnik,* vol. 125, no. 12, pp:409-414, Dec 2008.

[29] K. Dielman, A. Velden, "Virtual power plant (VPP)- A new perspective for energy generation," in *Proc. 2003 of 9th international scientific and practical conference of student*,pp: 18-20.

[30] D. Pudjianto, C. Ramsay, G. Strbac, "Virtual power plant and system integration of distributed energy resources," *IET Renewable Power Generation*, vol.1, no.1, pp:10-16, 2007.

[31] N. Hatziargyriou, H. Asano, R. Iravani and C. Manay, "Microgrid, " *IEEE Power and Energy*, vol. 5, no. 4, pp:78-94, 2007

[32] P. Lund, "The Danish cell project – part 1: Background and general approach," in *Proc. 2007 IEEE PES General Meeting*, Tampa, U.S.A.

[33] R. Lasseter, A. Abbas, et. al., Integration of distributed energy resources: The CERTS Microgrid concept., Consortium for Electric Reliability Technology Solutions, California Energy Commission, 2003: P50003-089F.

[34] T. L. Skvarenina, *The power electronics Handbook*, CRC Press, 2002

[35] A. M Trzynadlowski, *Introduction to Modern Power Eelectronics*, 2ed, John Wiley & Sons, 2010.

[36] A. Schönung and H. Stemmler, "Static frequency changes with subharmonic control in conjunction with reversible variable-speed ac drives," Brown Boveri Rev., vol. 51, pp:555-577, 1964

[37] R. C. Dugan, M. F. McGranaghan, S. Santoso, H. W. Beaty, *Electrical Power System Quality*, McGraw-Hill, 2002.

[38] T. Ishikawa, Grid-connected photovoltaic power systems: survey of inverter and related protection equipments, Report IEA-PVPS T5-05, Dec 2002.

[39] *Electromagnetic compactibility (EMC)*, IEC 61000-3-series.

[40] *Recommended practices and requirements for harmonic control in electrical power systems*, IEEE 519-1992.

[41] Eurelectric, *Application guide to the European Standard EN 50160 on voltage characteristics of electricity suplied by public distribution systems*, [Online], Available: http://www.eurelectric.org

[42] H. Akagi, E. H. Watanabe and M. Aredes, *Instantaneous Power Theory and Application to Power Conditioning*, Wiley-Interscience, 2007.

[43] B. K., Bose, *Modern Power Electronic and AC drives*, Prentice Hall, 2002

[44] C. Feltes, S. Engelhardt, J. Kretschmann, J. Fortman and I. Erlich, "High voltage ride-trhough of DFIG-based wind turbine, "

[45] T. C. Green and M. Prodanovic, "Control of inerter-based micro-grid," *Electrical Power System Research*, vol. 77, pp: 1204-1213, 2007

[46] R.H. Staunton and B. Ozpineci, "Microturbine power conversion technology review," Oak Ridge National Laboratory, Washington, DC, Tech. Rep. ORNL/TM-2003/74, Apr. 2003.

[47] W. I. Rowen, "Simplified mathematical representation of heavy duty gas turbines," *ASME Trans. Journal of Engineering for Power*, vol. 105, no. 4, pp: 865-869, Oct. 1983.

[48] S.R. Guda, C. Wang, M. H. Nehrir, "Modeling of microturbine power generation systems," *Electrical Power Component and Systems*, vol. 34, no. 9, pp:1027-1041, Sept. 2006

[49] D. N. Gaonkar, R. N. Patel, and G. N. Pillai, "Dynamic model of microturbine generation system for grid connected/islanding operation," in *Proc. 2006 IEEE International Conference on Industrial Technology*, pp: 305-310.

[50] D. N. Gaonkar and R. N. Patel, Modeling and simulation of microturbine based distributed generation system, IEEE 2006.

[51] D. N. Gaonkar, G. N. Pillai and R. N. Patel, "Dynamic performance of microturbine generation system connected to a grid," *Electrical Power Components and Systems*, vol. 36, pp:1031-1047, 2008

[52] P. Kundur, *Power System Stability and Control*, McGraw-Hill, Inc., 1994.

[53] M. Y. El-Sharkh, A. Rahman, M. S. Alam, A. A. Sakla, P.C. Byrne and T. Thomas, "Analysis of active and reactive power control of a stand-alone PEM fuel cell power plant," *IEEE Transactions on Power System*, vol. 19, no. 4, pp: 2002-2028, Nov 2004.

