THE EFFECTS OF DISTRIBUTED GENERATION SOURCES WITHIN COMMERCIAL RETAIL RETICULATION NETWORKS

by

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SUMMARY

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There is an increased implementation of renewable energy generation sources, such as solar PV, within electrical networks. This is due to the reduced cost of electricity generated from renewable energy systems as well as the world becoming more environmentally aware. There is therefore a need to understand the effects of Distributed Generation (DG) within commercial retail reticulation networks on load and networks parameters, such as coincident demand and load factor. These load parameters play an important role in network design as well as in load forecasting which influences network expansion and generation planning decisions.

A hypothetical study was conducted on a low-voltage commercial retail reticulation network to determine the effects of varying levels of DG penetration on load and network parameters. Two DG placement scenarios were investigated; centrally and de-centrally located within the reticulation network. Results from the hypothetical study were confirmed by conducting the same analysis on a commercial retail reticulation network in service, with measured load demand data available.

Results obtained indicated that load parameters such as coincident demand, load factor and diversity factor are significantly impacted at high levels of DG penetration. Further investigation is required to determine if the altering of load parameters, from the introduction of DG would require current design procedures or standards to be modified and updated; or if the standards applicable to the design of reticulation networks are still relevant when varying levels of DG penetration are introduced.

LIST OF ABBREVIATIONS

ADMD	After Diversity Maximum Demand
ANM	Active Network Management
AVC	Automatic Voltage Control
DG	Distributed Generation
DMS	Distribution Management System
DNOs	Distribution Network Operators
GOP	Garsfontein Office Park
GPS	Global Positioning System
HV	High-voltage
ICAE	International Conference on Applied Energy
IEEE	Institute of Electrical and Electronic Engineers
IPSO	Improved Particle Swam Optimisation
LV	Low-voltage
PSO	Particle Swam Optimisation
PV	Photovoltaic
RTU	Remote Terminal Unit
SANS	South African National Standards
SCADA	Supervisory Control and Data Acquisition
SLD	Single Line Diagram
USA	United States of America

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

Distributed Generation (DG) is defined as “an electric power source connected directly to the distribution network or on the customer side of the meter” [1]. Renewable energy DG sources are becoming increasingly utilised as electricity consumers globally become more environmentally conscious. Another factor that has contributed to the increased implementation of renewable energy DG sources is the decreased cost of electricity generation from sources such as wind and solar Photovoltaic (PV) system, as a result of the advance in technology [2].

Distribution networks are typically planned, designed and operated to be purely passive networks that deliver electricity to consumers in a unidirectional manner (from source to load) with minimal or no monitoring and control capabilities [3]. The introduction of DG into distribution networks alters conventional power flow within the network [4], and can results in bi-directional power flow [4]. This has an impact on load parameters of the composite load (as seen from the external grid) and network parameters within the network. A significant number of assumptions are made in order to determine suitable parameters used to predict the future load demands [5]. Understanding how load parameters are effected, from the addition of DG, is therefore important for predicting future load demands with DG sources present.

Load forecasting utilises a combination of the load parameters such as diversity factor, load factor, load demand profile, loss factor, growth rate and after diversity maximum demand (ADMD) [5]. Altering of any of these parameters from the introduction of DG can have an impact on planning and design of electrical networks [5].

The factors that define or impact the technical performance of an electrical distribution network are electrical losses, voltage regulation, equipment loading and utilisation, system fault levels, frequency and harmonics [6]. In contrast to distribution networks (typically medium-voltage); when considering low-voltage reticulation networks (and the integration of DG) only certain parameters need to be considered. These parameters are voltage, thermal loading of equipment, peak load demand, network losses as well as feeder protection [7].

1.1.2 Research gap

Understanding how load and network parameters are affected from the introduction of DG is important for many reasons. Altering of load parameters affects how reticulation networks are planned, designed and operated. Altering of load parameters can also affect load demand forecasting, which plays a critical role in transmission and distribution network planning. By analysis of load and network parameters at varying levels of DG penetration, the effect on load parameters, such as coincident demand, diversity factor and load factor can be determined.

