Benefit Analysis of Using Soft DC Links in Medium Voltage Distribution Networks

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Declaration

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Abstract

Soft DC Links are power electronic converters enabling the control of power flow between distribution feeders or networks. This thesis considers the use of Soft DC Links in Medium Voltage (MV) distribution networks to improve network operation while facilitating the integration of distributed generators (DGs). Soft DC Links include Soft Open Points (SOPs) and Medium Voltage Direct Current (MVDC) links. An SOP can be installed to replace mechanical switchgear in a network, providing controllable active power exchange between connected feeders, as well as reactive power compensation at each interface terminal. The deployment of an MVDC link enables power and voltage controls over a wider area, and facilitates the effective use of available capacity between adjacent networks. The benefits of using SOP and MVDC link in MV distribution networks were investigated.

A multi-objective optimisation framework was proposed to quantify the operational benefits of a distribution network with an SOP. An optimisation method integrating both global and local search techniques was developed to determine the set-points of an SOP. It was found that an SOP can improve network operation along multiple criteria and facilitate the integration capacity of DGs.

A Grid Transformer-based control method of an MVDC link was proposed, which requires only measurements at the grid transformers to determine the operation of an MVDC link. Control strategies considering different objectives were developed. The proposed control method is used in the ANGLE-DC project, which aims to trial the first MVDC link in Europe by converting an existing AC circuit to DC operation. It was found that an MVDC link can significantly increase the network hosting capacity for DG connections while reducing network losses compared to an AC line.

An impact quantification of Soft DC Links was carried out on statistically-similar distribution networks, which refer to a set of networks with similar but different topological and electrical properties. A model was developed to determine the optimal allocation of Soft DC Links. It was found that a Soft DC Link can reduce the network annual cost under a wide range of DG penetration conditions. The statistical analysis provides distribution network planners with more robust decisions on the implementation of Soft DC Links.

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Abbreviations

AC	Alternative Current
DG	Distributed Generation
DNO	Distribution Network Operator
DVR	Dynamic Voltage Restorer
ENA	Energy Networks Association
ENIC	Electricity Network Innovation Competition
EU	European Union
EV	Electrical Vehicle
FACTS	Flexible AC Transmission Systems
FLB	Feeder Load Balancing
GHG	Greenhouse Gases
GT	Grid Transformer
HC	Hosting Capacity
HVDC	High-voltage DC Transmission Systems
ICT	Information and Communication Technology
IEA	International Energy Agency
LBI	Load Balance Index
MID	Mean Ideal Distance

MOPSO	Multi-objective Particle Swarm Optimisation
MVDC	Medium Voltage Direct Current
NOP	Normally-open Point
OECD	Organisation for Economic Cooperation and Development
OLTC	On-load Tap Changer
PDF	Probability Density Function
PLR	Power Loss Reduction
PSO	Particle Swarm Optimisation
PV	Photovoltaic
RES	Renewable Energy Source
SOP	Soft Open Point
SSNG	Statistically-similar Networks Generator
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
UPFC	Unified Power Flow Controller
VPI	Voltage Profile Improvement
VSC	Voltage Source Converter

Chapter 1 Introduction

In this chapter, an introduction to the background, motivation, objectives, and contributions of this research is presented. An outline of the thesis is then provided.

1.1 Background

Electric power systems are facing new challenges as the progress is being made towards de-carbonising the energy supply in response to environmental consciousness and climate change, as well as the increase in electricity demand due to the continuous development of economy and the electrification of heating and transportation. In addition, a significant portion of system assets is approaching the end of their effective lifetime. Intelligent technologies are urgently required to modernise the power systems and make the supply of electricity sustainable, flexible, secure and cost-effective, which lead to the emergence of smart grid.

1.1.1 Emergence of Smart Grid

Future power systems are expected to make extensive use of modern information and communication technologies (ICT) to allow pervasive control and monitoring [1]. The concept of smart grid is therefore emerging, which is considered capable of controlling active networks intelligently, in order to facilitate the integration of renewable energy, to meet the continuous growth of electricity demand, and to optimally deploy the expensive assets.

Definitions of smart grid vary among different countries and there is no single universal concept.

The European SmartGrids Technology Platform published a definition of smart grid in 2006, in which the functionality of smart grid to facilitate the connection of generation, to provide flexibility for consumers taking part in the system operation, and to reduce the environmental impact was emphasised [2]:

"*A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.*"

The Energy Networks Association (ENA) defined smart grid as an efficient system with pervasive communication technologies, where smart meter is an important element [3]:

"A completely smart grid of the future will enable appliances in the home to communicate with the smart meter and enable the networks to ensure efficient use of infrastructure, demand response and energy management. These are all critical to making the most of intermittent renewables and keeping the lights on in an affordable low-carbon energy future."

In the UK, the development of smart grid has been mainly focused on distribution networks [4]. This is because distribution networks have taken the majority of electricity losses. It is of importance that distribution network operators (DNOs) can manage their carbon footprint. Moreover, the uptake of electric heat pumps and electric vehicles, the investment in small wind generations, household and community micro-generations and other initiatives to de-carbonise the energy could have profound impacts on the nature and pattern of distribution networks. To accommodate these changes, DNOs need to forecast and actively manage power flows across their networks. Consequently, distribution networks have the greatest opportunity for smart technology interventions, where investments consistent with revised network planning, operation, and control paradigms are required.

1.1.2 Driving Factors in the Move towards Smart Grid

- ***Integration of Renewable Generation***

Greenhouse gases (GHG) contribute to the climate change, which is recognised to be one of the greatest environmental and economic challenges facing humanity. Over the past decades, worldwide efforts have been made in preventing the climate change. In 2009, the European Commission passed legislation to ensure that the European Union (EU) meets its ambitious climate and energy targets for 2020. These targets are known as the “20-20-20” Renewable Energy Directive, in which three key objectives are set [5]:

- A 20% reduction in EU GHG emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU’s energy efficiency.

The UK Government’s Action Plan concludes that delivering 15% renewable energy by 2020 is feasible through domestic action and could be achieved with the following proportion of energy consumption in each sector coming from renewable sources [6]:

- Around 30% of electricity demand, including 2% from small-scale sources;

- 12% of heat demand;
- 10% of transport demand.

All these policies and objectives converge in a substantial increase in using renewable energies, in the form of distributed generations (DGs), and electricity lies at the heart of these changes. Figure 1.1 shows the electricity generated from renewable energies in different regions of the world. As reported by the International Energy Agency (IEA), renewable electricity generation is estimated to rise to 25% of gross power generation in 2018, up from 20% in 2011 and 19% in 2006. It can be observed that the strongest growth of renewable electricity generation is achieved by developing countries, and they are expected to contribute to two-thirds of all renewable market growth by 2018, compensating for slower growth and market volatility across Europe and the US [7].

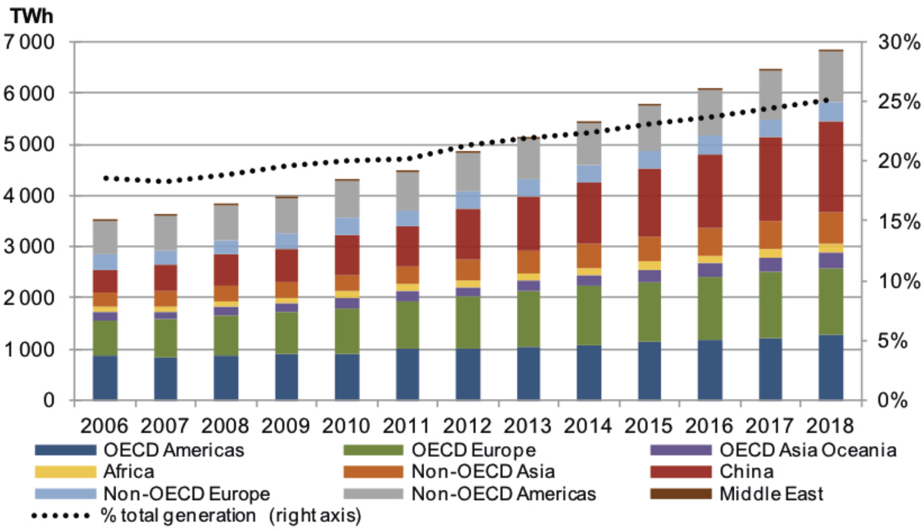


Figure 1.1 Global renewable electricity generation by region [7]

Although having economic and technical advantages, the significant integration of DGs may lead to reverse power flows, and the electrical distribution network is no longer a passive circuit supplying the demand but an active one with power flows and voltages determined by the generation as well as the demand [8]. Other challenges, such as violations of voltage and thermal limits, increase of fault levels, harmonics and flickers may also be introduced by DGs. New technologies and services are required to maintain safe and cost-effective operation of the power system.

- ***Increase of Electricity Demand***

Due to the global economic growth, the population increase and the process of urbanisation, global energy consumptions are expected to expand by 30% between today and 2040 [9]. Among all the energy consumptions, electricity is the rising force for its growth in the traditional domains and the electrification of heating and transportation. As shown in Figure 1.2, the global demand for electricity increased by over 50% from 1990 to 2011, and is expected to increase by over 80% from 2011 to 2030 [10]. Most of the world's electricity consumption occurs in countries outside of the Organisation for Economic Cooperation and Development (OECD), where strong, long-term economic growth drives the increasing demand for electricity. Non-OECD Asia (including China and India) is expected to account for about half of the total increase in electricity consumption between now and 2030.

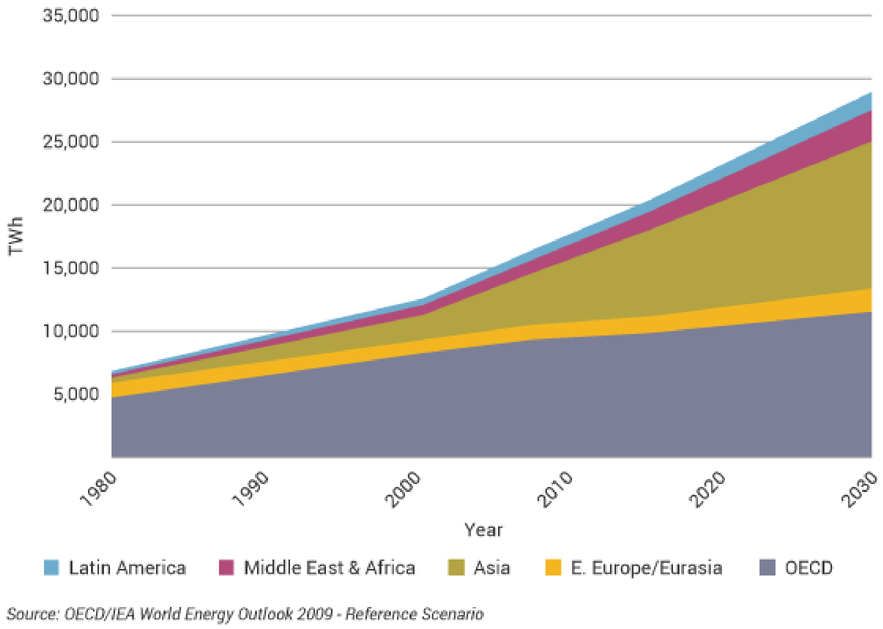


Figure 1.2 World electricity consumption by region [10]

To meet the growing demand for electricity, additional network capacities are required. Smart technologies are in need to bring efficiency, controllability and flexibility to the grid, as well as benefits to customers. Otherwise, the costly and time-consuming infrastructure reinforcements will be carried out.

- ***Security, Reliability and Quality of Supply***

Modern society has an increasing number of critical loads, which depend greatly on a secure and reliable supply of energy. Countries without adequate reserves of fossil fuels are facing concerns for primary energy availability. As the integration of renewable generation is increasing, the proportion of intermittent energy sources in the energy mix is getting higher, lowering the overall predictability of electricity supply. Furthermore, the ageing infrastructure of electrical transmission and distribution networks is increasingly threatening security, reliability and quality of supply. All these concerns are calling for innovative solutions, technologies and grid architectures.

1.1.3 Development of Soft DC Links

The emergence of smart grid has led to a radical reappraisal of the functions of distribution networks. Better control and supervision of network facilities to support their operation in facing the emerging challenges are therefore required.

Distribution networks are usually operated in radial configurations, where normally-open points (NOPs) are built, connecting adjacent feeders to provide alternative routes of electricity supply in case of planned or unplanned power outages. Such configuration has the benefits of inherent simplicity of operation and protection. However, it may constrain further integrations of demand and generation due to potential voltage and thermal violations, uncontrolled power flows, short-circuits problems, etc. As a result, assets may be stressed in places yet underutilised elsewhere. Rebalancing and rerouting of power flows are therefore needed.

One of the solutions is to close NOPs and form a meshed network configuration, which relieves the stress on feeders that are power flow constrained by transferring the power through less heavily loaded routes. However, such solution may lead to excessive fault current or violation of assumptions in the design of protection grading [11].

A hybrid solution combines the advantages of both radial and meshed configurations while effectively removing their disadvantages, is to form a flexible interconnection by using power electronic devices, i.e. a Soft Open Point (SOP). An SOP can provide controllable active power exchange between connected feeders in a continuous manner, as well as reactive power compensation at each interface terminal.

Distribution networks were usually built in proximity to each other, reliably serving their own local demand with no interconnections in between. Nowadays, as the electricity demand is growing, and intermittent renewables and other forms of electricity generation are being connected directly to distribution networks, DNOs are attempting to re-configure network components or to adopt new technologies in order to remain their networks below full capacities. Disparate demand growths and deployments of DGs in different distribution networks result in some networks reaching their capacity limits sooner than proximate ones. Having a means of "sharing" the capacity of one network with another would delay the costly infrastructure reinforcements and respond to the changes in demand and generation rapidly. However, such "sharing" between networks cannot be accomplished with mechanical switchgear for two primary reasons: increase in fault currents and difference in phase angles [12]. On the contrary, with the use of power electronic devices, a Medium Voltage Direct Current (MVDC) link can be formed to connect feeders from distinct distribution networks, allowing for the bridging of phase angle differences, as well as the isolation of undesired fault currents [13].

An MVDC link can achieve similar functionalities of an SOP, and is obtained by extending an SOP and having the devices in different locations. Hence, rather than installing at one site, the deployment of an MVDC link enables flexible power and voltage controls over a wide area, as well as facilitates the effective use of available capacities in proximate networks that would otherwise remain underutilised.

Both SOPs and MVDC links are considered Soft DC Links, which are power electronic converters enabling the control of power flow between distribution feeders or networks. The development of Soft DC Links can facilitate distribution network growths and improve power quality (e.g. power loss reduction, load balancing and voltage stability). To this end, the implementation of Soft DC Links in distribution networks is considered an alternative to potentially undesirable solutions, which include traditional network reinforcements, network reconfiguration with mechanical switchgears, participation of DGs in generation curtailment schemes, participation of customers through demand side management and load shedding. Moreover, these solutions are not mutually exclusive to Soft DC Link implementations and can be used in conjunction with Soft DC Links to further improve the network operation.

1.2 Research Motivation

Since Soft DC Links can provide flexibility and controllability to distribution network operation, as well as defer traditional network reinforcements and accommodate network growths, this thesis is motivated to analyse the benefits of using Soft DC Links in Medium Voltage (MV) distribution networks from the following three aspects.

1.2.1 Multi-objective Operational Benefits of Soft DC Links

A number of studies (detailed discussion in Section 2.3.3) have been carried out to investigate the benefits of using power electronic devices in distribution networks. However, the operational objectives (power loss reduction, load balancing, DG penetration increase, etc.) were considered separately. Since it is common that the objectives of real-world problems are incommensurable in nature and can be conflicting with each other, different objectives can lead to very distinct network performances. In order to explore the potential benefits and achieve wider applications of Soft DC Link, it is necessary to investigate the device's capability of bringing advantages along different objectives simultaneously, which makes the problem of distribution network operation with Soft DC Link a multi-objective one. Effective optimisation framework that quantifies the benefits offered by Soft DC Link to the network operation along multiple objectives is therefore required. Considering the multiple and incommensurable criteria, efficient optimisation method that explores the huge search space, and identifies the optimal trade-off surface among different criteria is therefore needed.

1.2.2 Grid Transformer-based Control of Soft DC Links

Currently, many studies on the evaluation of distribution-level power electronic devices relied on centralised control schemes, in order to achieve the flexible control and operation of networks. Such control schemes gather all the data at a single point, where a central processor makes the control decisions regarding the whole network. Since centralised control schemes require observability of the entire network, and heavily rely on measurement and communication infrastructures which might be subjected to malfunctions or failure, the accurate and fast responses to the changes of demand and generation in a network cannot be guaranteed. In addition, the cost of associated ICT infrastructure required for centralised control accounts takes a large portion of the total costs [14], which makes centralised control less attractive. Considering the existing communication infrastructure is not readily able to facilitate the centralised communication with a large number of demand/generation nodes, there is a clear need to develop efficient control methods, which require fewer measurements and less computation time, for the implementation of Soft DC links.

1.2.3 Impact Quantification of Soft DC Links

Smart technologies like Soft DC Links are effective tools to improve the controllability and flexibility of distribution networks. Their applications can also defer or eliminate significant infrastructure reinforcements, which will thereby bring advantages to network growths.

A major challenge for the government and industry is to assess the impacts of new technologies on the existing networks and make robust decisions and conclusions in the face of significant uncertainties. For example, it is important for policy making or for strategic decision making to have the ability to characterise and quantify how differently the urban networks and rural networks perform with different integration levels of smart technologies. A large number of simulation studies based on the real networks are required to make such robust decisions and conclusions. However, it is challenging to obtain detailed data from a large number of real networks. In most cases, the access to the real network data is very limited. Many researchers spend a large amount of time searching for real network data and processing the data. Network modelling and simulation platforms are also limited in the open literature which can provide random-realistic representations of electrical distribution networks of different types (e.g. rural and urban).

Previous studies (detailed discussion in Section 2.3.3) on Soft DC Links were mainly conducted on specific test networks. The conclusions made from such studies have limited applicability to other networks. Statistical assessments for distribution networks with Soft DC Links is therefore required, where a number of random, realistic models of electrical distribution networks, rather than specific models shall be used to derive more generic and robust impact analysis of Soft DC Links. It will also provide guidelines for distribution network planners to decide whether the implementation of Soft DC Links is suitable for them.

1.3 Objectives and Contributions of the Thesis

The objectives and contributions of this thesis are listed below:

- Investigate the capability of SOP in bringing advantages to distribution network operation along multiple objectives simultaneously.

  A multi-objective optimisation framework was proposed to quantify the operational benefits of a distribution network with SOP, whereby power loss reduction, feeder load balancing and voltage profile improvement were considered as the objectives. A novel optimisation method, which integrates both global and local search techniques, was proposed to determine the set-points of SOP. Comparisons between SOP and network reconfiguration were carried out to show the outperformance of SOP in operation optimisation. Impacts of increased DG penetration on the network performance with SOP were investigated as well.

The proposed multi-objective optimisation framework can provide decision makers with a range of feasible solutions, from which preferable solutions can be selected by DNOs based on their priority and the network conditions.

- Propose an effective control method for the implementation of MVDC link in distribution networks, whereby real-time data of the active power flow at grid transformers (GT) are used to specify the set-points of an MVDC link. Such GT-based control method does not require communication links with each network node or power flow solutions at each time step, thus requiring less real-time measurements and having faster response speed compared to centralised control schemes. Within the GT-based control method, control strategies considering different objectives were developed. Network performances between the conventional alternative current (AC) operation and the operation with an MVDC link were conducted and compared. Impacts of the MVDC link using different control strategies for reducing network losses and increasing the DG hosting capacity were investigated.
- Carry out statistical assessments of Soft DC Links on a number of random, realistic models of distribution networks that have similar topological and electrical properties. Develop a model to optimally allocate Soft DC Links in distribution networks, which aims to minimise the network annual cost, including the investment and operational cost of Soft DC Links, as well as the annual energy loss cost of the network. The intermittent characteristics of DG outputs were taken into consideration by adopting a scenario generation method to transfer the continuous probability density functions of DG outputs into several representative scenarios. Impacts of Soft DC Links on the network

performances were evaluated and quantified in order to derive generic conclusions of the implementation of Soft DC Links in distribution networks.

1.4 Thesis Outline

The rest of the thesis is organised as follows:

Chapter 2 provides a review on the emerging challenges in distribution networks due to the integration of renewable energy sources and demand growth. Innovative solutions provided by power electronic devices in order to address these challenges are then discussed. At last, a state-of-the-art review on Soft DC Links, including their benefits, types, and previous studies are presented.

Chapter 3 describes a multi-objective optimisation framework that quantifies the benefits of using SOP in distribution network operation. A novel optimisation method that integrates both global and local search techniques was developed to determine the optimal set-points of SOP. Case studies were conducted to validate the effectiveness of SOP in improving network operation, as well as in accommodating high DG penetrations.

Chapter 4 describes a Grid Transformer-based control method for MVDC link. Within the control method, strategies considering different control objectives were proposed. Case studies on a real network model were carried out to analyse the impacts of an MVDC link. Network performances with the MVDC link using different control strategies were evaluated and compared.

Chapter 5 provides an impact quantification of Soft DC Links on a number of statistically-similar distribution networks. A model to optimally determine the allocation of Soft DC Links was developed with the objective to minimise the network annual cost.

Chapter 6 presents the conclusions, main findings of the thesis and recommendations for the future work.

Chapter 2 Literature Review

This chapter introduces the emerging challenges in distribution networks. Functionalities provided by power electronic devices to address these challenges are discussed. Previous studies on Soft DC Links, along with the identified research gaps are then provided.

2.1 Challenges in Distribution Networks

A number of challenges have been emerging in distribution networks as the way of generating, distributing and consuming electricity is changing with advanced technologies. An increasing number of renewable energy sources (RES), in the form of DGs, are being directly connected to distribution networks. Although the integration of DGs can offset active power demand, it may also add to reactive power consumption, lead to reverse power flows and contribute to fault currents. The increasing demand may cause low voltage issues. Specifically, the anticipated demand from heat pumps and electrical vehicles (EVs) [15] due to the electrification of heating and transportation requires extra capacity of networks. In the meanwhile of the continuous growth of DG and demand, a significant portion of network assets are reaching the end of their effective lifetime and in need of replacement [16]. Furthermore, DGs and new forms of demand can cause additional harmonic current flows and therefore threaten to breach the harmonic voltage limits. Key technical challenges are discussed in details in the following sub-sections.

2.1.1 Ageing Assets and Limited Hosting Capacity

The power systems in many parts of the world are facing a very significant challenge of ageing assets. Electrical transmission and distribution network rollout proceeded apace around 1950s and 1960s, but has slowed down in recent decades. Many significant items of equipment are now operating close to, or even beyond their expected retirement age [17]. Replacements are required. However, the current slow rate of replacements means it would take hundreds of years to renew all the infrastructures, and the capital costs of like-for-like replacements will be very high [18]. Innovative alternatives instead of traditional replacements are therefore needed to make the most effective use of existing network assets.

Distribution networks are being affected by the increasing integration of DGs. Some of the existing distribution circuits are operating near their capacities, limiting further DG connections. The future scenario of distribution networks remains unclear, especially with the uncertainties in local power productions and consumptions. For this reason, it is of paramount importance for DNOs to quantify their networks' capacities for hosting DGs, i.e. the network hosting capacity (HC) [19, 20]. In addition, since traditional reinforcement techniques are unlikely to deliver additional capacities in a short term, intelligent technologies are needed to improve the HC in active distribution networks.

2.1.2 Voltage and Thermal Constraints

Distribution networks have a relatively low X/R ratio compared to the case of transmission networks, meaning that active power flows have significant effects on node voltages at the distribution level. The continuous growth of demand, especially with the uptake of heat-pumps and EVs, can give rise to local low voltage issues. Specifically, EVs bring great challenges to voltage management since they can lead to abrupt load increases during charging periods. In contrast, the large-scale integration of DGs can cause over voltage issues. It is reported in Germany that the voltage rise caused by high installations of domestic photovoltaic (PV) has already started to occur [21]. It is also reported that on the Orkney Islands, the UK, where a large capacity of wind turbine was installed, an active network management scheme has been deployed on the Orkney distribution network to constrain some generator outputs under the conditions when over voltage limits are reached or nearly reached [22]. Clearly, smart technologies that allow renewable generation to continue operating while maintaining voltages within the statutory limits would provide great benefits.

Due to the demand growth as well as the local reverse power flows brought about by DGs, thermal limits of existing distribution feeders and transformers are envisaged to be exceeded. Demand management has been suggested as a solution to this problem, limiting the power flow along feeders at times of high demand or high power injections from DGs [11]. Thermal limits of the network assets vary in different weather conditions. Therefore, the use of dynamic ratings that account for actual or estimated equipment temperature is gaining favour as a way to increase the circuit capacity in real time [23].

Smart technologies are required to address both voltage and thermal problems caused by the integration of DGs, and the growth and uptake of new forms of electricity demand.

2.1.3 Other Technical Challenges

- ***Reverse Power Flows***

Distribution networks were historically designed for unidirectional power flows to customers, meaning the electricity that power plants generate is delivered to customers through transmission and distribution power lines. The reverse power flows caused by large injections from DGs can affect the control and protection systems used in distribution networks.