[54] M. Uzunoglu and M. S. Alam, "Dynamic modeling, design and simulation of a combined PEM fuel cell and ultrcapacitor system for stand-alone residential applications," *IEEE Transactions on Energy Conversion*, vol. 21, no. 3, pp:767-775, Sept 2006.

[55] J. Padulles, G. W. Ault, and J. R. McDonald, "An integrated SOFC plant dynamic model for power system simulation," *Journal of Power Sources*, vol. 86, no. 1-2, pp: 495-500, Mar. 2000.

[56] C. J. Hatziadoniu, A. A. Lobo, F. Pourboghrat and M. Daneshdoost, "A simplified dynamic model of grid connected fuel cell generators," *IEEE Transactions on Power Delivery*, vol. 17, no. 2, pp:467-473, April 2002.

[57] K. Sedghisigarchi and A. Feliachi, "Control of grid-connected fuel cell power plant for transient stability enhancement," in Proc. 2002 IEEE PES Winter Meeting, pp: 383-388.

[58] M. Y. El-Sharkh, A. Rahman, M. S. Alam, P. C. Byrne, A. A. Sakla, T. Thomas, "A dynamic model for a stand-alone PEM fuel cell power plant for residential applications," *Journal of Power Sources,* vol. 138, pp: 199-204, 2004.

[59] M. Y. El-Sharkh, N. S. Sisworahardjo, M. Uzunoglu, O. Onar, M. S. Alam, "Dynamic behaviour of PEM fuel cell and microturbine power plants," *Journal of Power Sources*, 2006.

[60] C. Wang and H. Nehrir, "Fuel cells and load transients," *IEEE power and Energy magazine*, pp: 58-63, Jan./Feb. 2007.

[61] M. Z. C. Wanik and I. Erlich, "Dynamic simulation of microturbine distributed generators interconnected into multi-machines power system network," in *Proc. 2008 IEEE International Conference on Power and Energy*, pp: 1545-1550.

[62] *IEEE Standard for Interconnecting Distributed Resources with Electrical Power Systems*, IEEE Std. 1547, 2003

[63] *Standard for inverters, converters and controllers for use in independent power system*, UL 1741, 1999.

[64] G. Bertani, C. Bossi, F. Fornari, S. Massucco, S. Spelta, and F. Tivegna, "A microturbine generation system for grid connected and islanding operation," in *Proc. 2004 IEEE PES Power System Conference and Composition*, pp. 360-365.

[65] A.K. Saha, S. Chowdry, S. P. Chowdhury, P. A. Crossley, "Modeling and simulation of microturbine in islanded and grid-connected mode as distributed energy resource," in *Proc. 2008 IEEE PES General Meeting*,

[66] A. M. Azmy, Simulation and management of distributed generation units using intelligent techniques, PhD thesis, University Duisburg Essen, Germany, 2005

[67] Rockwell Automation, AC drive ride-through techniques, [Online]. Available: http://literature.rockwellautomation.com/idc/groups/literature/documents/wp/drives-wp003_-en-p.pdf

[68] K. Stockman, F. D'hulster, K. Verhaege, M. Didden and R. Belmans, "Ride-through of adjustable speed drives during voltage dips," *Electrical Power System Research*, vol. 66, pp: 49-58, 2003.

[69] E. F. Mogos and X. Guillaud, "A voltage regulation system for distributed generation," in *Proc. 2004 IEEE PES Power Systems Conference and Exposition*, vol. 2, pp:787-794.

[70] MATLAB/SIMULINK SimPowerSystem Documentation. [online]. Available:http//www.mathworks.com

[71] G. Newmann, S. Perera, V. Gosbell, V. Smith, "Voltage sag ride through improvement of modern AC drives: review of methods and a case study," in *Proc. of AUPEC 2001*, Perth, Australia, pp: 304-309.

[72] J. Morren, "Grid support by power electronic converters of distributed generation units," Ph.D thesis, Technical University of Delft, Netherland, 2006.

[73] M. Braun, G. Arnold and H. Laukamp, "Plugging into the zeitgeist," *IEEE Power and Energy*, vol. 7, no. 3, May/June 2009.

[74] M. Reza, P. H. Schavemaker, J.G. Slootweg, W.L. Kling, and L. van der Sluis, "Impacts of distributed generation penetration levels on power systems transient stability," in *Proc. 2004 Power Engineering Society General Meeting*, pp. 2150 – 2155.