A significant amount of research has been conducted regarding the optimal placement of DG within distribution networks to improve network parameters such as energy losses and voltage profiles; as well as a comparison of different optimisation techniques [3], [4], [6], [8] - [14].

Another area in which a significant amount of research has been conducted is with regards to network protection strategies for networks containing DG, implications of introducing DG into existing distribution networks on network protection and improved network protection schemes to increase DG penetration levels without comprising system performance [15] - [21].

Although the body of knowledge surrounding the integration of DG into distribution networks is vast, there is little focus on reticulation networks (low-voltage networks); in particular, on how the integration of DG into commercial retail reticulation networks affects load parameters.

Limited research has been conducted in this area; however, research on technical behaviour of low-voltage networks with varied levels of renewable penetration has been conducted [7]. The focus of this research was primarily on the effects of DG on voltage profiles and networks losses. Although relevant, the focus of the particular research did not cover the impact of DG on load parameters. The impact of DG on ADMD or coincident demand has been investigated [5]; however, not all load parameters which are under consideration in this research were investigated. Refer to section 3.3.1 for the definitions and formulas for the eight load parameters under investigation for this study.

The effect of varying levels of DG penetration for low-voltage networks has been analysed, with regards to voltage profile improvement. It was found that an improvement in the voltage profile was the most considerable when load demand profiles match with the energy generation source profile [7]. It was also found that if there was a mismatch between the energy generation source profile and load demand, there was not a reduction in network peak demand [7]. Although this information is valuable and could provide insight on how to plan or design a network that would include DG, there was no focus on the effects of DG on the different load parameters. The effects on load parameters provides insight into load behaviour which is of great importance during network planning and design.

Based on the fact that there has been limited research conducted on the impact of DG on load and network parameters within commercial retail reticulation networks, there is a clear research gap in the body of knowledge surrounding the topic. Further research is required to gain a better understanding of how load parameters, for the composite commercial retail load, are impacted by the introduction of varying levels of DG into the commercial reticulation network.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The objective of the research was to determine how DG effects load parameters (as seen by the external network) and network parameters within the reticulation network, when integrated into commercial retail reticulation networks.

The research question addressed was how the introduction of DG into commercial retail reticulation networks would affect load and network parameters. These effects could be used to determine if current planning and design procedures or standards are adequate for the design of reticulation networks containing varying levels of DG penetration. This topic is beyond the scope of this study.

1.3 APPROACH

To determine the effects that the introduction of DG has on load and network parameters within commercial retail reticulation networks, the research conducted was done in two separate phases; namely, a hypothetical study and a case study. The hypothetical study was based on assumed or publicly available information as well as a typical reticulation network topology. The case study was based on actual information obtained for an existing commercial retail facility. The research methodology applied for each phase is detailed in section 1.3.1 and 1.3.2 respectively.

1.3.1 Hypothetical study

Many factors needed to be determined, or assumed based on common practice, before results could be obtained for the hypothetical study. Developing the hypothetical study began with load modelling and developing load demand profiles of each of the hypothetical consumers. Once the load modelling was complete, a reticulation network model was developed.

The reticulation network was based on an assumed network topology and component sizes, such as transformer capacity and feeder cable sizes. Results obtained for the load parameters and network parameters under consideration, for this research, were obtained for the scenario with no DG integrated into the reticulation network. This is referred to as the base case scenario and serves as the reference point for which all comparisons are made. Varying levels of DG penetration (based on load demand) and integration points within the reticulation network were then analysed.

The first DG integration scenario analysed was with a DG source introduced at the common low-voltage busbar, of the step-down transformer which supplied all the customers. This scenario is referred to as the central DG scenario. The second DG integration scenario, referred to as the de-central DG scenario, introduced the DG source further down within the network at a customer sub-distribution board level.