- ***Increase in Fault Levels***

Distribution networks were designed to be capable of interrupting significant fault currents. However, many types of DGs use directly connected rotating machines and these will contribute to the network fault levels [8]. In urban areas where the existing fault levels are approaching the ratings of switchgears, this increase in fault levels can be a serious impediment to the development of distributed generation schemes. Increasing the short-circuit ratings of distribution network switchgears and cables can be extremely expensive and difficult, particularly in congested city substations and cable routes. The fault level contribution of DGs can be reduced by introducing impedance between the generator and the network with a transformer or a reactor, but at the expense of increased losses and wider voltage variations of the generator. Effective fault current limiting technologies are required to maintain the safe operation of active distribution networks.

- ***Power Quality and Efficiency***

Electrical blackouts can lead to significant cost and disastrous impacts on the society, e.g. shutting down productions at companies and critical infrastructures such as telecommunication networks, financial services, water supplies and hospitals [24]. The increasing amount of intermittent renewable generation will lower the predictability and reliability of electricity supply. In the meantime, the electricity capacity margin is reducing, which increases the risk to the security of supply [4]. This calls for effective restoration strategies and post-fault measurements to retain the supply in distribution networks.

The sudden increase or decrease in power outputs due to the intermittent nature of RES can cause power quality problems, e.g. flickering lights. Harmonics caused by non-linear loads and generators with power electronic interfaces can lead to the failure of capacitors, overheat of transformers or metering inaccuracy. To address these issues, improvements in the control of distributed generation systems [25] and the reduction in network impedance shall be considered.

Electrical losses are an inevitable consequence of transferring electricity across networks and have significant financial and environmental impacts. For example, they contribute to approximately 1.5% of Great Britain's greenhouse gas emissions [26]. At present distribution networks have power losses in the range of 3-9%, which account for 80% of power losses in combined transmission and distribution networks. Higher losses are anticipated for distribution networks in 2030, as an increased utilisation of assets is envisaged [27]. Improved efficiency of electricity supply is required, since all these losses are eventually paid for by customers and needed to be minimised.

2.2 Role of Power Electronic Devices in Distribution Networks

As discussed in the preceding sections, in order to address the challenges in distribution networks, traditional reinforcements with higher capacity lines and substation transformers, or shorter feeders from substations placed at higher density can be adopted but at great expense [28]. It will also take a significant amount of time before such investments are fully implemented. The growing need for power quality, in conjunction with the large scale integration of renewables and the electrification of heating and transportation, have boosted the demand for new technologies in distribution networks. Visibility, controllability and flexibility are becoming essential features, where distribution-level power electronic devices can play a key role [18].

Power electronics has been used for bulk power transfer for over 60 years in high-voltage DC transmission systems (HVDC) and flexible AC transmission systems (FACTS) [29]. From these examples, analogies are being made to distribution networks. Specifically, power electronic converters can be considered for deployment in large numbers to provide ancillary services rather than only for critical bulk power transfer applications. At the distribution level, it becomes more cost-feasible to use voltage source converters (VSCs) to realise the required control functionalities, due to less expensive components and larger production quantities of power electronic units. It is expected that increasing power densities of power electronics and their reducing cost through market volume makes the prospect of reinforcing the conventional AC network with DC components more appealing.

The applications of power electronic devices for medium-voltage industrial drives, small and medium size DGs, and energy storage systems are already widely available and have been designed to be relatively compact and self-contained [30]. However, these kinds of devices are out of the scope of this thesis. In this section, the wide variety of functions offered by distribution-level power electronic devices, for instance, phase load balancing, active power filtering, voltage control, and power flow control, are discussed as follows.

Phase load imbalance, which is caused by the difference in consumption patterns of customers, can result in higher power losses and constraint the utilisation of feeder capacity. Compensators such as static synchronous compensator (STATCOM), back-to-back and multi-terminal VSCs, allow the exchange of instantaneous power among different phases. Therefore, current flows of a feeder can be rebalanced by using power electronic devices.

Active power filters, which are generally used for controlling current harmonics, have seen a variety of circuit configurations, control schemes, and applications due to the increasing concerns over power quality [31, 32]. There are applications of active power filters with railway traction equipment and within customer premises, but not as network elements compensating a group of customers. In recent years, the value for filtering at the network level with power electronic devices has been recognised by DNOs [11].

Distribution network voltages can be regulated with devices like STATCOM, static synchronous series compensator (SSSC) and dynamic voltage restorer (DVR) [33]. Moreover, devices like unified power flow controller (UPFC) [34], back-to-back and multi-terminal VSCs have the capability to control both active and reactive power flows, and hence further functional flexibility can be achieved. Another form of using power electronic devices for voltage regulation is electronic transformers [35], transformers with electronic or hybrid on-load tap changers (OLTCs) [36]. Compared to traditional OLTCs which adjust voltages of all the outgoing feeders in concert, electronic transformers have the advantage of controlling voltage levels on the individual feeders, enabling fast and smooth voltage regulation as well as little wear and tear.

Control of power flow in distribution networks is traditionally achieved by network reconfigurations through changing the status of switchgears, manually or automatically [37]. However, practical applications of frequent network reconfigurations are very limited due to the excessive costs and wear and tear of switchgears. In addition, the rerouted power flow cannot be managed precisely, and the protection coordination requirement restricts the changes in the power flow direction [38]. On the contrary, power electronic devices, such as back-to-back and multi-terminal VSCs, can be used to control power flows without the disadvantages of network reconfigurations, where flexible interconnections between feeders can be formed and power flows can be controlled in a dynamic and continuous manner as required.

Recently, several pilot projects have initiated to offer solutions in distribution networks using power electronic devices.

In the Top and Tail project [39], power electronic approaches have been considered at the last mile of the electricity network - the customer side, in order to regulate power quality and voltage, as well as to release additional capacity from legacy cables.

The Flexible Urban Networks Low Voltage project [40] has evaluated various functionalities that power electronic devices can provide to low-voltage distribution networks, including capacity sharing between substations, regulating of voltages and controlling of fault levels.

The Network Equilibrium project [41] focuses on the balance of voltages and power flows across distribution networks, aiming to integrate additional DGs within the networks more efficiently, while delivering benefits to the customers. Three methods have been proposed to achieve such objectives and one of them is to form “Flexible Power Links” by using power electronic devices. The Flexible Power Links will allow power transfers across two different 33 kV networks, which cannot currently be connected due to a number of issues, including circulating currents, protection grading and fault level constraints.

The ANGLE-DC project [42] aims to demonstrate a novel network reinforcement technique by converting an existing 33 kV AC circuit into DC operation via an MVDC link. It will be the first MVDC link in Europe and one of the first tests to convert circuits from AC to DC operation.

This thesis focuses on using VSC-based Soft DC Links to improve MV distribution network operation, as well as to increase network hosting capacity for DGs. Detailed discussions on the benefits, types, and previous work of Soft DC Links are presented in the next section.

2.3 Soft DC Links

2.3.1 Benefits of Soft DC Links

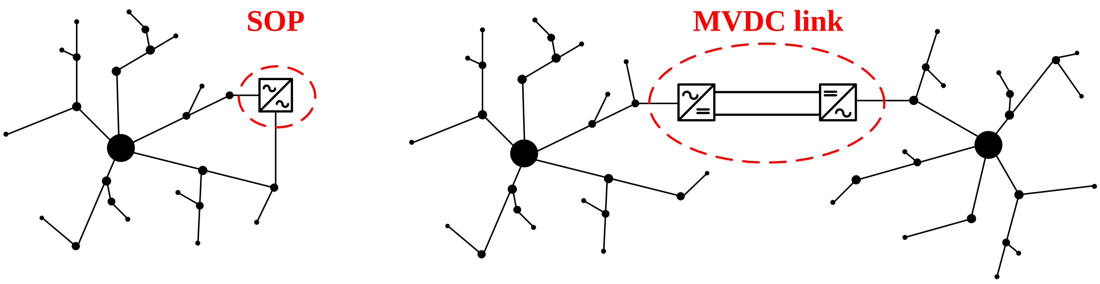
The most significant advantages provided by VSC-based Soft DC Links to MV distribution networks are [43, 44]:

- Active power exchange through connected feeders can be controlled in a continuous manner. Hence improved load balancing and loss reduction can be achieved;
- Reactive power output at each interface terminal of a Soft DC Link can be assigned as required, and therefore dynamic voltage supports can be achieved;
- Feeders can be interconnected regardless of their angular or rated voltage differences, which is critical for connecting the feeders that are supplied by different substations;
- With the VSC over current limiting, contributions to fault currents are small and controllable;
- Voltage imbalances, sags, flickers and low-order harmonics can be mitigated with VSC technology, and therefore power quality can be improved;
- Post-fault restoration to adjacent feeders can be achieved;
- Voltages and power flows throughout a broader network area can be controlled by adjusting both active and reactive power set-points of a Soft DC Link,

allowing for enhanced utilisation of existing assets and an increase in network hosting capacity.

2.3.2 Types of Soft DC Links

As discussed previously, Soft DC Links can be used to either connect adjacent feeders in a single distribution network, or to connect two or more distinct distribution networks. A schematic diagram of Soft DC Links installed in distribution networks is given in Figure 2.1.



(a) (b)

Figure 2.1 Schematic diagram of Soft DC Links in the forms of SOP (a) and MVDC link (b) in distribution networks

Power electronic topologies chosen to realise the functionalities of Soft DC Links are not limited to one type. Several options are feasible as shown in Figure 2.2, which include the following arrangements of VSCs:

- Back-to-back VSCs;
- Multi-terminal VSCs;
- Unified power-flow controllers (UPFC).

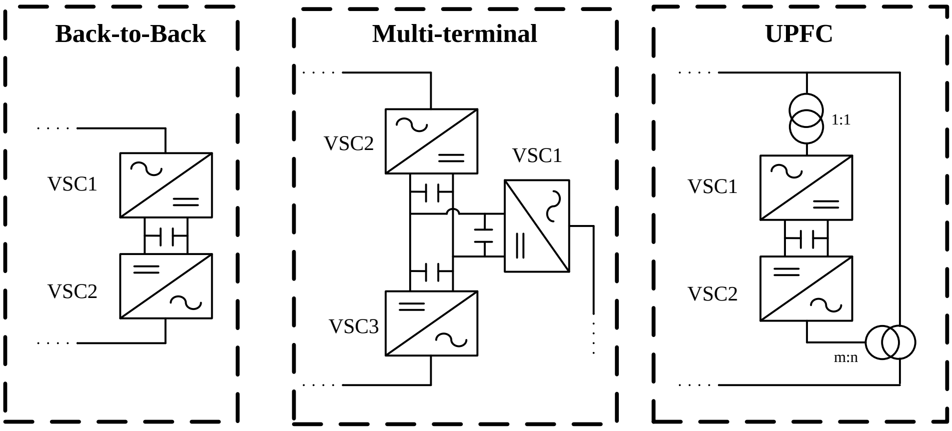


Figure 2.2 Topologies of VSC-based Soft DC Links [28]

A back-to-back VSC-based Soft DC Link consists of two VSCs connected via a common DC bus. Each VSC is controlled to allow active power exchange between the two AC interfaces while providing reactive power supports on each side. An asynchronous connection of two AC nodes can also be realised due to the intermediate AC/DC conversion stage involved with the device. From the back-to-back application, a point-to-point Soft DC Link can be formed by extending the DC bus in between, and having the two converters in different locations. A point-to-point Soft DC Link has the advantage of providing power flow control and voltage control to a broader area.

A multi-terminal VSC-based Soft DC Link is an extension of the back-to-back type, in which additional VSCs are connected to the common DC bus. The number of VSCs associated with a multi-terminal Soft DC Link is defined as 3 or greater. Many of the characteristics discussed for the back-to-back Soft DC Link are applicable to this type as well.

For back-to-back and multi-terminal VSC-based Soft DC Links, coupling transformers are usually equipped at the interface of each VSC with the connected feeder. There are also feasible transformerless topologies as proposed in [45] with reduced dimension and weight of the devices.

A UPFC-based Soft DC Link consists of two VSCs, with one in series and the other in shunt connecting to the feeders via transformers. The series converter injects voltage with controllable magnitude and phase angle, thereby controlling the power flow between connected feeders. The shunt converter supplies active power required by the series one, and provides reactive power support independently to the operation of the series converter. The power flow control capability of UPFC is determined not only by the device rating, but also dependent on the network topology, loading condition and device placement.

Since the back-to-back (point-to-point) VSC configuration offers the most flexibility in terms of power flow control capability, this thesis investigates the use of Soft DC Links in MV distribution networks with special focuses on 1) back-to-back VSC-based Soft DC Link (SOP) as an interconnector in a single network, and 2) point-to-point VSC-based Soft DC Link (MVDC link) connecting two distribution networks.

2.3.3 Previous Studies on Soft DC Links

The previous research on Soft DC Links will be discussed in the following with the research gaps identified in terms of:

- Multi-objective operation optimisation of a distribution network with SOP;
- Grid Transformer-based control of MVDC link;

- Impact quantification of statistically-similar distribution networks with Soft DC Links.

- ***Multi-objective Operation Optimisation of a Distribution Network with SOP***

The optimal operation achieved by using SOP in distribution networks has been investigated from different perspectives in the literature. In [46], the capability of SOP to regulate voltage profiles along feeders, and thus to facilitate DG integration was explored. Performances of other voltage control options, e.g. OLTC, reactive power compensation, and the use of meshing topology, were also carried out for comparative purposes. Results of the study elaborated that the presence of SOP can facilitate a large increase in possible DG penetration when compared with the passive network, and also when compared with other options for voltage control. A steady-state analysis framework was developed in [47] to quantify the benefits of SOP in distribution network operation, where active power loss minimisation and feeder load balancing were taken as the objective separately. An improved Powell's Direct Set method was developed and used for the determination of optimal SOP operation. In [48], a Jacobian matrix-based sensitivity method was proposed to define the operating region of an SOP when feeders at the two terminals of the SOP have various load and generation conditions. The exact SOP set-points were determined by adopting a non-linear optimisation considering separately different objectives, including voltage profile improvement, line utilisation balancing and energy loss minimisation. In [49], an algorithm that calculates the non-concurrent hosting capacity for demand and generation of each node in a distribution network was proposed. Such algorithm is used to appraise the capability of SOP in increasing the network hosting capacity. In order to mitigate the risk of voltage violations brought by large amounts of DG integration, a coordinated control method of voltage and reactive power for distribution networks was proposed in [50]. In this control method, the coordination of SOP, OLTC and capacitor banks was considered. In [51], the benefits of using multi-terminal SOP for feeder load balancing, and thus to relieve network congestion and make better use of existing assets were investigated. A combination of SOP with energy storage was considered in [52], in order to provide damping functionality and mitigate the effects of power output transients associated with photovoltaic systems. In [34], the use of UPFC as a centralised control device to attain better service quality in terms of all nodes voltage regulation, and power loss minimisation in loop distribution network was explored. In addition, a loop balance controller and a loop power flow controller, which have similar functionalities as SOPs, were proposed in [45] and [53], in order to investigate the devices' advantages in voltage control and power flow control.

In the above studies, operational benefits provided by SOPs in distribution networks were evaluated, whereby either single objectives were considered, or multiple objectives were considered separately. However, in order to explore potential benefits and achieve wide applications of SOPs, it is important to investigate the device's capability of bringing advantages along multiple criteria simultaneously. A multi-objective optimisation framework that quantifies the benefits of SOP in distribution network operation is therefore needed.

- ***Grid Transformer-based Control of MVDC Link***

A number of studies have investigated the benefits of using power electronic devices in distribution networks, and mainly focused on the deployment of the devices at one site of a network. However, the connection between distinct networks, i.e. an MVDC link, has not been considered much. The benefit of a point-to-point MVDC link is that it enables flexible power and voltage controls over a wider area.

Recent studies on MVDC links have been conducted from different perspectives. In [54], the utilisation of DC links to enhance the integration of DGs, and to reduce power losses was investigated through optimal power flows. The benefits of incorporating DC links in radial distribution networks were assessed in [55], where the maximum amounts of load or DG that can be accommodated in a network was determined. Benefits of using multi-terminal DC links to reduce power losses and improve voltage profiles, as well as to mitigate transient perturbations were analysed in [56]. A cost-benefit evaluation of using DC links in dense-load urban networks was carried out in [12]. The capability of using an MVDC link to increase network hosting capacity for DG connections was investigated in [57], where different levels of communication functionalities were considered. The above studies have focused on evaluating the benefits of MVDC links in reducing power losses, increasing system loadability or integrating more DGs, whereby centralised control schemes are required. However, centralised control schemes highly rely on the measurement and communication infrastructures which might be subjected to malfunctions or failure. To account for this, operational strategies for DC links in the case of a communication failure were proposed in [58]. Due to the limited number of available real-time measurements in distribution networks and the intermittency of renewable generation, distributed control strategies which require fewer measurements, are more viable than the centralised ones. In addition, the cost of associated ICT infrastructures in centralised control schemes accounts for a large portion of the total costs [14], which makes centralised control less attractive. Therefore, effective control strategies for MVDC links, which require less real-time measurements and have fast response speed, need to be investigated. In addition, since the performance of an MVDC link varies depending on the control objectives considered, different control strategies for an MVDC link need to be assessed and compared.

- ***Impact Quantification of Soft DC Links on Statistically-similar Distribution Networks***

Recently, models that quantify the cost-benefits of distribution networks with Soft DC Links have been proposed [59-61]. A stochastic planning model considering the investment in conventional assets, as well as in SOPs, to address the voltage and thermal issues caused by large PV penetrations was proposed in [59]. Results elaborated that SOPs hold significant option value under the uncertainty of future network growth. This work has been extended in [60] by considering the investment in several smart technologies, including demand-side response, coordinated voltage control, active power generation curtailment of DGs, and the utilisation of SOP. Through the case study on an 11 kV network, results demonstrated that smart technologies considerably alleviate the need for anticipatory conventional reinforcements as the network planners can take advantage of the strategic flexibility embedded in such technologies. In [61], the optimal siting and sizing of SOPs in order to reduce the annual cost of distribution network was investigated, whereby the long-term operation characteristics of DGs were taken into consideration. Results showed that the application of SOPs can significantly improve the operational economy of distribution networks.

In these previous works, case studies were carried out using specific network models. However, in network modelling, producing a single representation to mimic a real network with a set of input data, and making conclusions based on that single representation is not a robust approach. A single representation of a network may not capture all the diverse characteristics of the real one. The conclusions made from such studies have limited applicability to other networks. Therefore, it is important to generate as many as possible, realistic representations of a required distribution network with a single set of available inputs (i.e. statistically-similar networks). The statistics of the results obtained by using these ensembles of statistically-similar networks can then be used to derive robust conclusions.

Impacts of DG penetrations on the network performances and on the required capacities of Soft DC Links have not been fully quantified in the previous studies. The uncertainty around the magnitude, location, and timing of future DG capacity render DNOs unable to make fully informed decisions and integrate DG at a minimum cost. Therefore, statistical analysis quantifying the general impacts of Soft DC Links on distribution networks under various DG penetration conditions is required, where a number of random, realistic models of distribution networks rather than specific ones shall be used.

2.4 Summary

In this chapter, challenges in distribution networks brought by the ever-increasing customer demand, integration of DGs and ageing infrastructures were summarised. Power electronic devices, which can offer a variety of operational functionalities, are considered to deal with the emerging challenges and will play a key role to enable the controllability, flexibility and visibility of future distribution networks.

Soft DC Links, in the forms of SOPs and MVDC links, are one of the power electronic applications in distribution networks. Benefits provided by Soft DC Links and different types of Soft DC Links were discussed. A state-of-the-art review on the relevant studies on Soft DC Links was also presented, followed by the identified research gaps.

Benefits of using SOP to improve distribution network operation were explored in the literature. However, the potential of SOP in bringing advantages along multiple objectives simultaneously has not been investigated. In this thesis, a multi-objective optimisation framework that quantifies the benefits of SOP in distribution network operation was proposed. Moreover, a novel optimisation method to determine the SOP set-points was developed, which has the capability of searching for better and more diverse solutions in the multi-objective space.

The constrained capacity of a distribution network can be relieved by connecting to an adjacent network through an MVDC link. Recent studies on the benefit analysis of MVDC links mainly considered centralised control schemes, which require observability of the entire network and heavily rely on remote monitoring and the corresponding communication infrastructure. An efficient control method for MVDC links requiring fewer real-time measurements and less computation time is therefore developed. Network performances with an MVDC link using the proposed control method were assessed.

Previous studies have evaluated the benefits of Soft DC Links using specific network models. In addition, the impacts of DG penetrations on the network performance with Soft DC Links have not been fully quantified. In this study, impact quantification of Soft DC Links on a number of distribution networks with similar topological and electrical properties, but with different network layouts was carried out, in which various DG locations and penetrations were considered. From this statistical assessment, robust decisions and conclusions for the implementation of Soft DC Links can be derived.

Chapter 3 Multi-objective Operation Optimisation of a Distribution Network with SOP

This chapter investigates the multi-objective benefits provided by an SOP to distribution network operation, whereby power loss reduction, feeder load balancing and voltage profile improvement were considered.

3.1 Introduction

Over the past few decades, multi-objective optimisation problems have attracted considerable interests from researchers motivated by the real-world engineering problems [62]. Many multi-objective optimisation problems are solved under the concept of *a priori* method, in which the decision maker defines the importance amongst different objectives before the search performs, and the multi-objective problem is transformed into a single objective one. Afterwards, a classical single objective optimisation algorithm is used to find the optimum. The key drawback of the *a priori* method is the arbitrarily imposed limitation of the search space, which does not allow findings of all solutions in a feasible set [63]. In addition, since it is common that real-world objectives are incommensurable in nature and can be conflicting with each other, aggregating multiple objectives into one may result in losing significance. Pareto optimality, on the contrary, is based on a simultaneous optimisation of multiple objective functions. It provides a set of non-dominated solutions named Pareto optimal solutions, illustrating the nature of trade-offs among conflicting objectives. Evolutionary algorithms, e.g. the widely recognised SPEA2 [64] and NSGA-II [33] are suitable to solve multi-objective optimisation problems using the concept of Pareto optimality, since these techniques deal with a set of possible solutions simultaneously, which allow obtaining an entire set of Pareto optimal solutions in a single run. Particle Swarm Optimisation (PSO) is one of the most recently used evolutionary algorithms. It is a global search technique with the most attractive features of simple concept, easy implementation, fast computation and robust search capability. Compared with other evolutionary algorithms, PSO shows incomparable advantages in searching speed and precision [65]. There are different Pareto-based multi-objective PSO variants, and a state-of-the-art review was given in [66].

Despite the global exploration capability, evolutionary algorithms are comparatively inefficient in fine-tuning solutions (the exploitation) [67]. To overcome this deficiency and to enhance the search capability of evolutionary algorithms, appropriate integrations of global and local search techniques to maintain the balance between exploration and exploitation have been proposed. In [68], an adaptive local search method for hybrid evolutionary multi-objective algorithms was developed. In [69], a biogeography-based optimisation technique that combines the periodic re-initialisation with local search operators to search for a globally optimal solution was proposed. A memetic algorithm with a local search operator to improve the accuracy and convergence speed simultaneously was proposed in [70]. The impact of various local search methodologies on the multi-objective memetic algorithm was investigated in [71].

In this chapter, a multi-objective optimisation framework was developed to investigate the capability of SOP in improving network operation along multiple criteria simultaneously. In the framework, a mathematical model of SOP in distribution network was developed. Based on the model, a novel optimisation method, which integrates both global and local search techniques, was proposed to determine the optimal set-points of SOP. In this integrated method, Multi-Objective Particle Swarm Optimisation (MOPSO) serves as a global search technique to ensure the entire solution space is explored. A local search technique - the Taxi-cab method, is used to exploit and refine solutions based on the ones searched by MOPSO. Such integrated method can further improve the quality of the solution set.

The proposed optimisation framework was applied to a 69-bus distribution network. Impacts of high DG penetrations on the network performances with an SOP were evaluated. Assessments of the integrated method were conducted. Comparisons between SOP and network reconfiguration in operation optimisation were also carried out.

3.2 Mathematical Model of SOP in Distribution Networks

As discussed previously, an SOP can be implemented with different converter topologies. A back-to-back VSC-based SOP was considered here. A schematic diagram of a distribution network installed with an SOP is given in Figure 3.1.

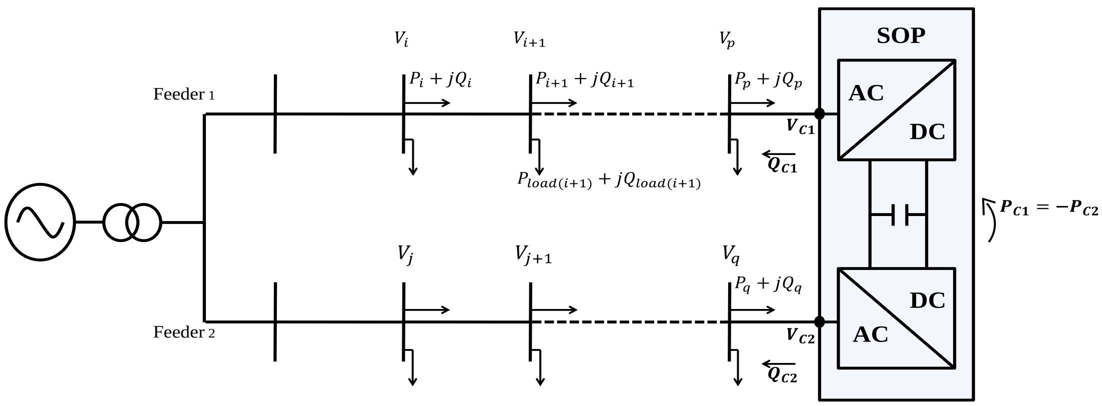


Figure 3.1 A distribution network installed with an SOP

Back-to-back VSCs can operate in four quadrants of the P-Q capability curve. The reactive power at both terminals of an SOP can be assigned independently to each other as required, which makes the device capable to provide flexible reactive power compensation to the network. In addition, the active power flow through an SOP can be controlled rapidly and accurately.