[75] M. Azmy and I. Erlich, "Impact of distributed generation on the stability of electrical power systems," in *Proc. 2005 IEEE PES General Meeting*, vol. 2, pp. 1056-1063

[76] M. Reza, P. H. Schavemaker, J.G. Slootweg, W.L. Kling, and L. van der Sluis, "Impacts of distributed generation penetration levels on power systems transient stability," in *Proc. 2004 Power Engineering Society General Meeting*, pp. 2150 – 2155.

[77] M. Reza, J.G. Slootweg, P. H. Schavemaker, W. L. Kling and L. Sluis, "Investigating impacts of distributed generation on transmission system stability," in *Proc. 2003 IEEE Bologna PowerTech Conference*, June 23-26, Bologna, Italy.

[78] Test Network, PST16, [online]. Available: http://www.uni-duisburg.de/FB9/EAN/doku/teeuwsen/PST16.html

[79] M. Z.C. Wanik and I. Erlich, "Simulation of microturbine generation system performance during grid fault under new grid code requirements," in *Proc. 2009 IEEE PES Powertech Conf.*, Bucharest, Romania.

[80] I. Erlich, J. Kretschmann, S. Mueller-Engelhardt, F. Koch and J. Fortmann, "Modeling of wind turbines based on doubly-fed induction generators for power system stability studies," *IEEE Transaction on Power System*, vol. 22, no. 3, pp: 909-919, Aug. 2007.

[81] T. Ackerman and V. Knyazkin, "Interaction between distributed generation and the distribution network: operation aspects," in *Proc. 2002 IEEE PES Transmission and Distribution Conference and Exhibition*, vol. 2, pp. 1357- 1362.

[82] S. Toma, T. Senjyu, Y. Miyazato and A. Yona, "Decentralized voltage control in distribution system using neural network," in *Proc. 2008 2nd IEEE International Conference on Power and Energy*, pp. 1557-1562.

[83] H. Hatta and H. Kobayashi, "A study of centralized voltage control method for distribution system with distributed generation," in *Proc. 2007 CIRED 19th International Conference on Electricity Distribution*, Vienna.

[84] IEEE Committe Report, "Load forecast bibliography, Phase 1," *IEEE Transaction on Power Apparatus and System*, vol. PAS-99, no. 1, pp:55-58, 1980.

[85] T. Senjyu, H. Sakihara, Y. Tamaki and K. Uezato, "Next-day load forecasting using neural network based on similarity," *Electrical Power Component and System*, vol. 29, pp:939-948, 2001.

[86] M.Z.C. Wanik, I. Erlich and A. Mohamed, "Intelligent management of distributed generators reactive power for loss minimization and voltage control," in *Proc. 2010 IEEE MELECON*, Malta.

[87] Maurice Clerc, "TRIBES, a parameter Free Particle Swarm Optimizer," French version: 2003-10-02. Presented at OEP' 03, Paris, France.

[88] V. S. Pappala, "Application of PSO for optimization of power systems under uncertainty," Dr.-Ing thesis, Universität Duisburg-Essen, 2009

[89] Erlich, "Analyse und simulation des dynamischen verhaltens von elektroenergiesystem (Analysis and Simulation of the Dynamic behaviour of Electrical Power Systems)," (in German) Habilitation Thesis, Dept. Elect. Eng., Tech. Univ. Dresden, Dresden, Germany, 1995.

[90] AEMO, Aggregated price and demand: 2006 – 2010, [Online]. Available: http://www.aemo.com.au/data/aggPD_2006to2010.html

[91] A. M. Azmy and I. Erlich, "Intelligent operation management of fuel cells and micro-turbine using genetic algorithm and neural network," in *Proc. 2004 International Conference on New and Renewable Energy Technologies for Sustainable Development*, July 2004, Evora, Portugal.

[92] T. S. Dillon and D. Niebur, *Neural Networks Application in Power System*, CRL Publishing, 1996

[93] R. K. Jardan, I. Nagy, T. Nitta, H. Ohsaki, "Environement-friendly utilisation of waste energies for the production of electric energy in disperse power plant," in *Proc. 2002 IEEE Int. Symp. on Industrial Electronics (ISEI 2002)*, vol. 4, pp: 1119-1124.

[94] Y. Zhu, K. Tomsovic, "Development of models for analyzing the load following performance of microturbien and fuel cells," *Electric Power System Research*, vol. 62, no. 1, pp: 1-11, 2002.

[95] W. R. Canders, J. Heldt, R. K. Jardan, I. Nagy, H. J. Prümper, "Application of 400 kW natural gas expansion system as a UPS system," in *Proc. 9th European conference on power electronics and application (EPE 2001)*, Graz, Austria, pp: 27-29.