The DG source capacity in both scenarios was varied to a maximum of the coincident load demand at the particular busbar it was connected to. The impact on load and network parameters for the varying penetration levels and DG scenarios was then obtained and analysed.

Modelling of the reticulation network was done using a suitable power system simulation software package. There are many suitable software packages that could have been utilised to perform the required simulation studies. The software package utilised was DIgSILENT Power Factory[1] software. The reason for the selection was primarily because DIgSILENT Power Factory software was available and it has the required functionality to perform the suitable simulation studies.

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[1] DIgSILENT Power Factory is a product of DIgSILENT GmbH
http://www.digsilent.de/index.php/products-powerfactory.html

1.3.2 Case study

A similar approach to the hypothetical study was followed for the case study. To validate the results obtained for the hypothetical study, a case study was conducted on a commercial retail reticulation network with actual measured load demand data and information gathered on the reticulation network in service. The information gathered from an on-site investigation was used to develop the network model. The analysis of the impact of the two different DG scenarios (central DG and de-central DG) on load and network parameters was also conducted.

1.4 RESEARCH GOALS

The goal of this research was to determine the effects of varying levels of DG penetration on load parameters (as seen by the external network) and network parameters within the network. The results and outcome from this study could potentially be used to assess the suitability of current design procedures and standards for reticulation networks that are proposed to contain DG sources. The assessment of current planning standards and design procedures, along with the findings of how DG affects load and networks parameters, will provide insight into which aspects of planning standards or design procedures require updating or improving. The assessment of current planning standards and design procedures is beyond the scope of this study.

1.5 RESEARCH CONTRIBUTION

The contribution from the research was the identification and quantification of the effects of varying levels of DG penetration on load and network parameters for commercial retail reticulation networks. An extensive literature study indicated that, although research has been conducted on the effects of DG on load parameters, the focus was on a single load parameter, ADMD as opposed to multiple parameters. Further research was therefore required to determine the effects of varying levels of DG penetration on all relevant load parameters.

The research has contributed to a better understanding of the effects of varying levels of DG penetration on multiple load parameters. These parameters are of great importance in network planning and design. The effect of varying levels of DG penetration on network parameters, such as supply voltage, were also determined and quantified. This parameter also plays a critical role in network planning and design.

1.6 RESEARCH OUTPUTS

From the research conducted for this study, an international conference paper was submitted to the 9th International Conference on Applied Energy (ICEA) and accepted. The conference paper was also published in the Energy Procedia, Volume 142.

1.7 DISSERTATION OVERVIEW

Chapter 2 presents the body of knowledge surrounding DG and the integration within distribution networks. It was found that the integration of DG into distribution networks poses many concerns but also has certain advantages. There are many factors that need to be considered when integrating DG into distribution networks and these are further discussed in chapter 2. Although the body of knowledge surrounding the integration of DG into distribution networks is vast, the same cannot be said for reticulation networks.

Chapter 3 details the load models developed for the hypothetical study as well as the associated reticulation network. Chapter 3 also presents the results obtained for hypothetical study.

Chapter 4 provides information on the existing commercial retail reticulation network as well as measured load demand data for all the customers assessed. Chapter 4 also details the analysis and results obtained for the case study in order to validate the results obtained by the hypothetical study.

Chapter 5 provides a discussion and comparison of results obtained from both the hypothetical study and the case study conducted.

Chapter 6 concludes the dissertation, summaries the findings and identifies further research areas based on the findings.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OVERVIEW

The objective of this chapter is to provide a comprehensive overview of the body of knowledge that surrounds DG, and in some cases, literature applicable to reticulation networks containing DG sources. Section 2.2 discusses how network topologies are being altered due to DG. Section 2.3 discusses the technical effects of DG on network parameters.