To fully evaluate the potential effects of SOP on steady-state network operations, a mathematical power injection model of SOP was developed. Using this model, active and reactive power injections at SOP terminals are integrated into the load flow algorithm without considering the detailed design of converter controllers. The backward forward sweep method was used for load flow calculations. Taking Feeder 1 in Figure 3.1 as an example, the load flow was calculated by the following recursive equations [72]:

$$P_{i+1} = P_i - P_{loss(i,i+1)} - P_{load(i+1)} = P_i - \frac{r_i}{|V_i|^2} \cdot (P_i^2 + Q_i^2) - P_{load(i+1)} \tag{3.1}$$

$$Q_{i+1} = Q_i - Q_{loss(i,i+1)} - Q_{load(i+1)} = Q_i - \frac{x_i}{|V_i|^2} \cdot (P_i^2 + Q_i^2) - Q_{load(i+1)} \tag{3.2}$$

$$|V_{i+1}|^2 = |V_i|^2 + \frac{r_i^2 + x_i^2}{|V_i|^2} \cdot (P_i^2 + Q_i^2) - 2 \cdot (r_i P_i + x_i Q_i) \quad i \in \{1,2, \dots , N_{bus}\} \tag{3.3}$$

where P_i and Q_i are the active and reactive power flowing from bus i to bus $i+1$. $P_{load(i)}$ and $Q_{load(i)}$ are the active and reactive power demand at bus i. $P_{loss(i,i+1)}$ and $Q_{loss(i,i+1)}$ are the power losses within the branch connecting buses i and $i+1$, and r_i and x_i are the resistance and reactance of that branch. V_i is the voltage at bus i. N_{bus} is the total number of buses in a network.

The operational boundaries of a back-back VSC-based SOP are:

$$P_{C1} = P_p - P_{loss(p,C1)} \tag{3.4}$$

$$P_{C2} = P_q - P_{loss(q,C2)} \tag{3.5}$$

where $P_{C1}$and P_{C2} are the active power flows of each VSC. $P_{loss(p,C1)}$ is the power loss between bus p and VSC 1, and $P_{loss(q,C2)}$ is the power loss between bus q and VSC 2.

The active power exchange of the two VSCs is constrained by:

$$P_{C1} + P_{C2} + P_{SOP\_loss} = 0 \tag{3.6}$$

where P_{SOP_loss} is the power losses at the SOP. These power losses are relatively low compared to the power losses of the entire network and thus can be neglected. Therefore, Eq. 3.6 is simplified as:

$$P_{C1} = -P_{C2} \tag{3.7}$$

The constraints on the device capacity and the terminal voltages are:

$$\sqrt{P_{C1}^2 + Q_{C1}^2} \leq S_{C1} \tag{3.8}$$

$$\sqrt{P_{C2}^2 + Q_{C2}^2} \leq S_{C2} \tag{3.9}$$

$$V^{min} \leq |V_{C1}| \leq V^{max} \tag{3.10}$$

$$V^{min} \leq |V_{C2}| \leq V^{max} \tag{3.11}$$

where Q_{C1} and Q_{C2} are the reactive power of each VSC. S_{C1} and S_{C2} are the rated capacity of each VSC. V^{min} and V^{max} are the minimum and maximum allowed voltages of the network. V_{C1} and V_{C2} are voltages at each terminal of an SOP.

Generally, the AC side of an SOP can be controlled in either PV mode or PQ mode. In this study the latter was considered. By choosing the optimal SOP set-points, power flows within a network can be controlled actively. Therefore, specific operational objectives can be achieved.

3.3 Problem Formulation

A schematic overview of the proposed multi-objective optimisation framework is presented in Figure 3.2. To determine the optimal set-points of an SOP, a novel optimisation method that integrates both global (the MOPSO method) and local (the Taxi-cab method) search techniques was developed. The performance metrics were compared with those of the conventional MOPSO method from the aspects of power loss reduction, feeder load balancing, and voltage profile improvement.

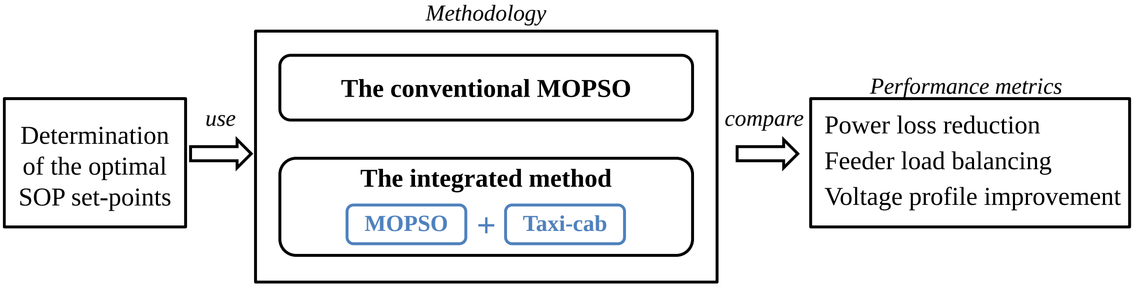


Figure 3.2 Schematic overview of the proposed framework

3.3.1 Objective Functions

Objectives considered in the optimisation framework were power loss reduction, feeder load balancing and voltage profile improvement. They are described in the mathematical expressions as follows:

$$OBJ = min[obj_1, obj_2, obj_3] \tag{3.12}$$

- ***Power Loss Reduction***

$$obj_1 = P_{loss} = \sum_{k=1}^{N_{branch}} I_k^2 \times r_k = \sum_{k=1}^{N_{branch}} \frac{P_k^2+Q_k^2}{|V_k|^2} \times r_k \tag{3.13}$$

where I_k, V_k, P_k and Q_k are the current flow, voltage drop, active and reactive power flow through branch k. r_k is the resistance of branch k. N_{branch} is the total number of branches.

- ***Feeder Load Balancing***

Feeder load balancing of a distribution network can be achieved by minimising the Load Balance Index (LBI), which is defined as:

$$obj_2 = LBI = \sum_{k=1}^{N_{branch}} \left(\frac{I_k}{I_{k-rated}}\right)^2 \tag{3.14}$$

where $I_{k-rated}$ is the rated current of branch k.

- ***Voltage Profile Improvement***

The improvement in voltage profiles of a distribution network can be achieved by minimising the Voltage Profile Index (VPI), which is defined as:

$$obj_3 = VPI = \sum_{i=1}^{N_{bus}} \left|V_i - V_{i,ref}\right| \tag{3.15}$$

where $V_{i,ref}$ is the nominal voltage of bus i, i.e. 1 p.u. was taken as $V_{i,ref}$ for all buses.

3.3.2 Constraints

In addition to the constraints illustrated in Eq. 3.1-3.11, the following limits were also considered:

- ***Bus Voltage Limits***

$$V^{min} \leq |V_i| \leq V^{max} \quad i \in \{1,2,\dots,N_{bus}\} \tag{3.16}$$

- ***Branch Capacity Limits***

$$|I_k| \leq I_k^{max} \quad k \in \{1,2,\dots,N_{branch}\} \tag{3.17}$$

where I_k^{max} is the maximum allowed current of branch k.

3.3.3 DG Penetration

In order to evaluate the impact of DG penetrations on distribution network operation, a range of DG penetrations was considered. DG penetration is defined as the ratio of the active power injection from DG to the maximum loading capacity of the network, and the minimum active power demand of the network was considered [73]. Since this case is recognised as the worst-case scenario [74, 75] and provides vulnerable network operating conditions.

3.4 Optimisation Framework

3.4.1 Pareto Optimality and Dominance

Under the concept of Pareto optimality, candidate solutions which satisfy the imposed constraints are compared according to their dominances, and thereby a set of non-dominated solutions that are of equal interests amongst different objectives can be obtained. Assuming a collection of objective functions are to be minimised, solution 'A' dominates solution 'B' if:

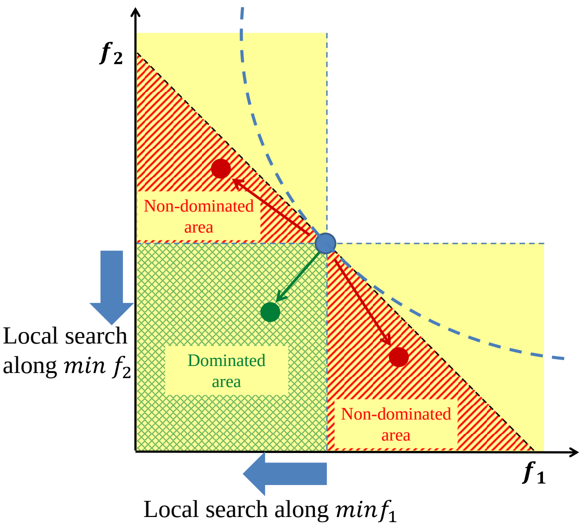
$$\forall\, n \in \left[1, 2, \dots, N_{obj}\right]: F_n(A) \leq F_n(B) \cap \exists\, n \in \left[1, 2, \dots, N_{obj}\right]: F_n(A) < F_n(B) \tag{3.18}$$

where F_n is the n_{th} objective function value of a solution, and N_{obj} is the total number of the objective functions. The set of all Pareto optimal solutions is called the Pareto set, and the mapping of the Pareto set in the solution space is called the Pareto frontier, on which alternative solutions bringing out the flexible operation of the network are presented. For instance, some solutions may lead to lower power losses while some others may cause branch loadings more balanced. The availability of the Pareto frontier provides a set of feasible solutions for the DNOs, and allows them to choose based on their priority or the network condition.

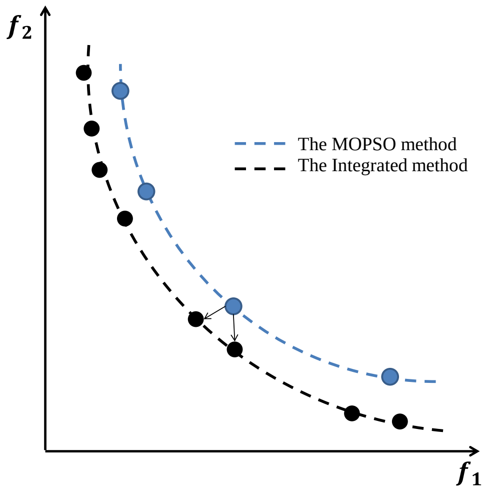
3.4.2 Overall Optimisation Framework

The schematic of the proposed method, which integrates the global search technique (i.e. the MOPSO method) and the local search technique (i.e. the Taxi-cab method [76]), is shown in Figure 3.3. The MOPSO is used for global search so as to obtain a set of Pareto optimal solutions. Then in order to avoid local optima trapping, the Taxi-cab method is used to fine tune the obtained Pareto solutions. The search space around each Pareto optimal solution is exploited further by the Taxi-cab method.

To illustrate the process of applying the Taxi-cab method to the Pareto solutions, a two-objective minimisation problem is taken as an example. In Figure 3.3 (a), the point at the centre of the dashed lines represents one Pareto solution. The Taxi-cab method can only optimise one objective function at a time. Therefore, the local search is carried out along the two objective functions separately, i.e. for one Pareto solution, a number of N_{obj} local searches are carried out and N_{obj} new solutions are generated. The possible area where new solutions might be located is shown in yellow. The possible area can be further divided into dominated area and non-dominated area. The dominated area refers to that both objective function values of the new solution are better than those values of the initial solution. The non-dominated area refers to that the new solution has a smaller value along one objective while sacrificing the value of another objective. The Taxi-cab method is then applied to all the Pareto solution points and an improved Pareto frontier is therefore obtained, as shown in Figure 3.3 (b). The Pareto solution points obtained by the MOPSO method are shown in blue, and the new Pareto frontier is shown in black. It can be seen clearly that with the integrated method (i.e. MOPSO+Taxi-cab), the Pareto frontier is pushed to lower values for both objectives, and better and more diverse Pareto solutions are generated.



(a) Applying Taxi-cab to one point of the Pareto frontier



(b) Applying Taxi-cab to all points of the Pareto frontier

Figure 3.3 Overall schematic of the integrated method (MOPSO+Taxi-cab)

3.4.3 Multi-Objective Particle Swarm Optimisation (MOPSO)

- ***Particle Swarm Optimisation (PSO)***

PSO algorithm is a population-based multi-point search technique developed by Eberhart and Kennedy in 1995 [77]. The search starts with a population of random search points named particles. Each particle is encoded by a position vector (x) containing M-dimensional information (i.e. M is the number of decision variables). In this study, the active and reactive power injections of the SOP: $[P_{C1}, Q_{C1}, Q_{C2}]$ (P_{C2} is not included since it is determined by P_{C1}) are considered as the decision variables. The position vector (x) is updated using the particle's velocity in successive iterations.

In each iteration, the velocity vector (v) of a particle is updated using two best values. The first one is the individual/personal best position (p_{best}) achieved by each particle itself. The other one is the global best position (g_{best}) obtained by any particle in the population, which is used as a guide leading the population towards optimum. The velocity and position update equations for the i_{th} particle are:

$$v_i^{iter+1} = \omega v_i^{iter} + c_1 r_1 \left(p_{best,i}^{iter} - x_i^{iter}\right) + c_2 r_2 \left(g_{best,i}^{iter} - x_i^{iter}\right) \tag{3.19}$$

$$x_i^{iter+1} = x_i^{iter} + v_i^{iter+1} \tag{3.20}$$

where ω is the inertia weight controlling the effect of the particle's previous velocity on the current one, i.e. the tendency of a particle to continue in the same direction it has been traveling. c_1 is the cognitive learning factor representing the attraction that a particle has toward its own best. c_2 is the social learning factor representing the attraction that a particle has toward the best among its neighbors. c_1 and c_2 are usually defined as positive constants [78]. r_1 and r_2 are two random numbers $\in [0,1]$, which are used to keep away from entrapment on local optimum as well as to permit the diversity of particles in the search space. The updating process of Particle Swarm Optimisation algorithm is illustrated in Figure 3.4.

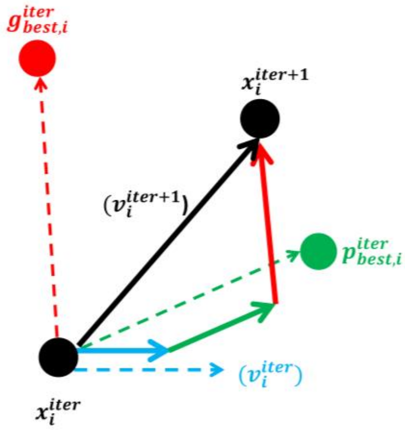


Figure 3.4 The updating process of a particle's position and velocity in Particle Swarm Optimisation

- ***Multi-Objective Particle Swarm Optimisation (MOPSO)***

- **Selection of p_{best} and g_{best}**

In Particle Swarm Optimisation algorithm, the selection of p_{best} and g_{best} relies on the fitness value of particles, which is determined by the objective function. However, in a multi-objective problem, the concept of the best position is substituted with a set of non-dominated solutions and each of the non-dominated solutions is a potential guide for particles.

The selection of p_{best} is straightforward: if the current position of the i_{th} particle dominates its personal best position, p_{best} is replaced by the current position. If the current and personal best positions non-dominate each other, p_{best} is replaced by either of them with equal probability. Otherwise, p_{best} remains unchanged.

Regarding the selection of g_{best}, research work has been carried out to avoid defining a new concept of the guide by adopting approaches that aggregate all the objectives into a single function [79, 80], or approaches that assign the objectives in order of importance. The solution is then obtained from optimising the most important one and proceeding according to the assigned order of importance [81, 82]. However, it is important to indicate that the majority of the currently proposed MOPSO approaches select guides based on the Pareto dominance. Several variations of the guide selection scheme are feasible and the MOPSO algorithm in this study is similar to the ones in [83-85], in which an archive is used to store the non-dominated solutions.

In the proposed MOPSO, the archive is updated iteratively using Pareto optimality. A random method is then used to select a guide for a particle from the archived solutions. Let a be the solutions in the archive A and x_i a particle's position. According to this method, if $A_{x_i} = \{a \in A | a \prec x_i\}$ (where the sign $\prec$ means 'dominate') is the set of archived solutions that dominate x_i, then the g_{best} for x_i is randomly chosen from A_{x_i} with equal probability. If $x_i \in A$, clearly A_{x_i} is empty. In this case the g_{best} for x_i is selected from the entire archive A [85]. Thus:

$$g_{best,i} = \begin{cases} a \in A \; with \; probability \; |A|^{-1} & if \; x_i \in A \\ a \in A_{x_i} \; with \; probability \; \left|A_{x_i}\right|^{-1} & otherwise \end{cases} \quad (3.21)$$

- **Retaining and spreading solutions in the archive**

It is important to restrict the size of the archive. Since the archive has to be updated in each iteration, the update may become computationally expensive if the size of the archive grows too large.

In the research of evolutionary multi-objective optimisation problems, different techniques have been adopted by researchers to bind the archive size while maintaining the diversity of solutions in the archive, e.g., niche technique [86], crowding distance sorting [33] and clustering [87]. More recently, the use of relaxed forms of dominance has been proposed. The main one adopted in Particle Swarm Optimisation is the ε-dominance method [88], which is used to filter solutions in the archive [66]. Moreover, it is found in [89] that when comparing it against the existing clustering techniques for fixing the archive size, the ε-dominance method obtains solutions with much faster speed. Therefore this method is adopted in the proposed MOPSO for retaining and spreading the non-dominated solutions in the archive. An example of using the ε-dominance method to filter solutions in an archive is illustrated in Figure 3.5.

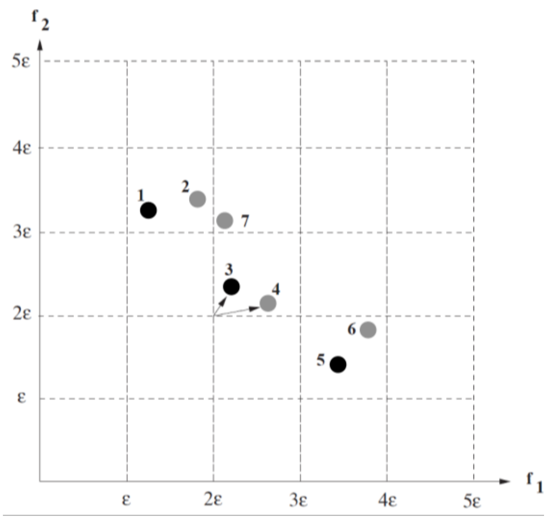


Figure 3.5 An illustration of using the ε-dominance method (assuming minimising f_1 and f_2 simultaneously): when selecting between solutions 1 and 2, solution 1 is preferred since it dominates solution 2 (same with selecting between solutions 5 and 6). Solutions 3 and 4 are incomparable. However, solution 3 is preferred since it is closer to the lower left corner represented by point (2ε, 2ε). Solution 7 is not accepted since its box, represented by point (2ε, 3ε) is dominated by the box represented by point (2ε, 2ε) [66]

- **Mutation operation**

The appropriate promotion of diversity in Particle Swarm Optimisation is an important issue in order to control its normally fast convergence [66]. Cauchy and Gaussian are two popular methods of mutation operations. An important difference between them is that the Cauchy distribution is heavier-tailed. This means that it is more prone to produce values that are far from its mean, thus making the Cauchy method have a higher chance of escaping premature convergences than the Gaussian method [90]. Therefore, in the proposed MOPSO algorithm, the Cauchy mutation operation is used. After each particle has completed its search, the Cauchy mutation is applied: if the previous position is dominated by the new one after mutation, the particle's position is then replaced by the new one. If neither of the previous position nor the new position dominates the other, one of them is selected to be that particle's position with equal probability. Otherwise, the position remains unchanged.

3.4.4 Taxi-cab Method

By applying the Taxi-cab method, a nonlinear function can be optimised in finite steps with fast convergence. The Taxi-cab method does not need any information of the derivative of the objective function, in which the search is performed by moving the decision variables along standard base vectors.

The process of the Taxi-cab method is as follows:

1) Select a particle from the archive and set its position as X;

2) Initialise the standard base vectors $e_m = [0, \dots, 1_m, \dots, 0]^T$, where $m = 1,2, \dots, M$, and M is the number of decision variables;

3) Select the objective function obj_n that to be optimised, where $n = 1,2, \dots, N_{obj}$. Set $X_0 = X$;

4) Let X_0 be the starting point of the search. Along each base vector, obj_n is treated as the function of one decision variable only, where an one-dimensional search technique, the golden section search [91] is applied to generate an optimal step size g_m. The search is performed by proceeding along each of the base vectors successively and generating a sequence of improved values along the objective function:

$$X_m = X_{m-1} + g_m e_m \tag{3.22}$$

5) The process is continued until X_M is obtained. Stop the search and set $n = n + 1$ then go back to step 3) if:

$$|obj_n(X_M) - obj_n(X_{M-1})| \leq convergence\ criteria \tag{3.23}$$

Otherwise, set $X_0 = X_M$ and go back to step 4);

The Taxi-cab method is applied to all particles in the archive after each iteration. Any new solutions obtained by the Taxi-cab method that are not dominated by any members in the archive are added into the archive, and any members in the archive which are dominated by the new solutions are deleted from the archive. This ensures that the archive always contains a set of non-dominated solutions.

3.4.5 Integrated Method (MOPSO and Taxi-cab)

In the integrated method, the MOPSO is used to explore the solution space globally, and the Taxi-cab method is used for fine-tuning the non-dominated solutions in the archive of the MOPSO. The pseudo code of the integrated method is shown in Figure 3.6.

1: archive $A = \emptyset$
2: for $i = 1 : N_{particle}$
3:     Initialize: $x_i \quad v_i$
4:     $EnforceConstraint(x_i)$
5:     $p_{best,i} = x_i$
6: end
7: $A = Dominance(p_{best})$
8: $iter = 0$
9: while $iter \leq MAXiter$
10:     for $i = 1 : N_{particle}$
11:         $v_i^{iter+1} = \omega v_i^{iter} + c_1 r_1 \left(p_{best,i}^{iter} - x_i^{iter}\right) + c_2 r_2 \left(g_{best,i}^{iter} - x_i^{iter}\right)$
12:         $x_i^{iter+1} = x_i^{iter} + v_i^{iter+1}$
13:         $EnforceConstraint(x_i)$
14:         $x_i = Mutate(x_i)$
15:         if x_i $dominates$ $p_{best,i}$
16:             $p_{best,i} = x_i$
17:         end
18:     end
19:     $A = Dominance(p_{best})$
20:     Taxi-cab (A)
21:     Update A
22:     $iter = iter + 1$
23: end

Figure 3.6 Pseudo code of the integrated method

At the beginning of the optimisation process, the archive A is empty (Line 1) and the positions and velocities of all particles are initialised randomly (Line 3). Since it is possible that the particle positions lie outside the feasible region, it must be ensured that the decision variables, which are the active and reactive power injections of SOP, are constrained within the SOP rated capacity. This is indicated in Line 4 and 13 by using the function $EnforceConstraint$, in which an upper and a lower limits are used to bind the particle positions. The initial personal best positions of all particles are set to their starting positions (Line 5). The function $Dominance$ (Line 7 and 19) is used to select the non-dominated solutions from all particles according to the concept of Pareto optimality, and to store them in the archive. In each iteration, the particle positions and velocities are updated using Eq. 3.19-3.20 (Line 11 and 12). Then the mutation operation (Line 14) as explained in Section 3.4.3 is applied to improve the diversity of solutions. Line 20 illustrates the local search procedure, where the Taxi-cab method is applied to the non-dominated solutions in the archive. When updating the archive (Line 21), the technique described in Section 3.4.3 is adopted for retaining and spreading the solutions in the archive.

3.5 Case Study and Results

3.5.1 Description of Test Network

The proposed multi-objective optimisation framework was developed in MATLAB and applied to a modified 69-bus distribution network [92]. The network is rated at 12.66 kV, with a total demand of 3802.19 kW and 2694.6 kVar, which was considered as the minimum demand. Four DGs were installed at bus 11, bus 12, bus 64 and bus 65, and an SOP was installed at $L72$, as shown in Figure 3.7. P_{loss}, LBI and VPI of the initial network are 225.01 kW, 10.82 and 23.26 respectively.

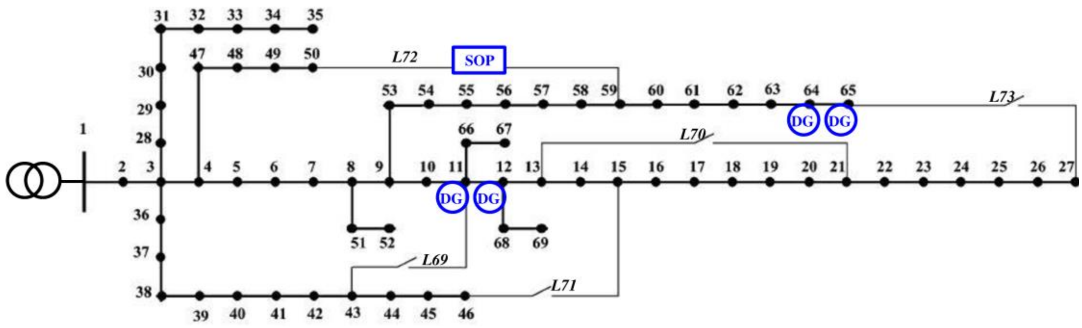


Figure 3.7 A modified 69-bus distribution network

Several assumptions were made:

- The system is three-phase balanced.
- The rated capacity of the SOP is 5 MVA.
- Buses with DG installations are PQ buses with unity power factor.
- The range of DG penetrations is from 0 to 200%, with a 5% increment.