[96] N. S. Sisworahardjo, M. Y. El-Sharkh, M. S. Alam, "Neural network controller for microturbine power plants," *Electrical Power System Research*, vol. 78, pp: 1378-1384, 2008.

[97] R. J. Yinger, "Behaviour of Capstone and Honeywell microturbine generators during load changes," CERTS Report LBNL-49095, July 2001.

[98] O. Perego, S. Belloni. (30 March 2005). Dispower project, The CESI cogeneration plant based on Turbec T100 microturbine CHP system, Dispower Project Highlight No. 16, [Online] Available: http://www.dispower.org

[99] H. Nikkhajoei, M. Reza Iravani, "A matrix converter based Micro-turbine distributed generation system," IEEE Trans. On Power Delivery, vol. 20, no. 3, pp: 2182-2192, July 2005.

List of Abbreviations

AC	Alternate Current
AFC	Alkaline Fuel Cells
ANN	Artificial Neural Network
APSO	Adaptive Particle Swarm Optimisation
BPFFNN	Back Propagation Feed Forward Neural Network
CAES	Compressed Air Energy Storage
CBEMA	Computer
CERTS	Consortium for Electric Reliability Technology Solutions
CHP	Combined Heat and Power
CIGRE	International Council on Large Electric Systems
CVPP	Commercial Virtual Power Plant
DC	Direct current
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DSP	Digital Signal Processor
EU	European Union
FACTS	Flexible AC Transmission System
FC	Fuel Cell
FCGS	Fuel Cell Generation System
FPGA	Field-programmable gate array
FRT	Fault Ride-through
GTO	Gate Turn-off Thyristors
HVDC	High voltage Direct current
HVRT	High Voltage Ride-through
ICE	Internal Combustion Engine
IGBT	Insulated Gate Bipolar Transistor
ITI	Information Technology Industry
LSC	Line Side Converter
LV	Low Voltage
LVRT	Low Voltage Ride-through
MCFC	Molten Carbonate Fuel Cell
MCT	MOS-controlled Thyristors
MOSFET	Metal oxide semiconductor field effect transistor
MT	Microturbine
MTGS	Micro turbine Generation System
MV	Medium Voltage
NARX	Nonlinear Autoregressive Network with Exogenous
NN	Neural Network
OLTC	On load Tap Changer
OPF	Optimal Power Flow
PAFC	Phosphoric Acid Fuel Cell
PCC	Point of Common Coupling
PEC	Power Electronics Converter
PED	Power Electronic Devices
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Permanent Magnet

PMSM	Permanent Magnet Synchronous Machine
PSD	Power System Dynamic
PSO	Particle Swarm Optimisation
PST16	Power System Transient Network with 16 synchronous Machines
PV	Photovoltaic
PWM	Pulse Width Modulated
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SCR	Silicon controlled rectifier
SH	Small Hydro
SM	Synchronous Machine
SMES	Superconducting Magnetic Energy Storage
SOFC	Solids Oxide Fuel Cell
TVPP	Technical Virtual Power Plant
USA	United States of America
VFD	Variable Frequency Drive
VPP	Virtual Power Plant
VSC	Voltage Source Converter
WT	Wind turbine
WTGS	Wind turbine generation system

List of Symbols

u_{ref}	Reference sinusoidal voltage
u_{tri}	Triangular voltage
$\hat{u}_{AC}$	AC voltage magnitude
m	Modulation ratio
u_{DC}	DC voltage
K_{GV}	Gain of the speed governor
t_m	Mechanical Torque
w_F	Fuel Input Signal
w_{MIN}	Fuel demand at no load
T_X	Lead time constant of the speed Governor
T_Y	Lag time constant of the speed Governor
T_{VP}	Lag time constant of the valve positioner
T_{FS}	Lag time constant of the fuel system
T_{CD}	Lag time constant of the compressor discharged
u_d	d-axis voltage
r_S	Stator resistance
i_d	d-axis current
ψ_q	q-axis flux linkage
$\dot{\psi}_q$	Time derivative of q-axis flux linkage
u_q	q-axis voltage
r_{Dd}	d-axis damping winding resistance
i_{Dd}	d-axis damping winding current
$\dot{\psi}_{Dd}$	Time derivative of d-axis damping winding flux linkages
r_{Dq}	q-axis damping winding resistance
i_{Dq}	q-axis damping winding current
$\dot{\psi}_{Dq}$	Time derivative of q-axis damping winding flux linkages
ψ_d	d-axis flux linkages
l_{hd}	d-axis main/mutual/magnetizing field inductance
$l_{\sigma S}$	Stator leakage inductance
i_{fd0}	d-axis field current
ψ_q	q-axis flux linkage
t_e	Electrical torque
t_m	Mechanical torque