2.2 HOW DISTRIBUTED GENERATION IS CHANGING NETWORK TOPOLOGIES

Traditional distribution networks were planned, designed, constructed and operated to be purely passive systems and used to deliver electricity to consumers in a unidirectional manner [3]. With the introduction of DG into a distribution network, conventional power flow within the network is altered and can become bi-directional [4]. This influences how networks should be planned, designed and operated so that the various impacts of the introduction DG can be taken into account.

The factors that define the technical performance of an electrical network are electrical losses, voltage regulation, equipment loading and utilisation, fault levels, stability limits, frequency and harmonics [6]. Understanding how DG affects the technical performance of the power system is key to being able to successfully plan, design and operate electrical networks that contain DG sources in a safe and efficient manner.

To address many of the issues involved with the integration of DG to the distribution network, smart grids are being developed. The definition of a smart grid, according to the Internal Energy Agency, is “an electricity network that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demand of the end user” [22].

2.2.1 Smart grids

Smart grids should be able to determine and co-ordinate the needs and capabilities of all generation sources, grid operators, end users and electricity market stakeholders in such a manner that they are able to optimise asset utilisation and operation as well as minimise both costs and environmental impacts in the process, all whilst maintaining system reliability, resilience and stability [22].

The introduction of DG requires distribution networks to move towards more intelligent networks that can monitor and control generation sources so that they align with load demands. This would then ensure the optimal use of DG, as well as electrical infrastructure, between the generation sources and the end user.

2.2.2 Micro-grids

The introduction of DG sources can also alter networks on a smaller scale, other than transmission or distribution networks. These small-scale networks are called micro-grids. A micro-grid is defined as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries, that acts as a single controllable entity with respects to the grid. A micro-grid can connect and disconnect from the grid to enable it to operate in both grid-connected mode and island mode” [23]. The addition of DG results in altering loads from passive uncontrollable entities to active controllable entities which has its associated advantages and disadvantages. The impact of altering load characteristics then needs to be determined in order to adequately plan and implement suitable electrical power systems.

2.3 EFFECTS OF DISTRIBUTED GENERATION ON TECHNICAL NETWORK PARAMETERS

With an increase in the implementation of DG, there are many factors that need to be considered when planning and designing electrical networks. These factors could either enhance the network performance or be detrimental to the network performance. This is dependent on many factors and can only be quantified on a case by case basis [4]. There are a number of technical issues that need to be taken into account when connecting DG sources to the distribution network, such as [24]:

- Thermal ratings of equipment;
- System fault levels;
- Stability;
- Reverse power flow capabilities of tap-changers;
- Line-drop compensation;
- Steady-state voltage rise;
- Network losses;
- Power quality (flicker and harmonics); and
- Network protection.

The effects of DG, on power systems, for each of the above-mentioned factors are further described in sections 2.3.1 to 2.3.7.

2.3.1 Minimise losses

The optimal placement of DG can have the effect of reducing energy losses within the network. This reduction of energy losses is achieved by reducing the current magnitudes that flow within the distribution networks, which reduces the energy losses (I^2R losses) within the network. This would be the effect of integrating a DG source at the end of a radial network and would reduce energy losses within the network. The current magnitudes are reduced by reducing the load current that would need to be supplied via the distribution network. This results in a reduction of energy losses along the network. This is a simplified scenario; however, the same cannot be assumed for more complex networks with multiple nodes. To determine the placement of DG within complex networks, which would result in minimal energy losses, requires optimisation. The optimisation can be achieved by making use of different techniques, objective functions or system constraints.

One paper which explored the placement of DG employed a particle swarm optimisation (PSO) technique focused on minimising real power losses in the primary distribution networks [12]. Results for a 69-bus network were in close correlation to other optimisation technique results obtained. PSO techniques could be further expanded to multi-objective optimisation with a focus on reducing real power losses, improving voltage stability and current balancing within certain sections of the power system within a radial distribution system [14].