3.5.2 Multi-objective Operation Optimisation Results

By applying the integrated optimisation method, a set of active and reactive power set-points of SOP can be found. Operating SOP at these set-points would obtain the optimal network performances along different objectives. Such results are presented in Figure 3.8, where the obtained Pareto optimal solutions for network operation under 50% DG penetration are shown in red circles. In addition, the results obtained by using the MOPSO method under the same network condition are shown in blue dots.

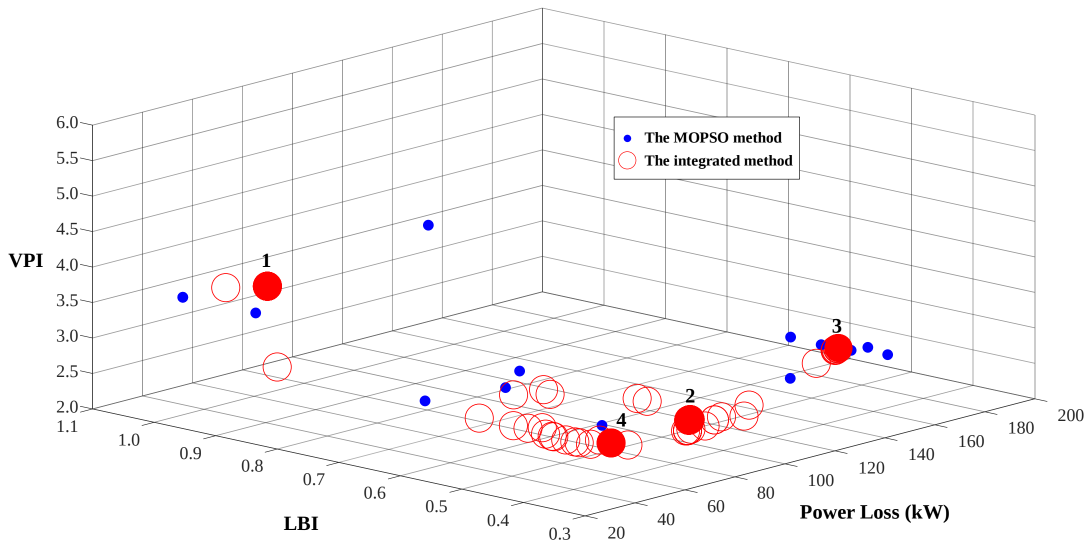


Figure 3.8 Pareto frontiers of network operation obtained by the MOPSO method and the integrated method (50% DG Penetration)

To illustrate the different performances of the Pareto optimal solutions, some of them were taken as examples here, as highlighted in solid circles and numbered 1-4 in Figure 3.8. Their values along the three objective functions were put into "()", and the corresponding set-points determined by the integrated method were put into "[]", which can be found in Table 3.1.

Table 3.1 The objective function values and corresponding set-points of Solutions 1-4 in Figure 3.8

Solution No.	**Set-points** [P_{c1}(kW), Q_{c1}(kVar), Q_{c1}(kVar)]	**Objective Function Values** (P_{loss} (kW), LBI, VPI)
1	[-622.2, 526.6, 1344.6]	(28.5, 0.9, 4.1)
2	[-347.9, 977.8, 2436.7]	(67.4, 0.3, 3.0)
3	[-84.2, 917.7, 3537.6]	(176.2, 0.5, 2.6)
4	[-659.4, 1022.3, 2051.3]	(43.2, 0.4, 2.8)

It can be seen that as Solutions 1-4 dispersed on the Pareto frontier, their values along the three objectives were different. Solution 1 gave the lowest power loss. Solutions 2 and 3 had the lowest values of load balance index and voltage profile index respectively. Regarding Solution 4, although not standing out in any single objective value, it had a moderate performance among different objectives and can be considered a trade-off option.

The corresponding two-dimensional, i.e. two-objective plots of the Pareto frontiers in Figure 3.8 are presented in Figure 3.9. It can be seen clearly that, the integrated method resulted in more numbers of Pareto optimal solutions than the MOPSO method. Moreover, better solutions were obtained by the integrated method, since these solutions resulted in smaller values for all objectives compared to those obtained by the MOPSO method.

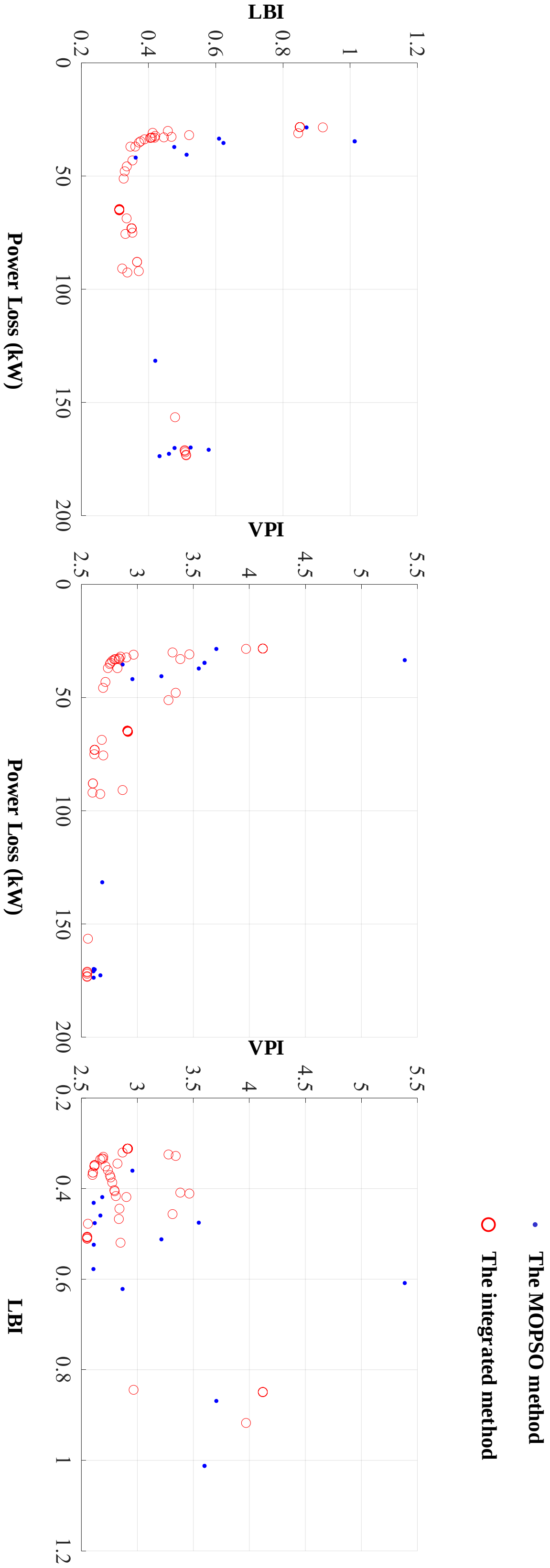


Figure 3.9 Two-dimensional plots of the Pareto frontiers shown in Figure 3.8

The extreme points along each axis of the Pareto frontier illustrate the optimal values that can be obtained along each objective function. These extreme points searched by both MOPSO and integrated methods are listed in Table 3.2. Values of power loss, load balance index, and voltage profile index are presented in a pair of brackets, i.e. (P_{loss}, LBI, VPI). The improvements in percentage were calculated in comparison to those values of the network under the same DG penetration but without the SOP.

In Table 3.2, the improvements in each column illustrate that, the network operation along all the objectives were improved by using SOP for all DG penetrations varying from 0 to 200%.

Table 3.2 reveals the correlations between different pairs of objective functions. The rows of 'min P_{loss} points' show that minimising the power loss resulted in decreases in LBI and VPI as well. The same situation occurred when minimising the LBI. As shown by the rows of 'min LBI points', P_{loss} and VPI were also decreased for all DG penetrations. The minimisation of VPI, however, caused increases in P_{loss} for all DG penetrations except for the case of zero DG penetration. It also caused increases in LBI when DG penetrations were high. Such conflictions are marked in red in Table 3.2.

It can be observed that improvements obtained by the integrated method were higher than those of the MOPSO method along all objectives and for all DG penetrations. This was due to the exploitation capability of the local search technique to fine tune the Pareto non-dominated solutions. The number of solutions obtained by the integrated method was 100, which reached the restricted archive size, whilst the average number of solutions found by the MOPSO method was 42. This proved that the integrated method is capable to find more diverse Pareto solutions, and hence providing enhanced feasibility for decision making.

Table 3.2 Extreme points obtained by MOPSO and integrated methods & corresponding improvements to the case without SOP

DG Penetration		**0**	**50%**	**100%**	**150%**	**200%**
Without SOP		(225.0, 10.8, 23.3)	(97.7, 4.3, 11.5)	(107.9, 2.2, 2.2)	(227.5, 3.7, 10.3)	(436.6, 7.3, 19.4)
MOPSO	min$\boldsymbol{P_{loss}}$ point	(60.0, 2.6, 9.3)	(29.2, 1.0, 4.9)	(50.2, 0.8, 1.9)	(121.2, 2.3, 7.6)	(234.8, 4.6, 11.9)
	Improvement	73.3%	70.1%	53.5%	46.7%	46.2%
Integrated (MOPSO+Taxi-cab)	min$\boldsymbol{P_{loss}}$ point	(60.0, 2.4, 9.2)	(28.5, 0.9, 4.1)	(49.7, 0.8, 1.8)	(119.3, 2.1, 6.5)	(233.5, 4.8, 11.6)
	Improvement	73.3%	70.8%	53.9%	47.6%	46.5%
MOPSO	min$\boldsymbol{LBI}$ point	(190.2, 1.0, 6.9)	(95.4, 0.3, 3.2)	(70.7, 0.7, 1.9)	(128.5, 2.1, 5.2)	(255.4, 4.3, 9.0)
	Improvement	90.7%	93.0%	68.2%	43.2%	41.1%
Integrated (MOPSO+Taxi-cab)	min$\boldsymbol{LBI}$ point	(137.9, 1.0, 6.7)	(67.4, 0.3, 3.0)	(61.2, 0.7, 1.9)	(122.5, 2.0, 5.1)	(246.4, 4.1, 8.9)
	Improvement	90.7%	93.0%	68.2%	45.9%	43.8%
MOPSO	min$\boldsymbol{VPI}$ point	(197.2, 1.2, 5.9)	(174.0, 0.6, 2.6)	(187.9, 1.9, 1.8)	(977.5, 5.4, 3.5)	(1052.8, 7.1, 6.9)
	Improvement	74.7%	77.4%	18.2%	66.0%	64.4%
Integrated (MOPSO+Taxi-cab)	min$\boldsymbol{VPI}$ point	(196.5, 1.2, 5.9)	(176.2, 0.5, 2.6)	(113.3, 1.2, 1.7)	(970.4, 5.5, 3.4)	(1509.2, 11.2, 6.1)
	Improvement	74.7%	77.4%	22.7%	67.0%	68.6%

The numbers in brackets represent the optimisation results of power loss, load balance index and voltage profile index, i.e. (P_{loss} (kW), LBI, VPI). The numbers marked in red represent the results that are worse than the case without SOP.

3.5.3 Impact of DG Penetrations on SOP Performance

In order to evaluate the impact of DG penetrations on the network operation, a range of DG penetrations were set as input during the optimisation process. For each penetration, a set of non-dominated solutions were obtained by the integrated method and plotted against that penetration value. Hence, variations of the objective functions with increased DG penetrations were obtained as shown in Figure 3.10, where each ‘o’ denotes one non-dominated solution.

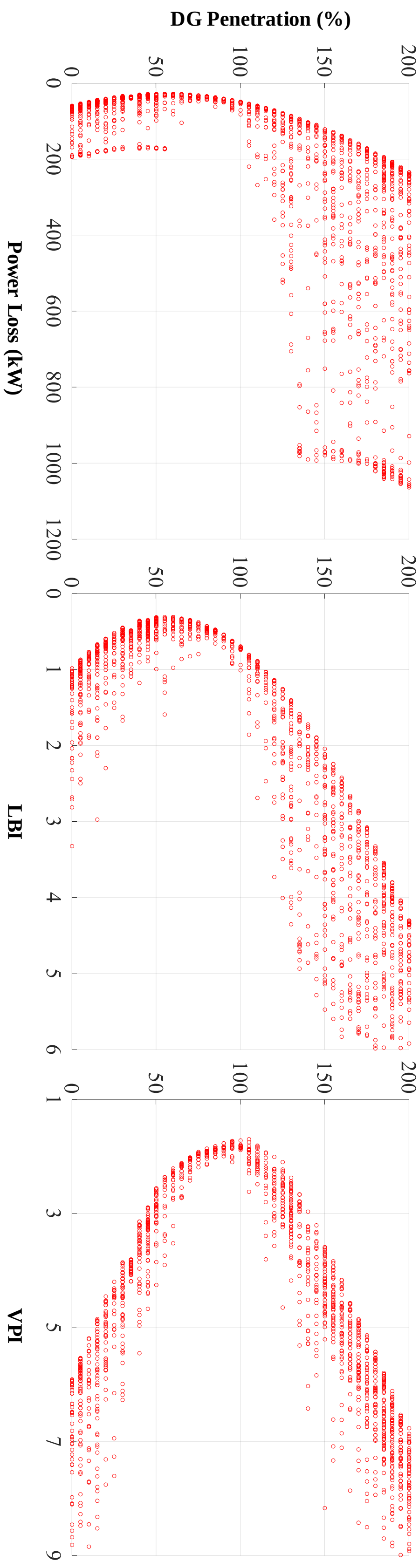


Figure 3.10 Variations of the objective functions with increased DG penetrations

It is observed in Figure 3.10 that, all the variations present U-shape trajectories. The network power loss, load balance index and voltage profile index started to decrease when DG penetration increased from 0. Once these minimum values were reached, if the DG penetration continued to increase, the objective function values started to increase. With further increase of the DG penetration, the objective function values were even higher than those of the network without DG. Figure 3.10 also provides an optimal range of DG penetrations that leads to improved network operations. For the test network under study, the optimal range of DG penetrations was around 20%-80%.

3.5.4 Performance Assessment of the Integrated Method

The performance assessment of multi-objective optimisation methods is different from that of single-objective optimisation methods, since a set of solutions rather than a single one are obtained. The diversity metric (Δ) and the mean ideal distance metric (MID) were used in this study to evaluate the quality of Pareto solutions. These two metrics give visions of how the Pareto solutions are dispersed and how they are close to the ideal values, which are formulated as follows:

$$\Delta = \sqrt{\sum_{n=1}^{N_{obj}} \left(max_{j=1,\ldots,N_{PS}}\{of_n^j\} - min_{j=1,\ldots,N_{PS}}\{of_n^j\} \right)^2} \tag{3.24}$$

$$MID = \sum_{j=1}^{N_{PS}} C_j / N_{PS} \tag{3.25}$$

where n denotes the n_{th} objective function and N_{obj} is the number of objective functions. j is the j_{th} Pareto solution in the Pareto set and N_{PS} is the number of solutions in the Pareto set. of_n^j is the value of the n_{th} objective function corresponding to the j_{th} solution. $max_{j=1,\dots,N_{PS}}\{of_n^j\}$ and $min_{j=1,\dots,N_{PS}}\{of_n^j\}$ represent the maximum and the minimum values of the n_{th} objective function. C_j is the Euclidean distance of the j_{th} solution from the ideal point $(0,0,0)$.

The larger the diversity metric (Δ), the more diverse the Pareto solutions are. The smaller the mean ideal distance metric (MID), the closer to the ideal point the Pareto solutions are. These two metrics were calculated based on the solutions obtained by the integrated method as well as the MOPSO method and are listed in Table 3.3.

Table 3.3 Performance metrics of Pareto solutions obtained by the MOPSO and integrated methods

Metrics / Methods	diversity Δ	mean ideal distance MID
The MOPSO method	8.00	5.02
The integrated method	10.02	4.52
Improvement (%)	25.3%	10.0%

As shown in Table 3.3, the integrated method improves Δ by 25.3% compared to that obtained by the MOPSO method, which illustrates that the integrated method results in more diverse solutions. The improvement of MID by 10% shows that, the integrated method is capable of obtaining Pareto solutions with higher quality than the MOPSO.

3.5.5 Comparisons of SOP with Network Reconfiguration

Comparisons of SOP and network reconfiguration in operation optimisation on the 69-bus distribution network with different DG penetrations are shown in Table 3.4.

Results listed are the optimal points along each objective function, which were selected from the Pareto frontiers obtained by using SOP and reconfiguration respectively. Again, the values of power losses, load balance index, and voltage profile index are presented in a pair of brackets, i.e. (P_{loss}, LBI, VPI), and improvements in percentage were calculated in comparison to those values of the network without reconfiguration or SOP. The results of Table 3.4 are visualised in Figure 3.11.

It can be seen from Table 3.4 that, with different DG penetrations, SOP outperformed network reconfiguration along all objective functions. For example, when the DG penetration is 50%, the power loss reduction obtained by reconfiguration is 37.2% while the reduction obtained by SOP is 70.8%. Under the same condition, improvements of load balance and voltage profile obtained by reconfiguration are 12.1% and 68.4%, while the corresponding improvements obtained by SOP are 93.0% and 77.4%.

Table 3.4 Comparisons of SOP and network reconfiguration in operation optimisation on the 69-bus distribution network

DG Penetration		0	50%	100%	150%	200%
Without reconfiguration /SOP		(225.0, 10.8, 23.3)	(97.7, 4.3, 11.5)	(107.9, 2.2, 2.2)	(227.5, 3.7, 10.3)	(436.6, 7.3, 19.4)
Network Reconfiguration	min$\boldsymbol{P_{loss}}$ point	(105.7, 6.3, 12.2)	(61.4, 3.8, 7.3)	(75.7, 2.6, 2.9)	(155.4, 2.7, 6.1)	(296.8, 3.8, 12.3)
	Improvement	53.0%	37.2%	29.8%	31.7%	32.0%
SOP	min$\boldsymbol{P_{loss}}$ point	(60.0, 2.4, 9.2)	(28.5, 0.9, 4.1)	(49.7, 0.8, 1.8)	(119.3, 2.1, 6.5)	(233.5, 4.8, 11.6)
	Improvement	73.3%	70.8%	53.9%	47.6%	46.5%
Network Reconfiguration	min$\boldsymbol{LBI}$ point	(106.2, 6.1, 13.7)	(61.6, 3.7, 6.6)	(105.4, 2.1, 2.2)	(279.4, 2.3, 4.3)	(501.7, 4.4, 19.8)
	Improvement	43.2%	12.1%	2.0%	38.7%	40.0%
SOP	min$\boldsymbol{LBI}$ point	(137.9, 1.0, 6.7)	(67.4, 0.3, 3.0)	(61.2, 0.7, 1.9)	(122.5, 2.0, 5.1)	(246.4, 4.1, 8.9)
	Improvement	90.7%	93.0%	68.2%	45.9%	43.8%
Network Reconfiguration	min$\boldsymbol{VPI}$ point	(114.9, 6.3, 9.9)	(100.2, 4.2, 3.6)	(106.0, 2.1, 1.8)	(170.6, 3.1, 4.0)	(320.3, 4.6, 7.9)
	Improvement	57.3%	68.4%	20.7%	61.4%	59.1%
SOP	min$\boldsymbol{VPI}$ point	(196.5, 1.2, 5.9)	(176.2, 0.5, 2.6)	(113.3, 1.2, 1.7)	(970.4, 5.5, 3.4)	(1509.2, 11.2, 6.1)
	Improvement	74.7%	77.4%	22.7%	67.0%	68.6%

The numbers in brackets represent the optimisation results of power loss, load balance index and voltage profile index, i.e. (P_{loss} (kW), LBI, VPI).

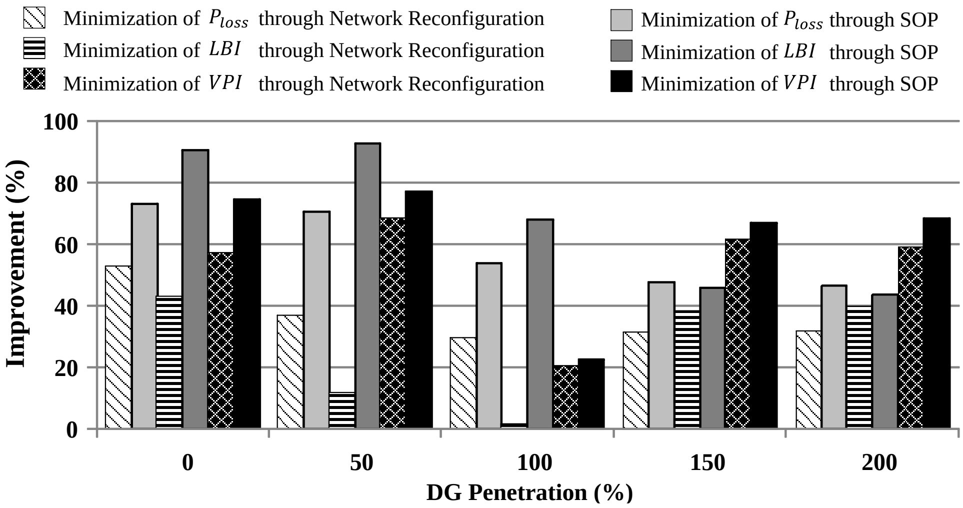


Figure 3.11 Comparisons of the improvements along different objectives obtained through network reconfiguration and SOP

3.6 Summary

A multi-objective optimisation framework was proposed to improve the operation of a distribution network with SOP. Power loss reduction, feeder load balancing and voltage profile improvement were taken as the objectives, and a variety of DG penetrations were taken into consideration. Firstly, a load flow algorithm incorporating the model of SOP was developed. Then a novel optimisation method that integrates both global and local search techniques was proposed to determine the optimal set-points of SOP. In this integrated method, a MOPSO algorithm is used to explore the solution space globally, which contains an archive to store the non-dominated solutions, as well as a mutation operator to search for a wider space and avoid pre-convergences. A local search technique - the Taxi-cab method is used for solution space exploitation, which refines the quality of non-dominated solutions in the archive of MOPSO and enhances the search capability.

The multi-objective optimisation framework was applied to a 69-bus distribution network. The results elaborated that SOP is an effective tool to improve the network operation in power loss reduction, feeder load balancing and voltage profile improvement. With the DG penetration increasing from 0 to 200%, on average, an SOP reduces power losses by 58.4%, balances feeder loadings by 68.3% and improves voltage profiles by 62.1%, all compared to the case without an SOP. The analysis of the impact of DG penetrations on SOP performance showed that, the use of SOP facilitates a large increase in DG penetration and provides a significant increase in the flexibility of network operation. When compared with the conventional MOPSO algorithm, the proposed integrated method increases the diversity metric by 25% and reduces the mean ideal distance metric by 10%. It is also found that the network with an SOP outperformed the one using network reconfiguration in operation optimisation under various DG penetrations. With the DG penetration increasing from 0 to 200%, on average, an SOP outperforms network reconfiguration on power loss reduction, feeder load balancing and voltage profile improvement by 21.7%, 41.1% and 8.7% respectively.

Chapter 4 Grid Transformer-based Control of MVDC Link

In this chapter, a real-time control method of an MVDC link, namely the Grid Transformer-based control, is proposed to investigate the impacts of an MVDC link on the performances of distribution networks.

4.1 Introduction

In this chapter, a real-time control method of an MVDC link, namely the Grid Transformer (GT)-based control was proposed, in which net active power through the network grid transformers is used to determine the MVDC link set-points.

The GT-based control method is considered to reduce the costs associated with communication and measurement systems significantly compared to centralised control schemes, because it only requires a few measurement points in a network (i.e. at the grid transformers). The high dependency of the centralised control on measurement and communication infrastructures, the limited number of available real-time measurements in distribution networks, and the intermittent characteristic of demand and distributed generation all make the GT-based control method more viable and attractive than centralised ones.

Using the GT-based control method, control strategies considering different objectives, i.e. power loss reduction (PLR), feeder load balancing (FLB), voltage profile improvement (VPI), and compromise options providing trade-offs among them were developed through a number of offline studies, where an improved multi-objective Particle Swarm Optimization (MOPSO) method was applied to the network with historical demand and generation data.

The proposed GT-based control method is used in the ANGLE-DC project [42]. This project aims to demonstrate a novel network reinforcement technique by converting an existing AC circuit to DC operation, and to trial the first flexible MVDC link in Europe. Assessments and comparisons between different GT-based control strategies were carried out on the ANGLE-DC network model. Impacts of the MVDC link on network performances with high DG penetrations were investigated.

4.2 MVDC Link in Distribution Networks

Figure 4.1 shows a schematic diagram of an MVDC link connecting two distribution networks. The MVDC link is constructed via fully controllable power electronic devices. A VSC station is used for the conversion between AC and DC at each terminal of the MVDC link. The MVDC link allows for active power exchange between the two terminals as well as reactive power supports at both sides. The VSC can perform as the control of: a) DC voltage V_{dc}; b) active power P; c) AC voltage V_{ac}; d) reactive power Q and e) AC frequency f. Typical control modes of an MVDC link under normal network operating conditions are listed in Table 4.1, where one VSC station controls the active power flowing through the link, and the other VSC station is used to maintain the DC voltage. In addition, for each VSC station either the reactive power or the AC side voltage can be controlled.