$\dot{\omega}_R$	Time derivative of rotor angular speed
T_m	Inertia constant (2H)
$\dot{\delta}_R$	Time derivative of rotor angle
ω_R	Rotor angular speed
ω_{R_ref}	Rotor angular speed reference
ω_0	Rated speed
u_{d0}	d-axis stator steady state voltage
u_{q0}	q-axis stator steady state voltage
H_2	Hydrogen
O_2	Oxygen
H_2O	Water
p_{H_2}	Partial pressure of hydrogen
p_{H_2O}	Partial pressure of water
p_{O_2}	Partial pressure of oxygen
q_{H_2}	Molar flow of hydrogen (kmols-1)
q_{H_2O}	Molar flow of water (kmols-1)
p_{H_2}	Hydrogen partial pressure (atm)
p_{H_2O}	Water partial pressure (atm)
k_{H_2}	Hydrogen valve molar constant (kmol (atm s)-1),
k_{H_2O}	Water valve molar constant (mol (atm s)-1)
k_{an}	Anode valve constant ($\sqrt{\text{kmol Kg}}$ (atm s)-1)
M_{H_2}	Molar mass of hydrogen (kg kmol-1)
M_{H_2O}	Molar mass of water (kg kmol-1)
k_{UNC}	Universal gas constant ((1 atm) (kmol K)-1),
t_k	Absolute temperature (K)
V_{an}	Volume of the anode (1)
$q_{H_2}^{in}$	Hydrogen input flow (kmols-1)
$q_{H_2}^{out}$	Hydrogen output flow (kmols-1)
$q_{H_2}^{r}$	Hydrogen flow that reacts (kmols-1)
N_0	A number of series fuel cells in the stack
I_{FC}	Fuel Cell stack current (A)
F	Faraday's constant (C kmol-1)
k_r	Modeling constant (kmol (sA)-1)
η_{act}	A function of the oxygen concentration CO_2 and stack current $I(A)$

η_{ohmic}	A function of the stack current and the stack internal resistance $R^{\text{int}}(\Omega)$
U_{NL}	No load voltage
N_0	Number of cells
T_{H_2}	Hydrogen time constant
T_{H_2O}	Water time constant
T_{O_2}	Oxygen time constant
r_{H-O}	Hydrogen-Oxygen flow ratio

Curriculum Vitae

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Publications

1. **M. Z. C. Wanik**, I. Erlich, A. Mohamed and A. A. Salam, *Influence of distributed generation and renewable energy resources power plant on power system transient stability*, in *Proc. of IEEE PECON 2010*, Kuala Lumpur, Malaysia.
2. **M. Z. C. Wanik**, I. Erlich, A. Mohamed and H. Shareef, *Predictive var management for distributed generators*, in *Proc. of IPEC 2010*, Singapore.
3. **M. Z. C. Wanik**, I. Erlich and A. Mohamed, *Inteligent management of distributed generators reactive power for loss minimization and voltage control*, in *Proc. of IEEE MELECON 2010*, Malta.
4. **M. Z. C. Wanik** and I. Erlich, *Simulation of Microturbine Generation System Performance during Grid Faults under new Grid Code Requirement*, in *Proc. of IEEE PES Powertech 2009*, Bucharest, Romania.
5. **M. Z. C. Wanik** and I. Erlich, *Dynamic Simulation of Microturbine Distributed Generators integrated with Multi-Machines Power System Network*, in *Proc. of 2nd IEEE International Conference on Power and Energy (PECon 08)*, Johor Baharu, Malaysia.
6. A. A. Salam, A. Mohamed and **M. Z. C. Wanik**, *A Dynamic PEM Fuel Cell Distributed Generation System for Grid Connected and Islanding Operation*, in *Proc. of 2nd International Conference on Engineering Technology 2009*, Kuala Lumpur, Malaysia
7. A. A. Salam, A. Mohamed, M. A. Hannan, H. Shareef and **M. Z. C. Wanik**, *Performance Evaluation of Microturbine Generation System for Microgrid Application*, in *Proc. of 3rd IASTED Asian Conference on Power and Energy Systems (AsiaPES) 2009*, Beijing, China.