Optimal placement and sizing of DG using the improved particle swam optimisation (IPSO) - monte carlo algorithm technique has been found to reduce active and reactive power losses, improve voltage profiles and enhance system reliability [8].

Multi-objective optimisation, using PSO with an alternative proposed algorithm, focused on the minimisation of power losses whilst simultaneously maximising voltage stability within the system [9]. The optimisation yielded reduced power losses and improved voltage stability by finding the bus within the network with the lowest voltage. The proposed algorithm was compared to other analytical techniques and was found to perform better [9].

2.3.2 Voltage profile improvement

By altering the parameters within the distribution network, such as current, there can would be effects noted on other system parameters such as voltage. System voltage is an important parameter within distribution systems since distribution network operators (DNOs) are required, by regulations, to maintain supply voltages within certain specified tolerances, i.e. ±5% of normal voltage. In weak networks voltage stability can often be a problem as system voltages may vary significantly as the loading of the network is increased, which could result in voltage violations occurring.

By introducing DG into the network, loading of the network is altered during the periods of generation. This would influence voltages within the distribution network. The influence on voltage profiles within the network can be improved if DG is placed correctly within the system [25]. To improve voltage profiles, optimal placement of DG must be done. This will also help improve voltage rise or fluctuations within the system [26].

Optimisation, in terms of placement and sizing of DG, could be done by using the same optimisation techniques used for minimising energy losses by implementing a different objective function. One such technique is sensitivity analysis [27] and results obtained were based on a new voltage stability index for optimal placement of DG in a radial system.

Another method for obtaining the optimal solution could be a combination of different techniques such as sensitivity analysis and PSO. One example of such a methodology is a combination of loss sensitivity factor, to determine the most optimal location for the DG source, and PSO for optimising the capacity of the DG system to reduce total system losses, as well as voltage improvements along a radial distribution system [10].

A hybrid algorithm between a genetic algorithm and PSO has been employed and yielded results of reduced system energy losses, improved system voltage regulations as well as improved system voltage stability [13]. Variations of PSO algorithms alone have also demonstrated the ability to optimise DG placement in terms of improving voltage profiles [9], [28].

Besides for several optimisation techniques available to improve voltage profiles or reduce the effects of excessive voltage rise, due to DG integration, the following alternatives could also be implemented [24]:

- Reduce primary substation voltage;

- Allow the generation source to import reactive power;
- Install auto-transformers or voltage regulators along the line;
- Increase conductor size;
- Constrain the generation output at times of low demand; or
- A combination of the above.

The selection of the most appropriate scheme must be done on a site-by-site basis as each of the above-mentioned schemes has its associated limitations [24].

Analysis of the effect of varying levels of DG penetration for low-voltage networks has been conducted and found that voltage profile improvement was the most considerable when load demand profiles match with the generation profile [7].

2.3.3 Network fault levels

Short-circuit fault level is an important parameter that needs to be considered when planning, designing and operating power systems. Fault levels dictate equipment rating which ensures that equipment can withstand the severe stresses that it experiences due to the high fault currents that occur when a fault on an electrical network takes place. Fault levels within the network could be altered and the direction of fault currents may change from the integration of DG. A change in fault current magnitude or direction may negatively affect protection devices if they are unable to respond in the manner which was originally intended, to safely protect the network [29].

The fault contribution of a single small DG unit is not significant but it is very seldom that a single DG unit is integrated into a distribution network. The cumulative contribution of many DG units can alter network fault levels which can result in mis-coordination of protection equipment [15]. Mis-coordination between protection devices is due to altering of the fault currents [30]. False tripping of feeders, relay mal-operation, fuse-fuse mis-coordination and fuse-recloser mis-coordination are common issues observed [21].

It was also found that the introduction of DG downstream from a substation decreases the fault contribution from the upstream substation [18]. This has an impact on the effectiveness of the protection system upstream.

Despite the impacts of introducing DG into the distribution network, on system fault levels and protection coordination, the effects are still dependent on the location of integration and network topology into which the DG source is incorporated [18], [29].