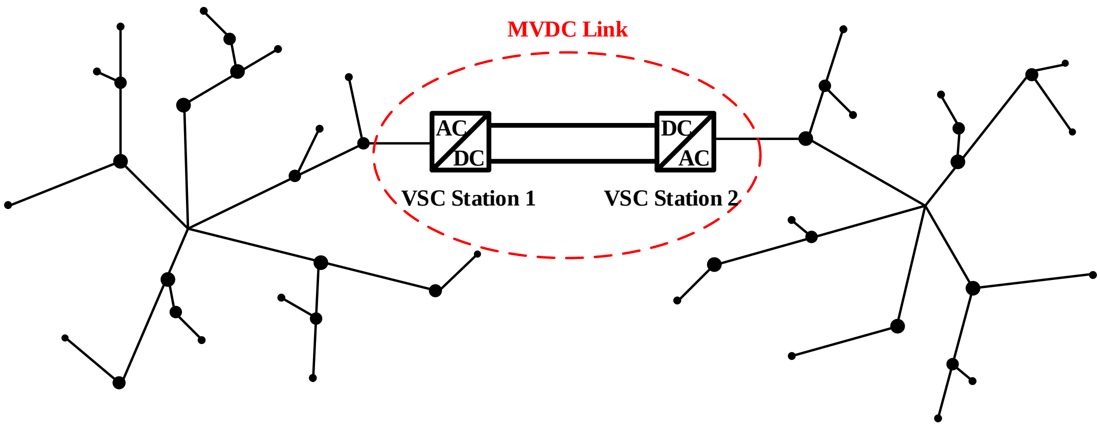


Figure 4.1 An MVDC link between distribution networks

Table 4.1 Control modes of an MVDC link under normal operating conditions

Control Mode	VSC Station 1	VSC Station 2
1	PQ/PV_{ac}	$V_{dc}Q/V_{dc}V_{ac}$
2	$V_{dc}Q/V_{dc}V_{ac}$	PQ/PV_{ac}

4.3 Modelling of MVDC Link

In this study, $PV_{ac} - V_{dc}V_{ac}$ was selected as the control mode of the MVDC link, and the reactive power outputs were adjusted in real time to maintain the voltage at specified value, e.g. 1 p.u. It is considered that fewer converters with higher power ratings are preferred than more converters with lower ratings of each. Since higher power rating VSC has the merits of higher efficiency, lower power losses and fewer peripheral devices associated, such as filters and line reactors. In addition, the footprint of the VSC station can be reduced with fewer VSCs [11].

The mathematical power injection model of an MVDC link was similar to that of an SOP as presented in Chapter 3, with following modelling constraints considered:

- ***Active Power Constraints:***

$$P_{VSC1} + P_{VSC2} + P_{DC-loss} = 0 \tag{4.1}$$

where P_{VSC1}, P_{VSC2} are the active power flow through each VSC station. $P_{DC-loss}$ is the loss within an MVDC link, which is relatively low (approximate 1~2% of the active power flowing through the link [93]) compared to the total losses within the network and thus can be neglected. Therefore, Eq. 4.1 can be simplified as:

$$P_{VSC1} = -P_{VSC2} \tag{4.2}$$

- ***Reactive Power Constraints:***

$$Q_{VSC,n}^{min} \leq Q_{VSC,n} \leq Q_{VSC,n}^{max} \quad (n = 1,2) \tag{4.3}$$

where $Q_{VSC,n}$ is the reactive power at the n_{th} terminal of the MVDC link (in this study $n = 1, 2$). $Q_{VSC,n}^{min}$ and $Q_{VSC,n}^{max}$ are the lower and upper limits of reactive power provided by the VSC station at terminal n. $Q_{VSC,n}^{max}$ is positive indicates that reactive power is injected to the network, and $Q_{VSC,n}^{min}$ is negative indicates that reactive power is absorbed from the network.

- ***Capacity Constraints:***

$$\sqrt{P_{VSC,n}^2 + Q_{VSC,n}^2} \leq S_{VSC,n} \tag{4.4}$$

where $S_{VSC,n}$ is the rated capacity of the VSC station at the n_{th} terminal of the MVDC link.

4.4 GT-based Control Method

Figure 4.2 gives an overview of the proposed GT-based control method, whereby data from the GTs are supplied to the controller of the MVDC link by a direct communication link [94]. Compared to the centralised control schemes, which require observability of the entire network and heavily rely on the remote monitoring and the corresponding communication infrastructure [95], the GT-based control is relatively simpler with lower cost, making the distributed control schemes attractive interim options [96, 97]. In Figure 4.2, Network 1 has a large amount of DG connections, and therefore power flow within Network 1 is becoming problematic and/or even approaching its voltage and thermal limits. In this context, Network 1 is focused on and the net power flows through its GTs are measured in real time to determine the set-points of the MVDC link.

It can be seen in Figure 4.2 that, a set of response curves with different control objectives are used in the GT-based control method. A response curve defines the linear relation between the active power set-point of the MVDC link (P_{MVDC}), and the net active power flowing through the GTs (P_{GT}). The idea of using the response curves is that, the adequate active power provided by the MVDC link is related to the net active power flowing through the GTs. When the net active power measured at the GTs is positive, i.e. the demand in the network is greater than the DG output, active power is required to be imported into the network. In this case, the active power provided to the network via the MVDC link would support the network's electricity demand. When the net active power measured at the GTs is negative, i.e. the DG output in the network is greater than the demand, active power is required to be exported from the network. In this case, exporting active power from the network via the MVDC link would support to consume the surplus generation in the network. However, different control objectives of the response curves lead to distinct performances of an MVDC link. In this study, a multi-objective optimisation model was used to derive response curves with different objectives. Evaluations and comparisons among these control strategies were carried out.

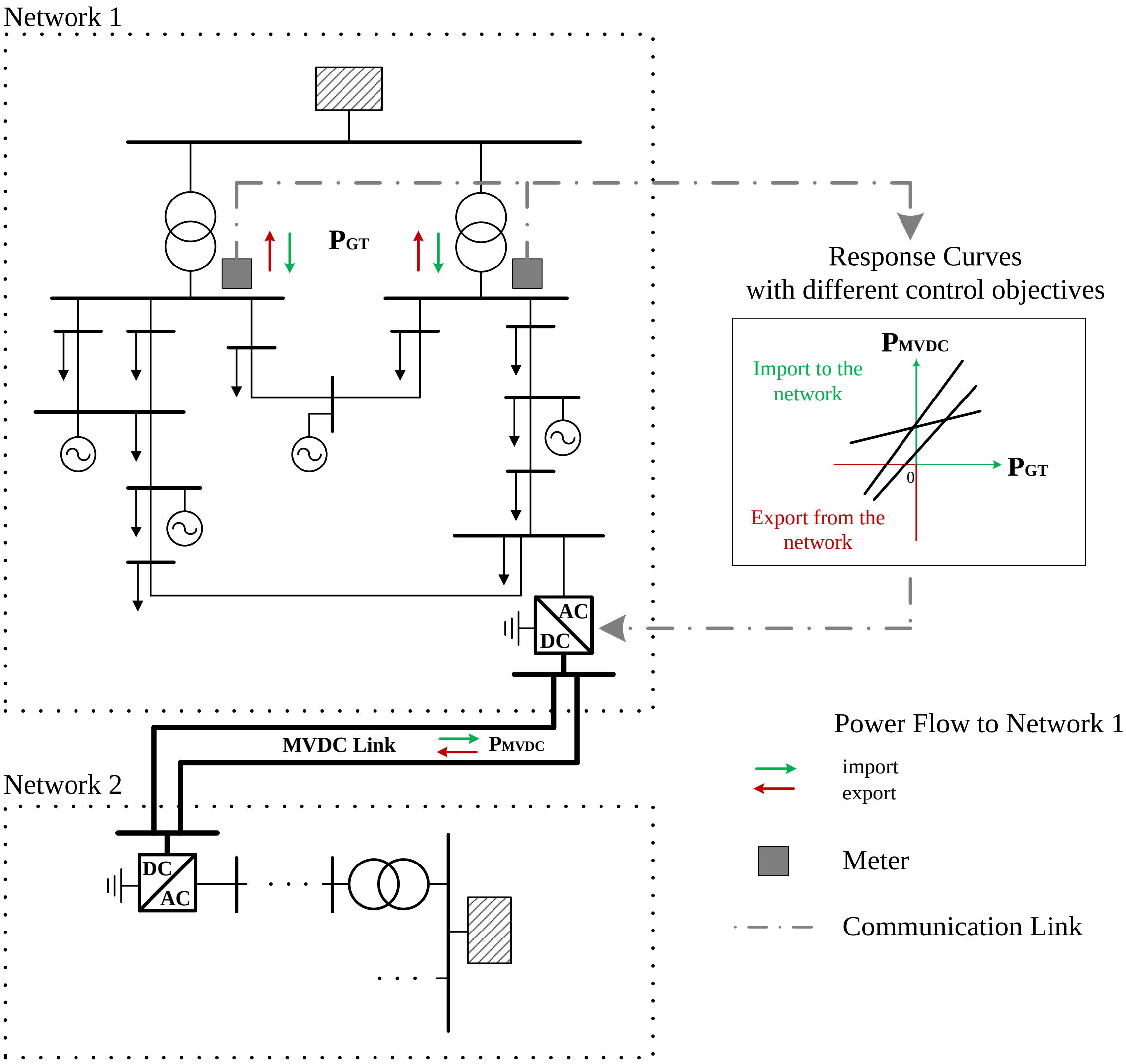


Figure 4.2 Overview of the proposed GT-based control

4.4.1 Problem Formulation

The determination of response curves with different objectives was formulated as a multi-objective optimisation problem. The operational objectives considered are formulated as:

$$Minimise\ [f_1, f_2, f_3] \tag{4.5}$$

where f_1 is the objective function for Power Loss Reduction (PLR), where active power losses in feeder lines and transformers of a network were considered:

$$f_1 = PLR = \sum_{k=1}^{N_{branch}} I_k^2 \times r_k \tag{4.6}$$

In Eq. 4.6, I_k is the current flowing through branch k. r_k is the resistance of that branch, and N_{branch} is the total number of branches including lines and transformers.

f_2 is the objective function for Feeder Load Balancing (FLB). The balance of loads within a network can be achieved by minimising the *line utilisation index*:

$$f_2 = FLB = \sqrt{\frac{\sum_{j=1}^{N_{line}}\left(\frac{S_j}{S_{j,rated}}\right)^2}{N_{line}}} \tag{4.7}$$

In Eq. 4.7, S_j is the apparent power flow in line j, and $S_{j,rated}$ is the rated capacity of the line. N_{line} is the total number of feeder lines. The *line utilisation index* reflects the average degree of utilisation of all feeder lines in a network.

f_3 is the objective function for Voltage profile improvement (VPI). The improvement of voltage profiles can be achieved by minimising the *voltage profile index*:

$$f_3 = VPI = \sqrt{\frac{\sum_{i=1}^{N_{bus}}\left(V_i - V_{i,rated}\right)^2}{N_{bus}}} \tag{4.8}$$

In Eq. 4.8, V_i and $V_{i,rated}$ are the real and nominal voltages at bus i. N_{bus} is the total number of buses. The *voltage profile index* reflects the average degree of dispersion of all bus voltages from the nominal value.

The network operational constraints considered are the same as those in Chapter 3, including power flow conservations and limits on voltages and thermal capacities.

4.4.2 Solution Methodology

- ***Multi-objective Optimisation Method***

Since the developed multi-objective optimisation method has been described in detail in Chapter 3, only the methods for selecting compromise solutions are discussed in this chapter.

- ***Selecting Compromise Solutions from Pareto Optimal Set***

A multi-objective optimisation procedure does not end once a Pareto optimal set is obtained. When solving real-world problems, a single solution is always required. Ideally, this solution must belong to the Pareto optimal set and must take into account the preferences of decision makers. There are methods available for the selection of compromise solutions from Pareto optimal set. In this study, two methods, namely the reference point approach [98] and the utopian point method [99] were used for selecting the trade-offs among multiple criteria.

The reference point approach aims to reach a solution on the Pareto frontier that locates near to a specific reference point, which is normally pre-defined by decision makers. In this study, since the information from decision makers is unknown, a hypothetical point that with the minimum values of each objective function is considered as the reference point. The normalised Euclidian distance between each solution on the Pareto frontier and the reference point is calculated as:

$$d_a = \sqrt{\sum_{n=1}^{N_{obj}} w_n \left(\frac{f_n(a)-\bar{R}_n}{f_n^{max}-f_n^{min}}\right)^2} \tag{4.9}$$

where N_{obj} refers to the number of objective functions considered, and in this study $N_{obj} = 3$. d_a is the fitness value of the a_{th} solution on the Pareto frontier defined by the reference point approach. f_n^{max} and f_n^{min} are the maximum and minimum values of the n_{th} objective function obtained from the Pareto optimal set. $f_n(a)$ is the value of the a_{th} solution along the n_{th} objective. $\bar{R}_n$ is the n_{th} component of the reference point. w_n is the weighting factor of the n_{th} objective reflecting the relative importance of different objectives. For the identification of a compromise solution, the one with lower distance to the reference point and, simultaneously, with higher weighting factor, will be selected preferentially.

The utopian point method first searches for the optimal value along each objective function. Then the intersection of these single-objective optimal values is defined as the utopian point, which is normally located outside of the actual solution space. The point on the Pareto frontier with the shortest distance to the utopian point is selected as the compromise solution:

$$D_a = \sqrt{\sum_{n=1}^{N_{obj}} (f_n(a) - \bar{U}_n)^2} \tag{4.10}$$

where D_a is the fitness value of the a_{th} Pareto optimal solution defined by the utopian point method, and $\bar{U}_n$ is the value of the utopian point along the n_{th} objective function.

When applying the proposed MOPSO method to the network, the size of archive A was set to 50, i.e. the maximum number of Pareto optimal solutions stored in the archive in each iteration was 50. At the end of the search process, the stored Pareto solutions in the archive were 50 or about 50, and they were used for the determination of the best compromise solutions. The number, diversity and distance to the ideal points of Pareto solutions all have impacts on the quality of the Pareto frontier. Hence, Pareto frontiers with higher diversity and quality were considered to provide better compromise solutions.

The compromise solutions obtained by using the reference point approach (C1) and the utopian point method (C2), together with the optimal solutions along every single objective, were used to derive different response curves of an MVDC link.

- ***Process of Obtaining Responsive Curves***

The idea of GT-based control method is that, the active power provided by an MVDC link (P_{MVDC}) is related to the net active power flowing through the grid transformers (P_{GT}). In this study, their relationship was simplified to linear relation, i.e. $P_{MVDC} = \alpha P_{GT} + \beta$. From a number of offline studies using optimal power flows and historical data of the test network, such relationship can be observed and quantified.

A schematic diagram showing the process of obtaining the response curves is given in Figure 4.3, and the process is illustrated as follows:

1) Historical data of both demand and generation of the network under study are required, and are categorised into several levels. For instance, demand levels

include summer minimum and maximum, winter minimum and maximum. Levels with scaled-up magnitude can also be used to reflect the forecasted demand and generation in the future. Generated levels of demand and generation are then combined into different operating scenarios, and applied to the network model;

2) For each demand and generation scenario, the net active power flowing through the GTs is first calculated by considering the active power set-point of the MVDC link is zero. Next, with the MVDC link in operation, the proposed multi-objective optimisation method is applied to the network. Since $PV_{ac} - V_{dc}V_{ac}$ is selected as the control mode of the MVDC link, its active power set-point is the decision variable during optimisation, and its reactive power outputs are adjusted to maintain the terminal voltage at specified value, e.g. 1 p.u. A set of Pareto optimal solutions is then obtained, which contains the optimal set-points along each objective, as well as compromise set-points among them;

3) Repeat the procedure in 2) for all scenarios. As a result, for each scenario, a net active power at GTs and a group of set-points of the MVDC link are obtained. Linear approximation of the GT net active power and the corresponding MVDC set-points is then carried out to derive five response curves (i.e. with objectives for power loss reduction, feeder load balancing and voltage profile improvement respectively, and two compromise ones). In this study, the least squares method was adopted for linear approximation to find the most appropriate curves.

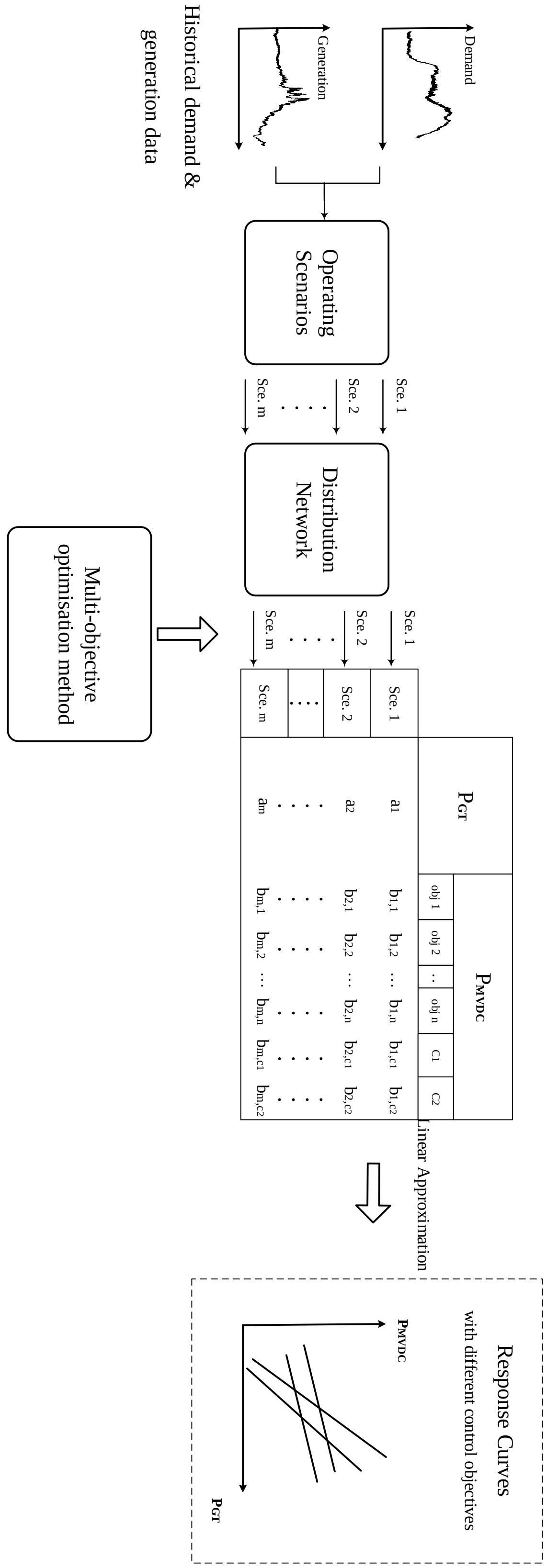


Figure 4.3 Process of developing response curves of an MVDC link with different objectives

4.5 Case Studies

4.5.1 ANGLE-DC Project and Challenges on Anglesey Network

As part of the Ofgem Electricity Network Innovation Competition (ENIC) award, the ANGLE-DC [42] project aims to demonstrate a novel network reinforcement technique by converting an existing double 33 kV AC circuit into DC operation, i.e. an MVDC link, between the Isle of Anglesey and North Wales.

Figure 4.4 shows the 33 kV Anglesey network and a portion of the network on the mainland in North Wales, which are interconnected by the 400 kV transmission network. The meshed 33 kV Anglesey network is supplied by three 132/33 kV GTs at Amlwch and Caergeiliog. Currently, the Anglesey network has high penetrations of DG and is sensitive to the configuration of the transmission network, demand and generation levels. Three wind farms with a total capacity of 34.7 MW, and two solar farms with a total capacity of 28.5 MW are already installed on Anglesey as shown in Figure 4.4. Three additional DGs, with a total capacity of 67.8 MW have been contracted and will be installed in the next few years. There is also a significant amount of forecasted additional demand on Anglesey due to planned regional redevelopment. The main challenge on Anglesey is that uncontrolled power flows are predicted to exceed the thermal limits of cables and overhead lines. Managing the network within voltage and thermal limits are becoming problematic, due to the network topology, high levels of demand and DG penetrations. The adoption of MVDC link represents a solution to expand network operational flexibility, and to provide extra capacity for the integration of renewable generations.

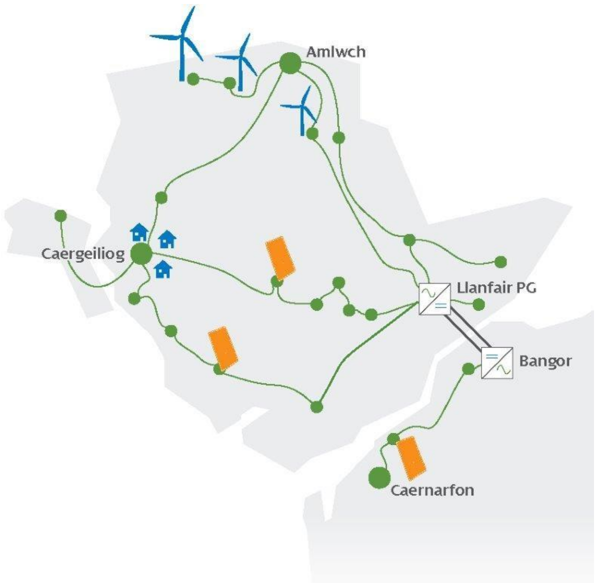


Figure 4.4 The 33 kV Anglesey network [100]

A model of real Anglesey network was built and analysed in IPSA 2 software. The multi-objective optimisation model and the proposed GT-based control strategies were implemented with python scripting. In the simulation, the capacity of each VSC is rated at 30.5 MVA, with the active power ranging from -25 MW to 25 MW, and the reactive power ranging from -15 MVAr to 15 MVAr. The voltage limit is set to be ±6% of the nominal voltage. The capacity limit of each branch is according to its real rating.

4.5.2 GT-based Control for the MVDC Link

To derive response curves of the MVDC link, the procedure illustrated in Section 5.4 was applied. Firstly, net power flows through the Anglesey GTs were calculated under different network operating scenarios, while assuming no active power transfer was provided by the MVDC link. Historical and forecasted demand and generation data of Anglesey were used to form different scenarios. For the demand, five levels from 24.56

MVA to 81.82 MVA were taken into account, corresponding to: summer minimum (24.56 MVA); summer maximum (37.64 MVA); existing winter maximum (74.70 MVA); existing winter maximum uniformly increased by 5%, denoting the forecasted winter maximum in 2019 (77.94 MVA); and existing winter maximum uniformly increased by 11%, denoting the forecasted winter maximum in 2023 (81.82 MVA). For the generation, five levels between 0 MW and maximum capacity of 125 MW were considered, which included both connected and contracted DGs on Anglesey.

Table 4.2 shows the net power flows (in MW) through GTs. A positive sign means the power is imported from the upstream transmission system to Anglesey, and a negative sign means a reverse power flow from Anglesey to the transmission system.

For each scenario, the MVDC link was in operation with its set-points calculated by using the multi-objective optimisation model. Two compromise set-points were also obtained by applying the reference point approach, and the utopian point method to the Pareto frontier of each scenario.

Table 4.2 MW flows through GTs on Anglesey under 25 scenarios of demand and generation

		DEMAND (MW)				
		summer MIN	**summer MAX**	**winter MAX**	**winter MAX_2019**	**winter MAX_2023**
	0	23.45	36.06	75.08	78.47	82.58
	31.25	-8.04	4.45	43.12	46.48	50.51
DG (MW)	***62.50***	-39.08	-26.69	11.61	14.94	18.89
	93.75	-69.66	-57.39	-19.42	-16.13	-12.20
	125.00	-99.69	-87.55	-49.94	-46.67	-42.80

Figure 4.5 shows the response curves of the MVDC link with different control objectives, where the net power flowing through GTs (Table 4.2) and the corresponding set-points of the MVDC link were firstly plotted by many dots (i.e. marked by circles, crosses, triangles, rhombuses, and squares to differentiate the control strategies). The circles correspond to the MVDC link set-points when considering power loss reduction (PLR) as the objective. The crosses represent the set-points when considering feeder load balancing (FLB) as the objective. The triangles are the set-points when improving the voltage profiles (VPI) was considered as the objective. The rhombuses are the compromise set-points (C1) obtained by using the reference point approach, and the squares are the compromise set-points (C2) obtained by using the utopian point method. These five sets of dots were then used to derive five straight lines by applying the least squares method, and the obtained parameters of each line are listed in Table 4.3, where α denotes the slope, and β denotes the intercept on the vertical axis of each line. These straight lines are the most appropriate operational curves for the active power set-points of the MVDC link. It can be seen from Figure 4.5 and Table 4.3 that, different control parameters result in different

slopes and intercepts on axes of the response curves, which lead to distinct performances of the MVDC link. However, the trends of these response curves are similar.

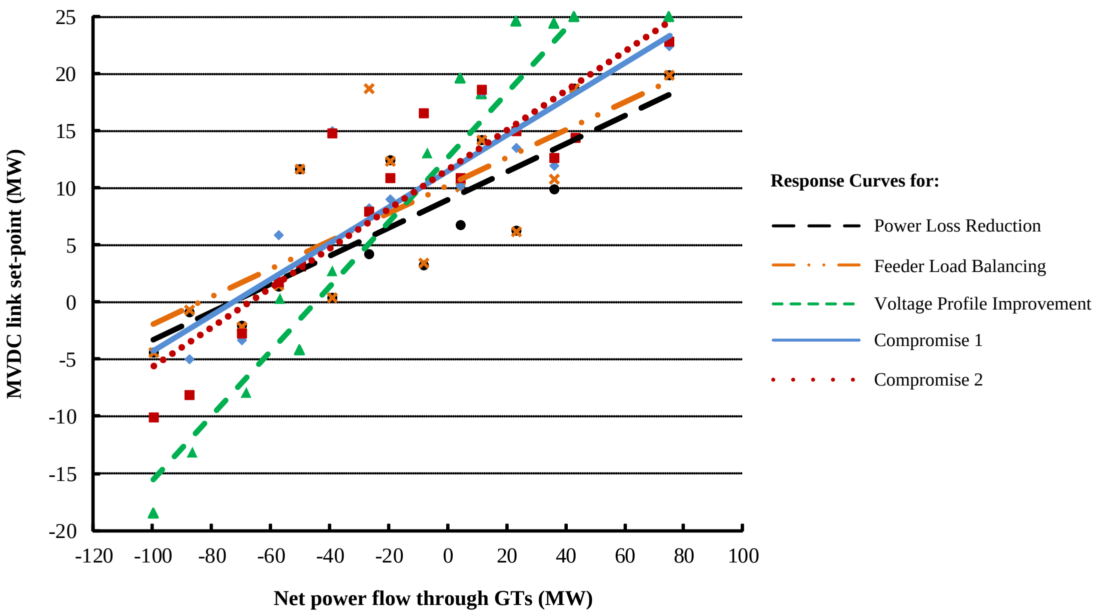


Figure 4.5 Response curves of the MVDC link in Anglesey network with different control objectives

Table 4.3 Control parameters of different response curves

Response Curves	$P_{MVDC} = \alpha P_{GT} + \beta$	
	α	β
Power Loss Reduction	0.1225	8.91
Feeder Load Balancing	0.1216	10.16
Voltage Profile Improvement	0.2833	12.69
Compromise 1	0.1582	11.45
Compromise 2	0.1727	11.58

4.5.3 Daily Operation of Different Cases

- ***Case 1: Daily network operation with the MVDC link using different control strategies***

The GT-based control strategies use the measurements at GTs to provide the active power set-points of the MVDC link, while the operating condition of the wide area of the network is unknown to the MVDC link. Therefore, it is essential to assess the real-time performance of the network.

One-day demand and generation profiles of Anglesey obtained from measurements on the real network are shown in Figure 4.6. Taking half-hourly time steps, power losses of the Anglesey network with the MVDC link using different control strategies are shown in Figure 4.7. The power losses of the network when the link is operated in AC are used as a reference case. The daily average power losses and energy losses when using different strategies are listed in Table 4.4. It can be seen in Figure 4.7 and Table 4.4 that, with the MVDC link, regardless the control strategy used, power losses of the network were reduced significantly compared to those when the link is operated in AC. Comparisons between control strategies showed that, the one for voltage profile improvement led to higher power losses than other strategies. This is due to the extra power injections from the MVDC link for voltage regulation. Power losses obtained with the strategy for power loss reduction remained the lowest over the day, and losses obtained with the strategy for feeder load balancing were the second lowest. The two compromise control strategies achieved medium performances among these objectives.

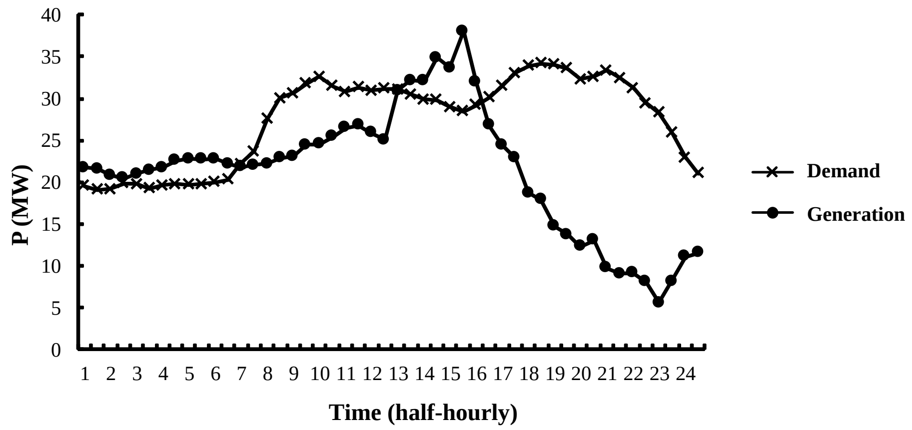


Figure 4.6 Case 1: daily profiles of total demand and generation on Anglesey

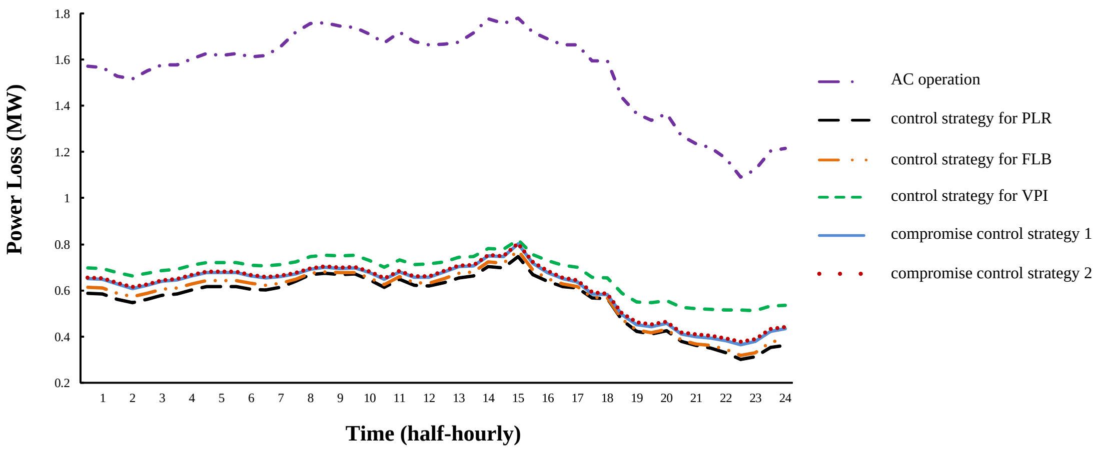


Figure 4.7 Power losses over a day of the network by using MVDC link and the original AC operation

Table 4.4 Power and energy losses by using different control strategies as shown in Figure 4.7

	Daily Average Power Loss (MW)	**Daily Energy Loss (MWh)**
AC operation	1.556	37.35
Control strategy for PLR	0.562	13.49
Control strategy for FLB	0.578	13.87
Control strategy for VPI	0.673	16.15
Compromise control strategy 1	0.607	14.58
Compromise control strategy 2	0.613	14.72

- ***Case 2: Daily network operation with modified demand and generation profiles***

To consider the impact of high DG penetrations, the demand profile in Figure 4.6 was scaled down to the summer minimum, while the generation was scaled up by multiplying the normalised daily profile of each DG. This case is recognised as the worst-case scenario [74, 75] and provides the most vulnerable network operating condition. The modified daily profiles are shown in Figure 4.8, and the half-hourly power loss over a day under the worst-case scenario is shown in Figure 4.9. The corresponding average power losses and energy losses when using different strategies are listed in Table 4.5.

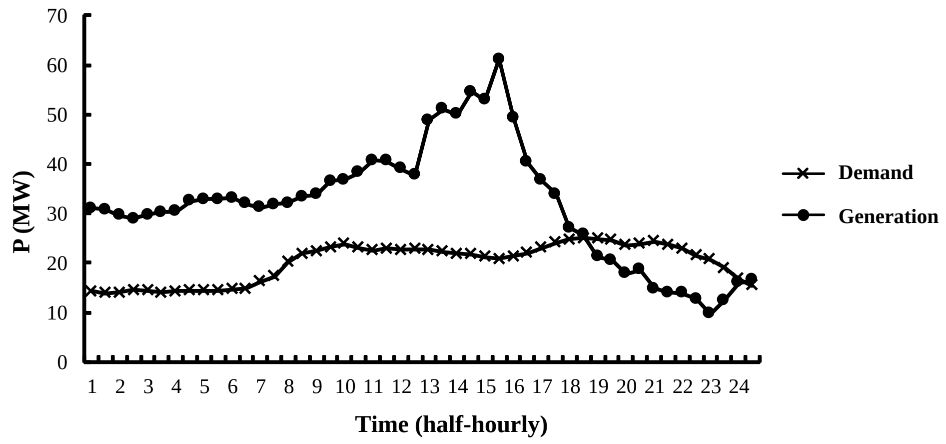


Figure 4.8 Case 2: modified daily profiles of total demand and generation on Anglesey representing the worst-case scenario

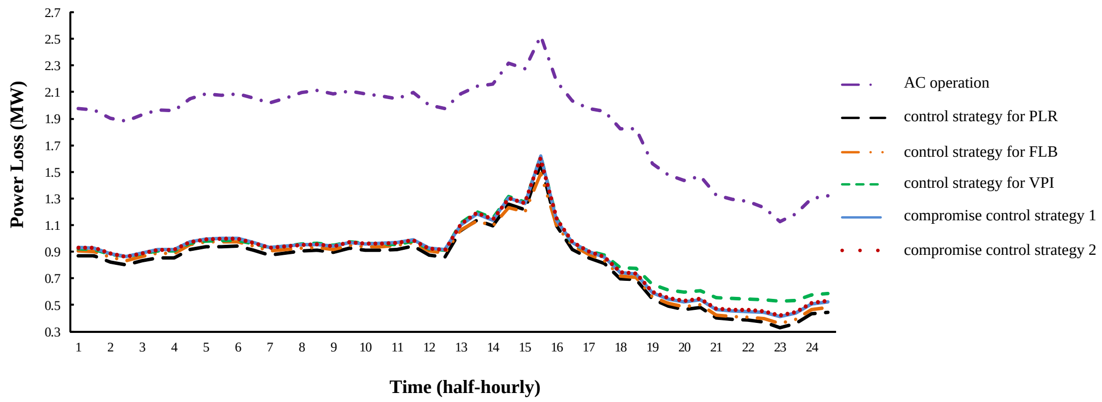


Figure 4.9 Power losses over a day of the network by using MVDC link and the original AC operation (worst-case scenario)

Table 4.5 Power and energy losses by using different control strategies as shown in Figure 4.9

	Daily Average Power Loss (MW)	**Daily Energy Loss (MWh)**
AC operation	1.875	45.01
Control strategy for PLR	0.810	19.44
Control strategy for FLB	0.831	19.95
Control strategy for VPI	0.887	21.28
Compromise control strategy 1	0.865	20.77
Compromise control strategy 2	0.867	20.82
Switching to the strategy incurring lowest power loss accordingly	0.807	19.38

Comparing the results in Figures 4.7 and 4.9, it can be found that the control strategy leading to minimum power loss over a day was not the one for power loss reduction at all times. When the outputs from DGs were much greater than the demand, (e.g. during the hours 13:00-16:00), the control strategy for feeder load balancing resulted in lower power losses than others. However, when the demand was greater than the generation, (e.g. from 17:00 to 24:00), the control strategy for power loss reduction became the one with lowest losses again. Results indicated that there was no particular control strategy bringing minimum power losses to the network at all times. However, switching between different strategies as the net power demand within the network varied would be necessary. The results of switching between strategies that incurred lowest power loss in Figure 4.9 are shown in the last row of Table 4.5.

4.5.4 Impacts of DG penetration

Although there is no unified definition of DG penetration in the literature, this study follows the commonly used one, and this is the same as in [46, 101]: DG penetration is the percentage of total capacity of DG units over the maximum loading capacity of the network. For example, if a distribution network is operating at its peak load with a DG penetration of 25%, then 75% of the power will be coming from the transmission system.

In the simulations, the worst-case scenario was applied, in which Anglesey network was at its minimum demand. The maximum allowable DG penetration reflects the maximum capacity of DG units the network can accommodate before any violation occurs, i.e. the DG hosting capacity. DG penetration was increased from 0 with an increment of 5%. Three network performance metrics: daily energy loss; the maximum line utilisation over a day; and the maximum bus voltage over a day were evaluated.

Firstly, the DG hosing capacity of the network was investigated with results shown in Figure 4.10.

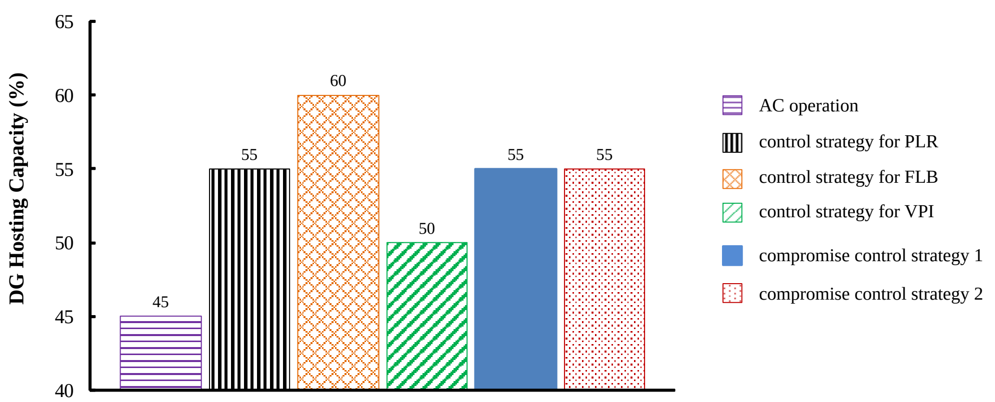


Figure 4.10 DG hosting capacity of the network by using MVDC link and the original AC operation

From Figure 4.10, it can be seen that MVDC link has the capability to increase the DG hosting capacity over the AC operation. The control strategy for feeder load balancing achieved the highest DG hosting capacity, followed by the control strategy for power loss reduction, and the two compromise control strategies. With the MVDC link, an increase of DG hosting capacity up to 15% can be achieved in the Anglesey network.

Impacts of DG penetrations on the network performance metrics were also investigated. Results are shown in Figures 4.11-4.13. It can be seen that, the degree of improvements along the performance metrics is different, depending upon the control strategy used. The maximum allowable DG penetration is also different among control strategies. With the control strategy for voltage profile improvement, a maximum DG penetration of 50% can be obtained, followed by the AC operation, of which the maximum DG penetration was 45%. The control strategy for feeder load balancing achieved the highest DG penetration of 60%. These results are consistent with the results shown in Figure 4.10.

It can be seen in Figure 4.11 that, with the MVDC link, daily energy losses first decreased slightly as the DG penetration increased from 0 to 10%. Then as the DG penetration further increased, energy losses started to increase due to a large amount of reverse power flow. The control strategy for power loss reduction led to minimum daily energy losses under all DG penetrations from 0 to 55%. Figure 4.12 shows that, as DG penetrations increased, the line utilisation first decreased due to the offset of demand and generation. Then line utilisations became saturated gradually due to large amounts of reverse power flows brought by DG outputs. The control strategy for feeder load balancing led to the lowest line utilisation under all DG penetrations. Although the control strategy for voltage profile improvement led to higher energy losses and line utilisations under all DG penetrations, it outperformed in mitigating the voltage rise issue as shown in Figure 4.13. Such control strategy can be used when voltage issues are the major concern of a network. It is also shown that, although not outperforming along any single operational metric, the compromise control strategies can always achieve medium performances along different criteria and relatively high DG penetrations. Such control strategies can be used as trade-off solutions for the MVDC link operation.

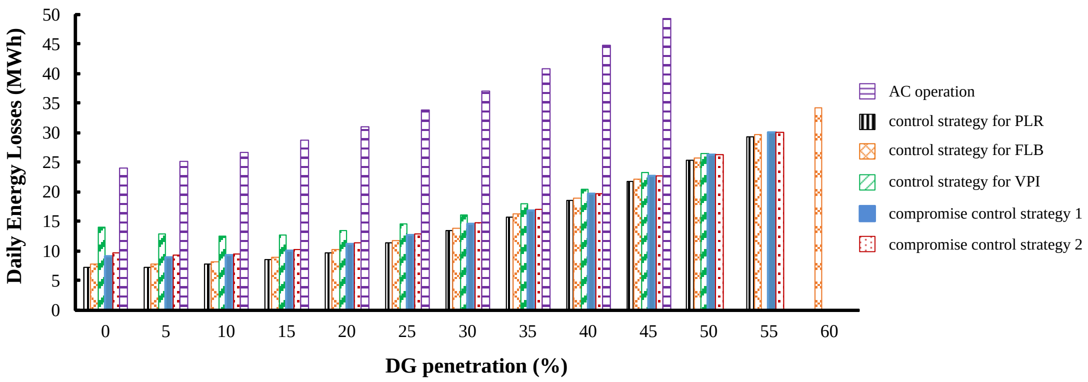


Figure 4.11 Impacts of DG penetration on daily energy losses

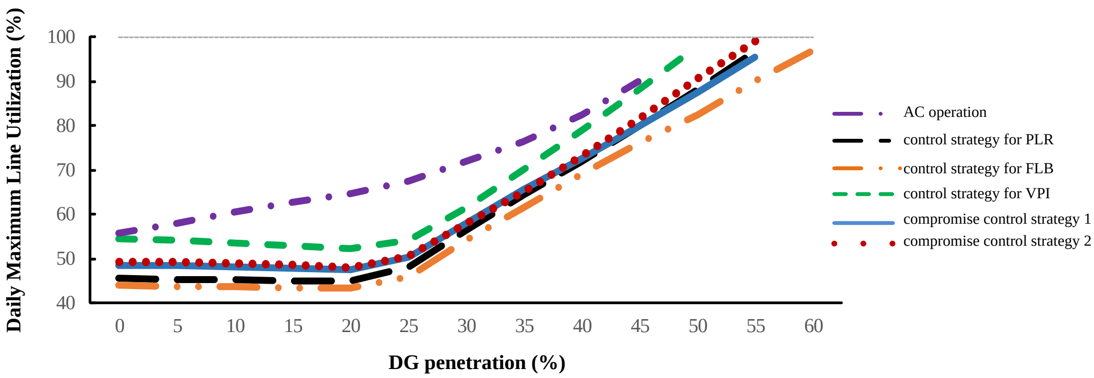


Figure 4.12 Impacts of DG penetration on daily maximum line utilisations

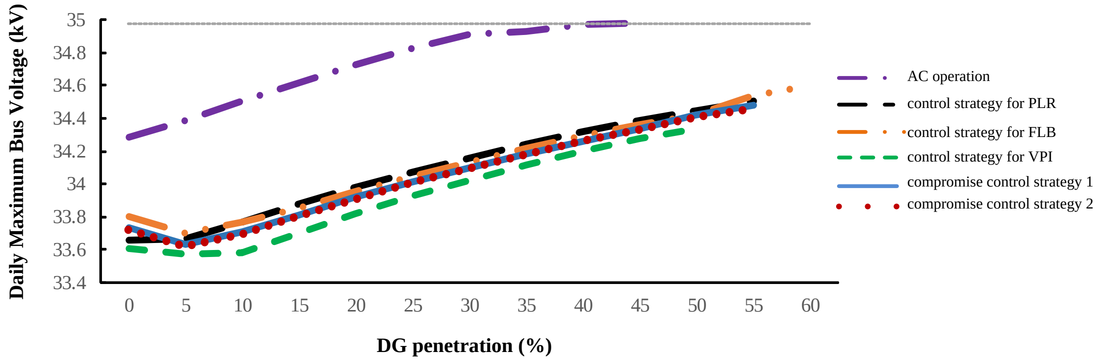


Figure 4.13 Impacts of DG penetration on daily maximum bus voltages

4.6 Summary

In this chapter, impacts of an MVDC link on the performances of a distribution network with high DG penetrations were investigated. A real-time control method for MVDC link was proposed, whereby net power flows at the grid transformers are used to determine the set-points of the MVDC link. Control strategies considering different objectives, i.e. power loss reduction, feeder load balancing, voltage profile improvement, and compromise options among these criteria were developed by applying an improved MOPSO method to the network with historical demand and generation data. The feasibility and effectiveness of implementing an MVDC link with the proposed control method were validated on a real network. Performances of the network with MVDC link were evaluated and compared between different control strategies using real demand and generation profiles. Results indicated that, for an MV distribution network, it might be beneficial to switch among different control strategies with the variations of demand and generation. The impacts of DG penetrations on the network with MVDC link were investigated. Results showed that, regardless of the control strategy used, an MVDC link significantly increases the network hosting capacity for DGs compared to the AC operation. For the network under study, the MVDC link could bring up to 15% increase in DG hosting capacity over AC operation. The control strategy for feeder load balancing resulted in the highest DG hosting capacity since main challenges brought by the high DG penetration to the network are thermal overloading issues.

It is to be mentioned that, compared to using optimisation method at each time step with thorough network information, using the GT-based control can only achieve sub-optimal network operation due to the limited measurements used. However, it reduces the requirement and investment in communication infrastructures significantly. The simplicity, low cost and adequate performance make the GT-based control an effective control option.

Chapter 5 Impact Quantification of Soft DC Links on Statistically-similar Distribution Networks

In this chapter, an impact quantification of Soft DC Links on distribution networks was carried out in a statistical manner. This study could provide distribution network planners with more robust decisions on the implementation of Soft DC Links.

The work presented in this chapter is a collaboration with Sathsara Abeysinghe of Cardiff University, School of Engineering, UK, who developed the statistical assessment tool for electrical distribution networks.

5.1 Introduction

The integration of smart technologies, e.g. Soft DC Links is introducing changes in distribution networks. It is important for government and industry to have their impacts analysed and quantified. However, various networks perform differently with these technologies. Assessments carried out using specific network models may not capture all the diverse characteristics of the real networks. Therefore, it is necessary to generate as many as possible, realistic representations (i.e. statistically-similar networks) of a required distribution network with a single set of available inputs. A number of case studies conducted on these networks can then be used provide robust conclusions on the implementation of certain smart technologies.

In this chapter, an impact quantification of Soft DC Links on statistically-similar distribution networks was carried out, where the term 'statistically-similar networks' refers to a set of distribution networks with similar but different topological and electrical properties.

Statistically-similar networks were generated to provide a number of realistic models of electrical distribution networks based on a statistical analysis of data from real networks. An optimisation model was developed to determine the siting and sizing of Soft DC Link in a distribution network for minimising the network annual cost. Intermittent characteristics of renewable generation outputs were taken into consideration by adopting a scenario generation method, with which representative scenarios of DG outputs can be derived from their probability density functions (PDFs). Statistical assessments of Soft DC Links were conducted on a number of statistically-similar networks. Impacts of DG penetrations on the network performances, as well as on the allocation of Soft DC Links were also investigated. From the study, generic impacts and conclusions of the implementation of Soft DC Links in distribution networks can be derived.

5.2 Connection of DG

5.2.1 DG Placement and Penetration

Impacts of DG on the network performances were considered in this study. For the DG placement, the sites of DGs were selected randomly, rather than considering specific buses as the installation sites for a given network. This is because DG integration over time is a random process [46] with the uncertainties around magnitude, location, and timing of future installations. Since large concentrations of DGs were observed to cause constraint violations at lower penetration levels, this type of placement can be considered as a more challenging scenario for network operation. Regarding the DG penetration, a range of penetration levels were considered, and the definition of DG penetration is the same of that used in the previous chapters, which is the percentage of total capacity of DG units over the maximum loading capacity of a network.

5.2.2 Representative Scenarios of DG Operation

In order to consider the intermittent characteristic of renewable generation outputs, a method based on the Wasserstein distance [61, 102] was used to derive representative scenarios of DG operation over a year. Firstly, the PDFs of DGs were generated from their historical data. Then the continuous distributions of DG outputs were converted into discrete ones by using the Wasserstein distance method, from where representative scenarios of DG operation over a certain period can be generated. By using these representative scenarios, the computational burden of the optimisation procedure can be reduced.

Assuming $f(x)$ is the continuous PDF of a variable x, and is to be converted into N_S discrete distributions, i.e. the number of representative scenarios is N_S. Each scenario sce ($sce = 1,2,\dots,N_s$) and its corresponding probability p_{sce} can be obtained as follows:

$$\int_{-\infty}^{sce} f(x)^{1/2} dx = \frac{sce-1}{2N_S} \int_{-\infty}^{+\infty} f(x)^{1/2} dx \tag{5.1}$$

$$p_{sce} = \int_{\frac{(sce-1)+sce}{2}}^{\frac{sce+(sce+1)}{2}} f(x) dx \tag{5.2}$$

Specifically, the scenarios $sce = 0$ and $sce = N_s + 1$ refer to the lower and upper limits of the variable x.

5.3 Statistically-similar Networks Generator

A statistical assessment tool for electrical distribution networks proposed and developed by Sathsara Abeysinghe, who was also pursuing her PhD in Cardiff University, School of Engineering, was used to provide a number of random and realistic network models. The concept of the tool is shown in Figure 5.1.

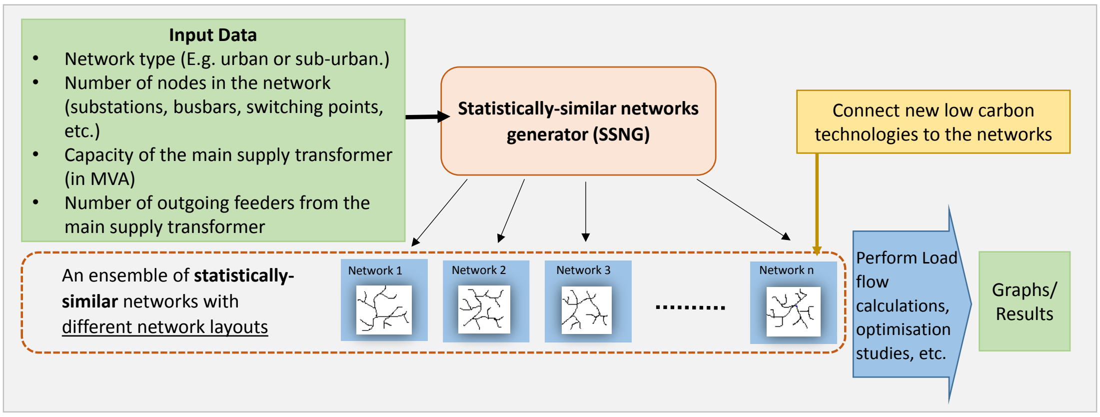


Figure 5.1 The concept of the network assessment tool

The statistically-similar networks generator (SSNG) is the core of the assessment tool, which was used to generate a number of statistically-similar distribution networks.

An overview of the development procedure of the SSNG is given in Figure 5.2. The SSNG is a data-driven model. Its development procedure consists of four stages: data pre-processing, training, network generation, and validation. The development procedure of the SSNG is summarised in the following sub-sections.

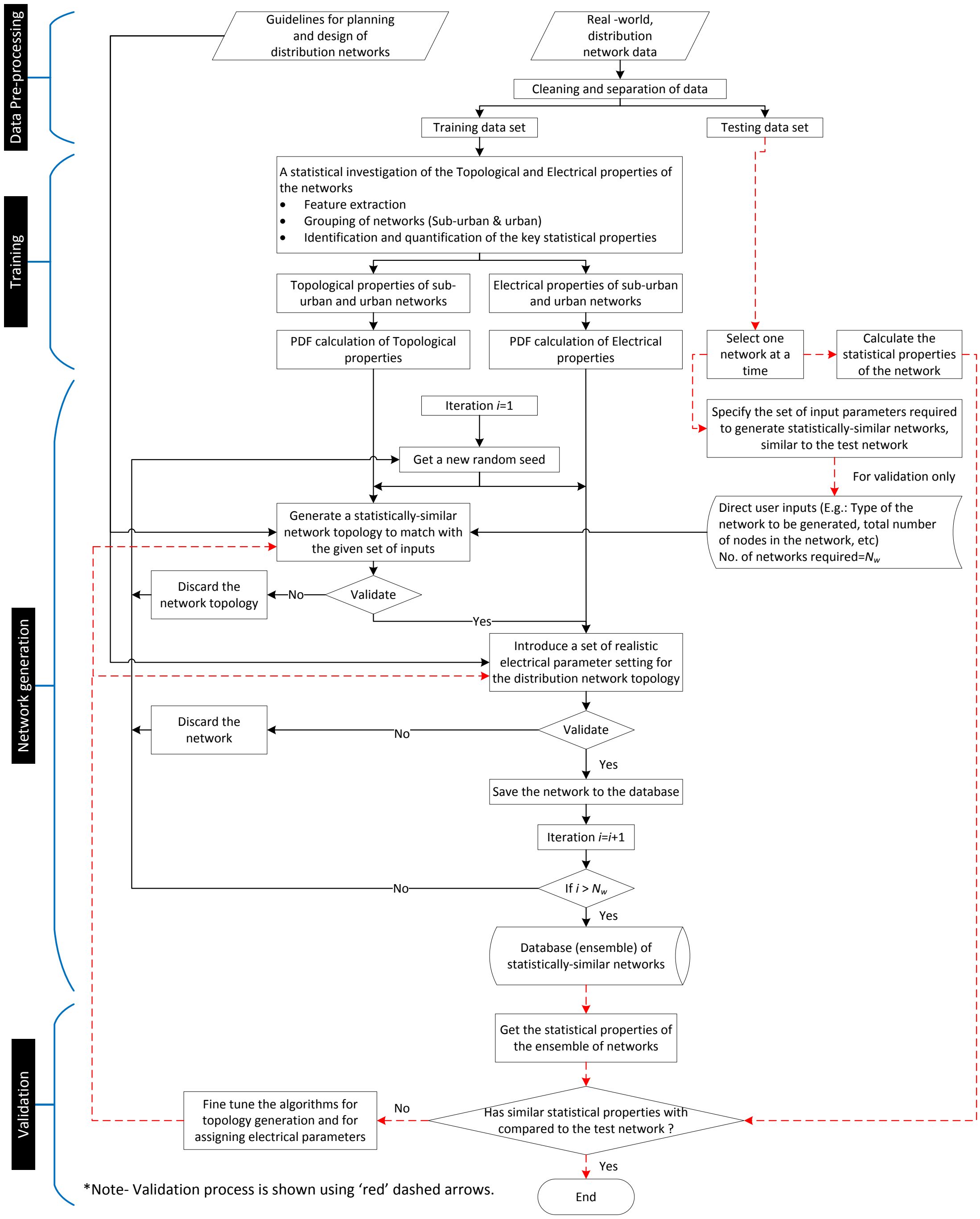


Figure 5.2 Overview of the development procedure of the SSNG

5.3.1 Data Pre-processing Stage

A data pre-processing stage is used to prepare the inputs for the SSNG model. There are two key inputs: real-world distribution network data, and guidelines for planning and design of distribution networks.

The collected real-world network data includes the technical and geographical information of transmission, sub-transmission, and distribution level networks and also the population data of the supplied areas of the networks.

It is important to select the correct set of the input data for the model and eliminate the unwanted set (i.e. cleaning of data). Only data of the distribution networks at certain voltage level is used for the development of the SSNG, and all selected networks have a radial structure. The planning and design guidelines which are applicable for the selected set are then identified and used in the model.

The selected data of real-world networks is divided into two data sets, namely training and testing data sets. The network data in the training data set is used in the training process, where different network types and various topological and electrical properties of real-world networks are identified and quantified. The testing data set represents the actual network data (to be forecasted) and is used to validate the SSNG model. The majority of the real-world network data is used to form the training data set, whereas the rest of the network data is used in the testing data set.

5.3.2 Training Stage

Identification and quantification of the important topological and electrical properties of real-world distribution networks is a key requirement when developing random, but realistic network models.

- ***Topological Properties of Distribution Networks***

Topological properties of a distribution network describe how different network components are located and connected, which is critical to evaluate the network performances. Simple models which assume equal spacing between the consumers and equally spaced substations are not accurate enough to represent the realistic topological structures of the distribution networks. Therefore, an investigation of the topological properties of real-world distribution networks is conducted using the training data set. PDFs describing the topological properties (e.g. branch length distributions) of different types of distribution networks (e.g. urban or sub-urban) are obtained [103].

- ***Electrical Properties of Distribution Networks***

Electrical properties, such as distributions of cable impedances and consumer loads are important to study the performances of electrical distribution networks including voltage drops, power losses, network reliability and costs, etc. The assumptions of uniform distributions of consumer loads and uniform cross sections for the feeders are not accurate to describe the realistic electrical structures of distribution networks. Therefore, an investigation of the electrical properties of real-world distribution networks is conducted using the training data set. Due to the limited availability of the consumer load information, installed capacities of the secondary substations are used to capture the distribution of actual consumer loads within a network. Distributions of cable impedances within the network topology are also studied. PDFs are obtained to describe the electrical properties of different types of distribution networks.

5.3.3 Network Generation Stage

The network generator is developed in a hierarchical manner. As shown in Figure 5.2, each iteration starts with a new random seed. This is to ensure that different sets of values are generated by the PDFs, which characterise the topological and electrical properties of the networks in different iterations of the algorithm.

Several inputs are required from the user at this stage. They are: the type (sub-urban/urban) and number of statistically-similar networks that need to be generated, the total number of nodes (e.g. substations, buses, and NOPs) in the network, the capacity of the main supply transformer (in MVA) and the number of outgoing feeders from the main supply transformer.

A network topology that matches the user inputs is always generated before introducing its electrical properties. PDFs that characterise the topological properties of the network type as user required, and the planning and design guidelines are used in the process of generating a network topology. Next, realistic electrical parameter settings are assigned to the generated network topology. In this process, PDFs that characterise the electrical properties of the network, as well as the user inputs and the planning and design guidelines are used.

There are two separate validation steps in each iteration. Network topologies and the network topologies with assigned electrical parameter settings are validated against the planning and design guidelines. Any generated topology or network with assigned electrical parameter settings that violate the design standards will be discarded, and the networks satisfying the design standards are stored in a database.

In each iteration, the network generator starts with a different random seed to ensure a number of statistically-similar distribution networks are generated with a single set of user inputs.

5.3.4 Validation Stage

A validation stage is required to fine-tune the algorithms for network generation as well as to validate the complete development procedure of the SSNG. Only one network from the testing data set is selected at a time. From each selected test network, the basic set of user inputs required to generate statistically-similar networks are then identified. An ensemble of statistically-similar networks to the selected test network is generated with these user inputs and by following the above hierarchical approach for network generation. Then, the statistical properties of the ensemble of the statistically-similar networks are compared with that of the selected test network. A successful comparison is able to validate the development procedure of the SSNG.

5.4 Optimisation Model for Allocating Soft DC Links

5.4.1 Modelling of Soft DC Link

Soft DC Links comprise various types of power electronic arrangements. In this study, the back-to-back VSCs were used for instance, and $PQ - V_{dc}Q$ was selected as the control mode. Although the operation efficiency of back-to-back VSCs is sufficiently high, they inevitably produce power losses when there is a large-scale transfer of active power. Therefore, a loss coefficient was considered in this model. The constraint of active power exchange between the converter stations of a Soft DC Link is described below:

$$P_{VSC1,sce} + P_{VSC2,sce} + \eta P_{VSC1,sce} + \eta P_{VSC2,sce} = 0 \tag{5.3}$$

The reactive power output of each VSC station is independent to the other due to the DC isolation in between, and should satisfy its own capacity constraint:

$$\sqrt{P_{VSC1,sce}^2 + Q_{VSC1,sce}^2} \leq S_{SL} \tag{5.4}$$

$$\sqrt{P_{VSC2,sce}^2 + Q_{VSC2,sce}^2} \leq S_{SL} \tag{5.5}$$

where $P_{VSC1,sce}$, $P_{VSC2,sce}$, $Q_{VSC1,sce}$, and $Q_{VSC2,sce}$ are the transmitted active and reactive power of each VSC station at scenario sce. η is the loss coefficient, and S_{SL} is the capacity of a Soft DC Link.

The relationship between the capacity and location of a Soft DC Link is:

$$S_{SL} = mS_{module}(1 - b_i) \quad for \;\; i \in [1,2, \dots N_{branch}] \tag{5.6}$$

where S_{module} is the minimum capacity of the basic power electronic module in a Soft DC Link, and m is the number of modules. S_{SL} equals to the summation of the module capacity. The binary variable b_i indicates whether a branch is equipped with a Soft DC Link (e.g. $b_i = 0$ means a Soft DC Link is installed in branch i). N_{branch} is the total number of branches in a network.

5.4.2 Optimisation Model to Site and Size Soft DC Link

The annual cost of a distribution network was taken as the objective function, and is formulated below:

$$min\, F = C_{inv} + C_{ope} + C_{loss} \tag{5.7}$$

The network annual cost consists of the following parts:

- Investment cost of a Soft DC Link:

$$C_{inv} = \frac{r_{inv}(1+r_{inv})^y}{(1+r_{inv})^y - 1} c_{SL} S_{SL} \tag{5.8}$$

where r_{inv} is the discount factor of the Soft DC Link investment cost; y is the device economical service time; c_{SL} is the investment cost per unit capacity of a Soft DC Link.

- Operational cost of a Soft DC Link

$$C_{ope} = r_{ope} c_{SL} S_{SL} \tag{5.9}$$

where r_{ope} is the discount factor of the Soft DC Link operational cost.

- Annual energy loss cost of a network:

$$C_{loss} = 8760 \cdot c_{ele} \sum_{sce=1}^{N_S} \left(P_{loss,sce} + \eta P_{VSC1,sce} + \eta P_{VSC2,sce}\right) \cdot p_{sce} \tag{5.10}$$

where c_{ele} is the electricity price per kWh. N_S is the set of all scenarios considered over a year, and p_{sce} is the probability corresponding to scenario sce. $P_{loss,sce}$ is the power loss of the network per unit time at scenario sce.

The optimisation method integrating both global and local search techniques as proposed in Chapter 3, was used for the determination of the optimal allocation of Soft DC Links. The active and reactive power outputs of a Soft DC Link during each representative scenario, as well as the capacity and location of the device, were taken as the decision variables. Rather than considering multiple operational objectives as in Chapter 3, in this study a single objective, i.e. minimisation of the network annual cost was used.

5.5 Case Study and Results

5.5.1 Assumptions and Considerations of Case Studies

- ***Networks***

In this study, the real network data used in the SSNG was collected from the Chinese power grid. The applicable planning and design guidelines for the selected data set were identified [104] and used in the SSNG. User inputs considered in the case studies are shown in Table 5.1.

Table 5.1. User inputs considered in the SSNG

Parameter	**Value**
Network type	Sub-urban
Voltage level	10 kV
Number of nodes	250
Number of outgoing feeders from the main transformer	7
Capacity of the main transformer	20 MVA
Number of statistically-similar networks required for the study	30

Due to the limited availability of the consumer load information, installed capacities of the secondary substations (10/0.4 kV) were used to capture the distribution of actual consumer loads within a network. 60% of the installed capacity of each substation was used as the demand of that node, since the load factor for most distribution transformers is 40-60% [105]. The permitted voltage range for 10 kV distribution networks in China is $\pm$7% [106], and the thermal limit of each branch is according to its real rating.

The box-whisker plot representations of the topological and electrical properties of the 30 networks generated by the SSNG are shown in Figure 5.3. On each box, the central mark indicates the median of the data, and the bottom and top edges indicate the first (Q1) and third (Q3) quartiles of the data. The whiskers extend to the lowest and highest data points which are within 1.5 interquartile range of the first and third quartiles (interquartile range=Q3-Q1). The outliers are plotted individually with the '+' symbol [107].

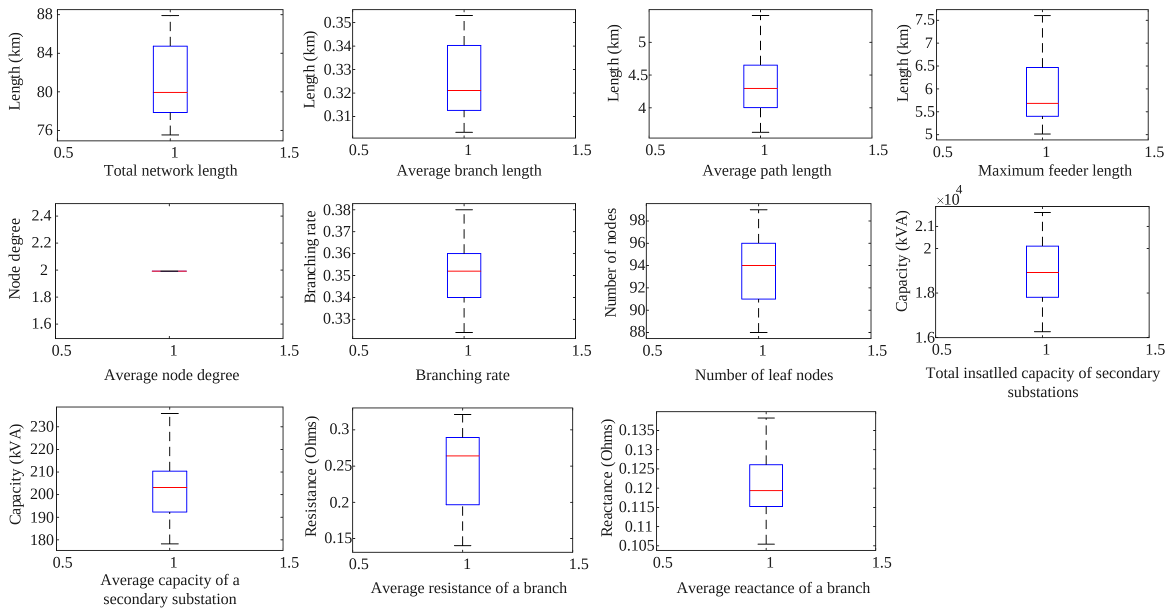


Figure 5.3 Box-whisker representations of the topological and electrical properties of 30 distribution networks generated by the SSNG

From the box-whisker plots, it can be observed that the networks generated by the SSNG share very close topological and electrical properties making them statistically-similar to each other. However, these networks have different layouts, any of which is a possible realisation of a real distribution network.

Some definitions of the network properties shown in Figure 5.3 are listed below [103]:

- Total network length is the summation of all the branch lengths in a network.
- Average branch length is obtained by dividing the total network length by the number of branches.
- Average path length is defined as the average length along the shortest paths for all possible pairs of network nodes.
- Average node degree k_{avg} of a network is obtained from the following equation:

$$k_{avg} = \frac{1}{N}\sum_{i=1}^{N} k_i \quad (5.11)$$

where k_i is the degree of node i, illustrating the number of branches connected to that node. N is the total number of nodes in a network ($k_{avg} > 2$ denoting the network has a meshed structure).

- Branching rate is obtained from the following equation:

$$b_r = \frac{Number\ of\ nodes\ with\ degree \geq 3}{Total\ number\ of\ nodes\ in\ a\ network} \quad (5.12)$$

- Leaf nodes are those with the node degree equals to 1. The number of leaf nodes in a network equals to the total number of secondary substations.

- ***DG***

Renewable generations in the forms of wind and PV were considered in this study. Since Weibull distribution [108] and Beta distribution [109] have been extensively used in the literature to describe PDFs of wind speed and light intensity, they were used in this study for the generation of representative scenarios of wind and PV outputs based on the Wasserstein distance method.

The wind speed and light intensity curves over a year as shown in Figure 5.4, and the PDFs derived from these curves, where obtained in [61]. The PDFs were then used with the Wasserstein distance method to derive five representative scenarios of wind outputs (P_{wind}), five representative scenarios of PV outputs (P_{PV}), as well as their corresponding probabilities. From these scenarios, 25 combined scenarios of annual DG operation and their probabilities can be obtained, which are shown in Table 5.2.

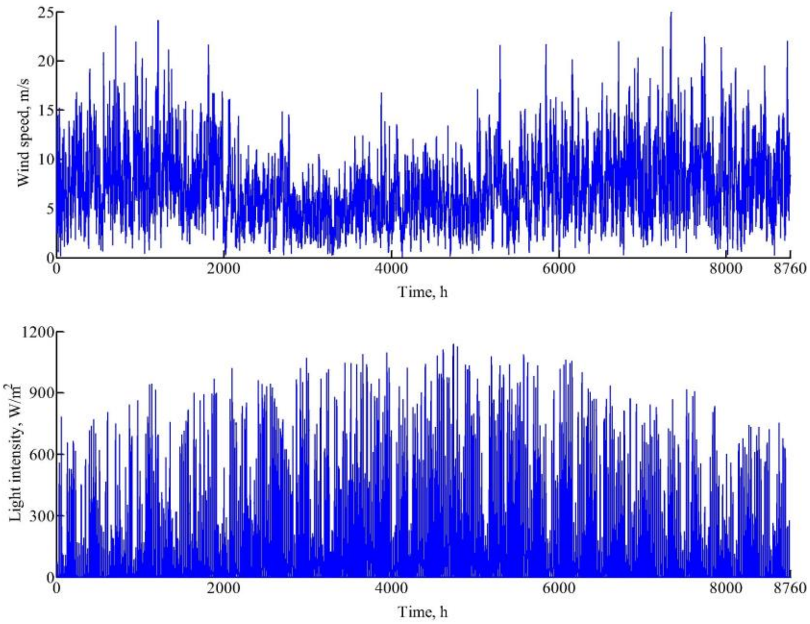


Figure 5.4 Wind speed and light intensity curves over a year

Table 5.2 Representative scenarios and corresponding probabilities of DG outputs

P_{wind}		P_{PV}				
		$sce\ 1$	$sce\ 2$	$sce\ 3$	$sce\ 4$	$sce\ 5$
		0.09	0.29	0.49	0.72	0.91
$sce\ 1$	0	0.018	0.0174	0.0173	0.0174	0.018
$sce\ 2$	0.08	0.0916	0.0885	0.0882	0.0885	0.0915
$sce\ 3$	0.32	0.0468	0.0452	0.0451	0.0452	0.0468
$sce\ 4$	0.71	0.0268	0.0259	0.0258	0.0259	0.0268
$sce\ 5$	1	0.021	0.0203	0.0203	0.0203	0.021

All DGs were assumed to operate at unity power factor. DG penetrations from 0 to 100% with an increment of 20% were considered, and identical capacity of DGs was assumed under each penetration level.

- ***Other Assumptions***

The range of candidate capacities of Soft DC Links was set from 500 kVA to 2500 kVA. Parameters used in the optimal allocation model of Soft DC Links are listed in Table 5.3. In this study, one Soft DC Link was considered to be allocated in a distribution network. However, a greater number of device installations can be incorporated into the model.

Table 5.3 Parameters used in the case studies

Parameters	**Value**
Loss coefficient: η	0.02 [93]
Module capacity: S_{module} (kVA)	100
Economical service time: y (year)	20
Discount factors: r_{inv}, r_{ope}	0.08, 0.01
Investment cost per unit capacity: c_{SL} (£/kVA)	230 [110, 111]
Electricity price: c_{ele} (£/kWh)	0.12

5.5.2 Results

The diversity of the generated distribution networks means that each network will face different stresses in voltage or thermal constraints when large amounts of DG is connected.

For each network, the load flow over a year was firstly conducted under each DG penetration without considering Soft DC Links, i.e. the reference case. The network annual cost, maximum and minimum bus voltages over a year, maximum branch loading over a year, and the maximum allowable DG penetration the network can accommodate before any limits being breached, were recorded. This process was then repeated for the case with Soft DC Links.

- ***Network Annual Cost***

The annual costs of each network under various DG penetration conditions, with and without Soft DC Links, are shown in Figure 5.5. The red dot denotes the annual cost of a network without using a Soft DC Link. The blue dot denotes the annual cost when using the device. The grey and green triangles represent the average costs of the networks without and with Soft DC Links. The minimum, maximum and average costs at each DG penetration are listed in Table 5.4.

It can be observed from Figure 5.5 and Table 5.4 that, as DG penetrations increased from 0 to 100%, the annual costs decreased at first, which was due to the fact that the generation firstly offset the demand and the total power losses were reduced. Then the annual costs gradually increased, for the large amounts of reverse power flow brought by DGs caused more power losses in the networks. Under different DG penetrations, the average network costs with Soft DC Links were always lower than those without using Soft DC Links. It can also be observed that, the number of dots reduced as the DG penetration increased, this is because networks with high DG penetrations are more vulnerable to encounter voltage and thermal issues, and only results of the networks without constraints violations are shown here.

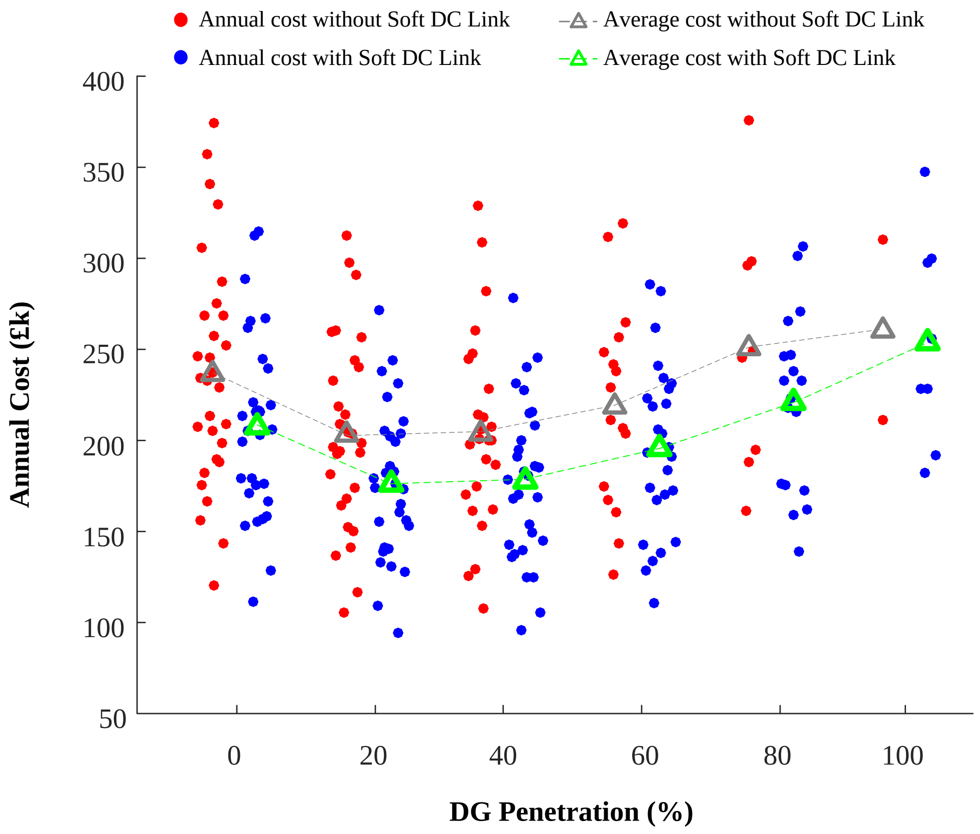


Figure 5.5 Annual costs of the networks under different DG penetrations

Table 5.4 Minimum, maximum and average network costs

DG (%)	**Minimum Cost (£k)**		**Maximum Cost (£k)**		**Average Cost (£k)**	
	without Soft DC Link	with Soft DC Link	without Soft DC Link	with Soft DC Link	without Soft DC Link	with Soft DC Link
0	120.65	111.40	374.51	314.39	236.57	207.33
20	105.48	94.27	312.51	271.53	203.94	176.29
40	107.66	95.68	328.75	278.62	204.03	177.45
60	126.46	110.35	319.17	285.42	218.91	195.44
80	161.19	138.94	375.66	306.57	251.01	221.13
100	211.21	182.05	309.93	347.84	260.57	253.83

The annual cost saving achieved by using Soft DC Link in each network is shown in Figure 5.6, with its definition given in Eq. 5.13. The minimum, maximum and average savings are listed in Table 5.5. The economic benefits of Soft DC Links over a wide range of DG penetration conditions were revealed from the results in Figure 5.6 and Table 5.5. With DG penetrations increased from 0 to 100%, the annual cost savings brought by using Soft DC Links were around 10-20%.

$$Annual\ Cost\ Saving(\%) = \frac{F^{ref} - F^{SL}}{F^{ref}} = \frac{C_{loss}^{ref} - (C_{inv}^{SL} + C_{ope}^{SL} + C_{loss}^{SL})}{C_{loss}^{ref}} \cdot 100 \qquad (5.13)$$

where F^{ref} and F^{SL} are the network annual costs for the reference case (without using Soft DC Links) and the case with Soft DC Links.

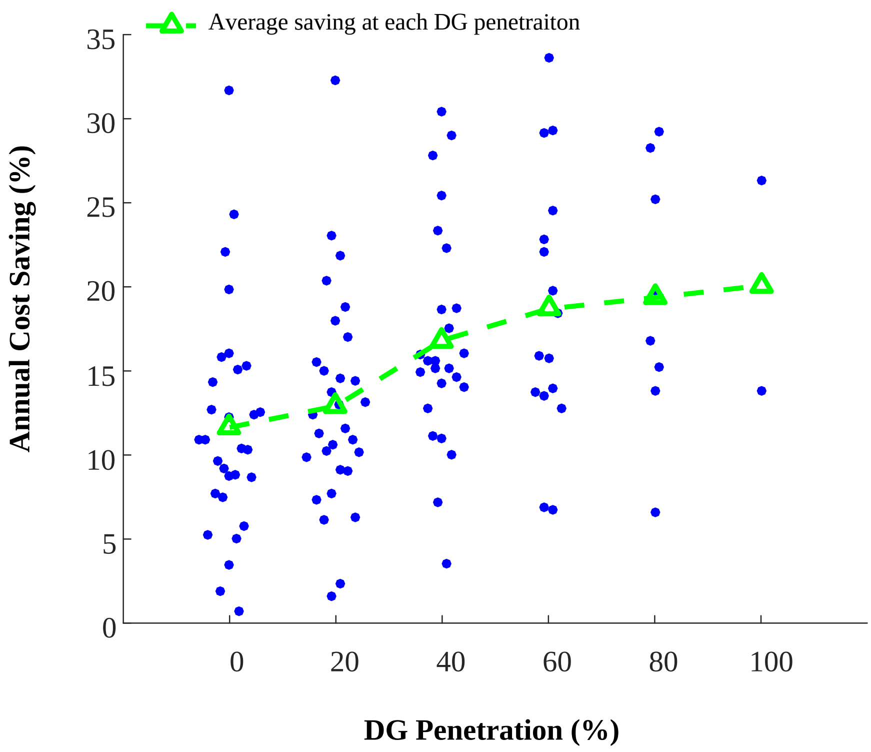


Figure 5.6 Annual cost savings by using Soft DC Links under different DG penetrations

Table 5.5 Minimum, maximum and average cost savings by using Soft DC Links

DG (%)	Minimum Saving (%)	Maximum Saving (%)	Average Saving (%)
0	0.73	31.66	11.64
20	1.58	32.27	12.91
40	3.56	30.45	16.82
60	6.72	33.66	18.69
80	6.58	29.25	19.36
100	13.81	26.34	20.07

- ***Impact of DG Penetration on Soft DC Links***

The obtained optimal capacities of Soft DC Links for each network are shown in Figure 5.7, where the triangle denotes the average capacity at each DG penetration. The minimum, maximum and average capacities of Soft DC Links under different DG integration conditions are listed in Table 5.6. It can be seen that as the DG penetration increased, the required capacities of Soft DC Links first decreased due to the offset of demand and generation. Then as more DG integrated into the networks, larger capacities of Soft DC Links were required.

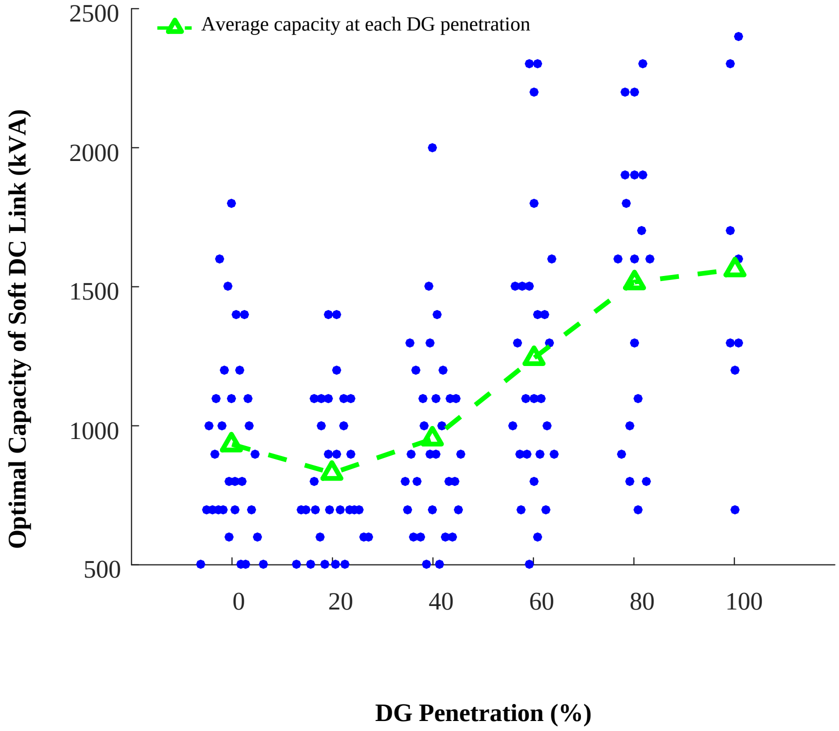


Figure 5.7 Optimal capacities of Soft DC Links under different DG penetrations

Table 5.6 Minimum, maximum and average capacities of Soft DC Links

DG (%)	Minimum Capacity (kVA)	Maximum Capacity (kVA)	Average Capacity (kVA)
0	500	1800	933
20	500	1400	830
40	500	2000	953
60	500	2300	1242
80	700	2300	1517
100	700	2400	1563

- ***Network Performances***

As the amount of DG integrated into the network increases, over voltage and thermal overloading issues are envisaged. Soft DC Links are able to provide voltage and power flow controls such that mitigating or eliminating these issues. Consequently, more renewable generations can be integrated into the network.

The maximum and minimum bus voltages of each network over a year are shown in Figure 5.8. In addition, their average values, with and without using Soft DC Links, are shown in green and grey triangles respectively. It can be seen from these average values that Soft DC Links can always bring the voltages closer to the rated value. It can also be seen that Soft DC Links were able to provide voltage regulations over a wide range of DG penetrations. When there was no DG injection in the networks, Soft DC Links mainly compensated for under voltage issues. With more DG being integrated into the networks, Soft DC Links not only compensated for under voltages, but also reduced the occurrence of over voltages to an effective level.

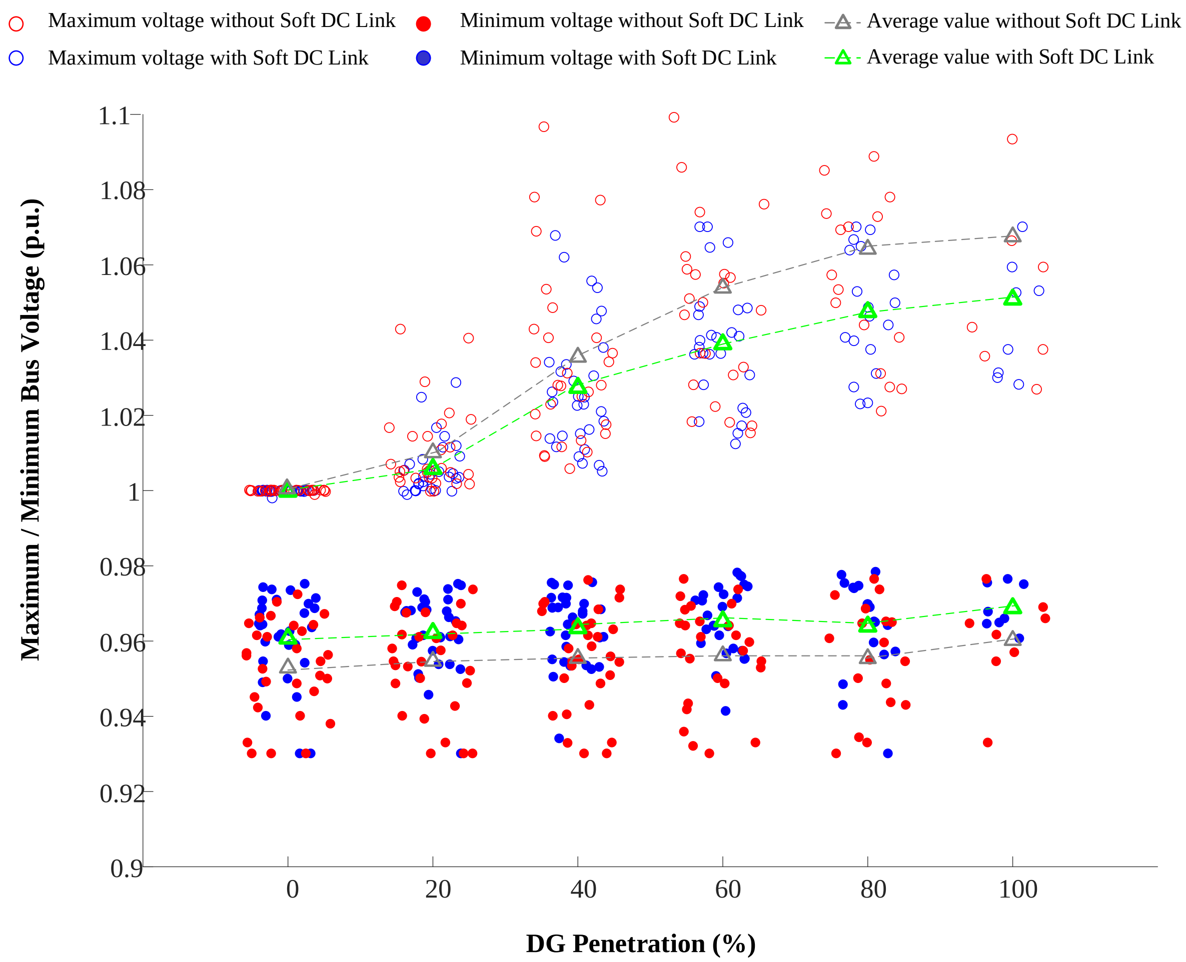


Figure 5.8 Maximum and minimum voltages of each network over a year

Soft DC Links are capable to balance feeder loadings by transferring power from a constrained feeder to a lightly loaded one. Figure 5.9 shows the maximum branch loadings of each network over a year. Their average values obtained by using and not using Soft DC Links are shown in green and grey triangles respectively. From these average values, the capability of Soft DC Links in relieving feeder congestions can be revealed. It can also be observed that, as DG penetration increased to 40% and above, overloading issues started to occur for the reference case without using Soft DC Links. However, such issues were eliminated by using Soft DC Links.

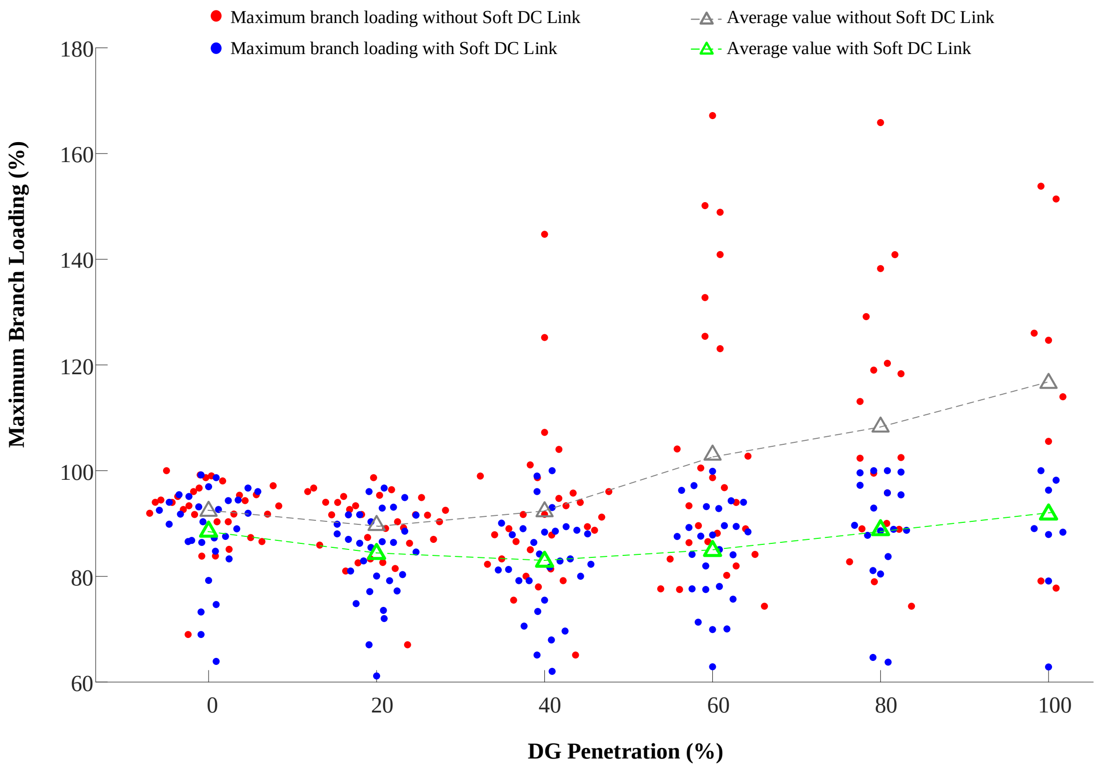


Figure 5.9 Maximum branch loadings of each network over a year

The maximum allowable DG penetrations of the networks are shown in Figure 5.10, together with the average values represented in histograms. It can be observed that Soft DC Links significantly facilitated the integration of DGs, where an increase in DG penetration of 21%, compared to the case without using Soft DC Links was obtained for the studied networks.

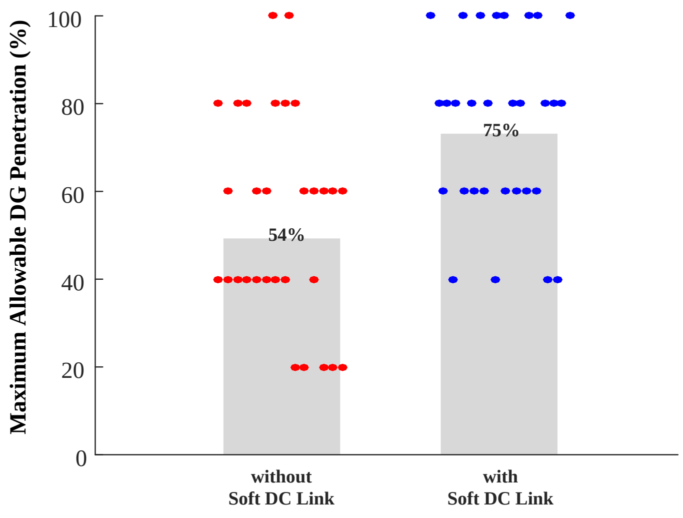


Figure 5.10 Maximum allowable DG penetrations

5.6 Summary

An impact quantification of Soft DC Links on a number of statistically-similar distribution networks was carried out in this chapter. A model determining the optimal siting and sizing Soft DC Links was developed, which takes the minimisation of network annual cost as the objective function. The intermittent characteristics of DG outputs were taken into consideration by using a scenario generation method, and representative scenarios of DG outputs over a year were derived from their PDFs. Impacts on the performances of a number of statistically-similar distribution networks, with and without Soft DC Links, were quantifies and compared under various DG penetrations. Results showed that Soft DC Links can reduce the network annual cost by about 10-20% for the 30 statistically-similar networks under study, over a wide range of DG penetration conditions. Due to the capability of Soft DC Links in voltage regulation and feeder load balancing, more DGs can be integrated into the networks.

Results of the case studies showed that an average increase in DG penetration of 21% can be obtained by using Soft DC Links.

Chapter 6 Conclusions and Future Work

This chapter outlines the main findings and conclusions of the thesis. Future work in the research area of Soft DC Links is also discussed.

6.1 Conclusions

Soft DC Links are power electronic devices connecting previously isolated distribution feeders. They are capable to flexibly control active power exchange between connected feeders, and to provide reactive power compensation at each interface terminal. Soft DC Links are characterised as innovative solutions to address concerns raised by the increasing integrations of renewable energy and customer demand in distribution networks.

In this thesis, benefits of using Soft DC Links in MV distribution networks were investigated. The key findings are summarised below:

- Soft DC Links are capable to improve distribution network operation along multiple criteria, e.g. providing great benefits in power loss reduction, load balancing and voltage profile improvement. However, due to the incommensurable nature of the multiple objectives considered, these benefits cannot be achieved simultaneously, especially when the penetration of DG is high. Therefore, a careful consideration of the objectives is required for operating Soft DC Links;

- Soft DC Links can facilitate the effective use of available capacity between adjacent distribution networks, which greatly increase the network hosting capacity for DG growth and defer expensive infrastructure reinforcements;

- The impact quantification of Soft DC Links on a number of distribution networks and under a wide range of DG penetration conditions shows that, using a Soft DC Link with a relatively small rating can reduce the network annual cost considerably.

6.1.1 Multi-objective Operational Benefits of SOP

In Chapter 3, a multi-objective optimisation framework was developed to investigate the capability of an SOP in improving network operation along multiple criteria simultaneously. A generic mathematical model of the device was developed, in which active and reactive power injections of an SOP are integrated into the load flow algorithm without considering the detailed design of converter controllers. A novel optimisation method, which integrates both global and local search techniques and has enhanced search capability, was proposed to determine the set-points of an SOP. Benefits of using an SOP in power loss reduction, feeder load balancing and voltage profile improvement were quantified. Key findings and contributions of this chapter are:

- An SOP can improve distribution network operation along multiple objectives effectively. For the network under study, with the DG penetration increased from 0 to 200%, on average, an SOP reduced the power loss by 58.4%, balanced the network loading by 68.3% and improved the voltage profile by 62.1%, all compared to the case without using an SOP;

- Comparisons between SOP and network reconfiguration showed the superiority of SOP in operation optimisation. For example, when 50% DG penetration was integrated into the network under study, the power loss reduction obtained by network reconfiguration was 37.2% while the reduction obtained by using an SOP was 70.8%. Under the same condition, improvements of load balance and voltage profile obtained by network reconfiguration were 12.1% and 68.4%, while the corresponding improvements obtained by using an SOP were 93.0% and 77.4%;

- The integrated optimisation method can effectively solve the problem of multi-objective operational optimisation of distribution network with an SOP. The results of performance assessment elaborated that the proposed optimisation method is capable to achieve better and more diverse Pareto optimal solutions than the conventional MOPSO algorithm;
- The proposed multi-objective optimisation framework can provide DNOs with a set of feasible solutions for their network operation considering SOP, from which DNOs can make options based on their priorities or the network conditions.

6.1.2 Grid Transformer-based Control of MVDC Link

In Chapter 4, a Grid Transformer-based control method of an MVDC link was proposed. The GT-based control method requires only real-time measurements at the grid transformers, rather than extensive load and generation data at each substation of a network to define the operation of an MVDC link. Compared to centralised control schemes, the GT-based control has the advantages of relatively low cost, fast response and not highly depending on the reliability and accuracy of ICT infrastructures. Within the GT-based control method, control strategies considering different objectives, i.e. power loss reduction, feeder load balancing, voltage profile improvement, and compromise strategies serving as trade-off options among them were developed through a number of offline studies, where an improved multi-objective Particle Swarm Optimisation method was applied to the network with historical demand and generation data. Assessments and comparisons among the control strategies were carried out. Impacts of an MVDC link on network performances with high DG penetrations were investigated. Key findings and contributions of this chapter are:

- Simulation results showed that is no particular control strategy could bring the optimal operation of a network at all times. Therefore, switching between different strategies as the demand and DG outputs vary would be necessary. The compromise control strategies have moderate performances over a wide range of DG penetration conditions. Therefore, they can be used as assured options when the main challenge brought by large amounts of DG to a network is unclear;
- Regardless of the control strategy used, an MVDC link can significantly reduce power and energy losses compared to the AC operation;
- For the network under study, the MVDC link brought up to 15% increase in DG hosting capacity, and reduced about 50% of power loss compared to the AC operation. The control strategy for feeder load balancing resulted in the highest DG hosting capacity, since the main challenge brought by high penetrations of DG to the test network is thermal overloading issue;
- The proposed GT-based control method is considered to reduce the costs associated with communication and measurement system significantly compared to centralised control schemes, because the GT-based control only requires a few measurement points in a network (i.e. at the grid transformers). Therefore, the relative simplicity and low cost make the GT-based control an attractive interim option before the implementation of more complex centralised control schemes.

6.1.3 Impact Quantification of Soft DC Links

In order to investigate the general impacts of Soft DC Links and make robust decisions for their implementations in distribution networks, an impact quantification of Soft DC Links on a number of statistically-similar distribution networks was carried out in

Chapter 5. An optimisation model to determine the siting and sizing of Soft DC Links for minimising the network annual cost was developed, in which the network annual cost includes the investment and operational costs of a Soft DC Link, as well as the annual energy loss cost of a network. In order to consider the intermittent characteristics of DGs, a scenario generation method was used to derive representative scenarios of DG outputs over a year from their probability density functions. Impacts of DG penetrations on the network performances and on the allocation of Soft DC Links were analysed. Key findings and contributions of this chapter are:

- Soft DC Links reduced network annual costs by 10-20% over a wide range of DG penetration conditions for the statistically-similar networks under study;
- By using Soft DC Links, an average increase in DG penetration of 21% was obtained compared to the case without using Soft DC Links for the test networks;
- The use of statistically-similar distribution networks reduces the uncertainties of using a single representation to mimic real networks. Therefore, more generic and robust impact analysis of Soft DC Links can be derived, which will provide guidelines for distribution network planners to decide whether the implementation of Soft DC Links is suitable for them.

6.2 Future Work

Followings are the future work identified to extend the studies in this thesis:

6.2.1 Performances of Soft DC Links Considering Different Load Types

For the studies presented in this thesis, constant-power loads were considered. However, there are other load characteristics in real world, such as constant-impedance and constant-current loads, which can lead to different network behaviours. In order to reflect a more realistic situation, future studies shall consider the performances of distribution networks with Soft DC Links when different load characterises, and/or a combination of different types of loads are connected.

6.2.2 Use of Soft DC Links in Unbalanced Three-phase Distribution Networks

In this thesis, balanced distribution networks were assumed. However, most residential and some commercial customers have single-phase connections to distribution networks. Therefore, the loads in distribution networks cannot be perfectly balanced.

The common DC bus within a Soft DC Link enables the exchange of instantaneous power among different phases, whereby the rebalance of power flows on connected feeders can be achieved. New controllers shall be investigated for the operation of Soft DC Links to address unbalanced three-phase conditions. Moreover, the benefits of using Soft DC Links for the operation of unbalanced distribution networks shall be evaluated and quantified in future studies.

6.2.3 Evaluation and Comparison of Different Types of Soft DC Links

This thesis focused on the utilisation of back-to-back, and point-to-point VSC-based Soft DC Links in distribution networks. However, there are other topologies of Soft DC Links that can achieve similar functionalities. In future studies, the capabilities of different types of Soft DC Links in relieving network constraints and accommodating DGs shall be assessed and compared. The economic impacts of different device topologies need be compared as well.

6.2.4 Impact of Device Power Loss of Soft DC Links

In this thesis, when investigating the capability of Soft DC Links in power loss reduction, the assumption was made that the device power loss was relatively low compared to the overall loss in the network. However, in practical application, the internal power loss reflects the device efficiency, which varies with many factors, such as the power transferred and the device configuration. In future studies, the impact of device power loss on the overall loss reduction shall be analysed.

6.2.5 Comprehensive Economic Analysis of Using Soft DC Links in Distribution Networks

In this thesis, the economic benefit of using Soft DC Links in distribution network was investigated for minimising the network annual cost, which includes the capital cost, annual operational cost of a Soft DC Link, and the annual energy loss cost of a network. Future research can be carried out to compare the relative costs of Soft DC Link interventions with other smart technologies. A wide range of conventional reinforcement options can also be considered and compared. For example, different conductor types, each with its own technical characteristic and cost profile. Furthermore, sensitive analysis can be carried out to evaluate the impacts of internal losses and life cycles of Soft DC Links on their implementations.

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