2.3.4 Protection strategies

Distribution networks are conventionally radial in topology, and the protection strategies for these networks assume a single-source of supply and single direction current flow within branches [19]. Conventional protection strategies for radial distribution networks usually take the form of overcurrent and time-current graded protection. These strategies are cost effective and simple to coordinate and provide clear discrimination for fault currents between protection devices [19].

The introduction of DG into a distribution network alters the network from a radial network with a single source of supply to a radial network with multiple sources of supply. This results in bi-directional power flow within the network [19]. Based on this, the conventional distribution network is subjected to varying faults levels which further compromises protection coordination [19].

Distribution network systems which have a high penetration levels of DG may exhibit poor protection coordination and thus negatively impact system reliability [31]. Due to reduced system reliability and safety concerns, more advanced protection schemes need to be developed for such distribution systems.

Integration of DG into the distribution network can lead to various problems with regards to the protection system namely [18];

- False tripping of feeders;
- Nuisance tripping of generation plants;
- Blinding of protection relays;
- Increased or decreased fault levels;
- Unwanted islanding;
- Prohibition of automatic reclosing; and
- Unsynchronised reclosing.

False tripping occurs when a protection relay detects and opens its associated circuit breaker based on a fault signal for a fault that has occurred in an unrelated network region [19]. The cause of such false tripping is because of reverse current flowing from the downstream DG source to the upstream faulted network [18]. To avoid false tripping, it is important to ensure that proper protection coordination is achieved within power systems [18]. Distribution networks typically make use of non-directional protection equipment and a change to directionally sensitive protection equipment would eliminate false tripping due to the introduction of DG [19].

‘Blinding’ of protection relays occurs when the system fault level is reduced by the introduction of DG. This results in the overcurrent protection relays being unable to detect fault currents [18].

Certain DG types can source significantly large short-circuit currents. As a result, feeder protection relays could not operate as intended [18]. Since DG can also reduce system fault currents, overcurrent protection may no longer be suitable for the protection of distribution networks with large amounts of DG connected. One protection scheme that is more advanced than overcurrent protection is distance-based feeder protection. Distance-based feeder protection schemes have fixed zones of protection that are independent of system conditions [20].

The integration of DG sources upstream of such protection relays does not alter the impedance that the protection relay monitors. This is because the protection relay monitors the voltage and current downstream of the DG source to compute impedance [20].

The integration of DG sources downstream of the protection relay causes the impedance that the protection relay perceives to be higher than the actual value. This results in the protection relay not detecting a fault due to the altering of system impedance. This problem is known as under-reaching [19].

Protection solutions that are employed in transmission networks (such as differential current detection) could be implemented in distribution networks with DG present. The cost of implementation of such a protection system would be high and the system would be more complex to implement in distribution networks due to the network size. One technique that could be implemented in a distribution network with DG sources integrated is communication assisted protection [32].

These types of protection systems are multi-level systems that implement fault detection equipment (level 1), inter-breaker communications (level 2) and adaptive relay settings as well as supervisory control (level 3) [32]. These systems require extensive communication infrastructure to be put in place, within the distribution system, that would not conventionally be present. This adds significantly to the cost and complexity of the distribution network.

Simpler, more cost-effective techniques, by making use of already existing protection devices, have been investigated to determine the maximum allowable DG capacity that could be integrated into the distribution network while still maintaining proper protection coordination [17]. The research only identified the maximum DG capacity that could possibly be integrated, based on the protection equipment already installed. No new protection strategies were identified.

Research into adaptive microprocessor based methods has been undertaken to ensure proper coordination between re-closers and fuses [16]. The proposed scheme would make use of a main relay that is computer based. The computer based relay would be able to analyse large amounts of data and communicate with other protection devices such as zone breakers or DG relays [16]. The main disadvantage of such a system would be that it requires input from several sensing equipment devices located throughout the distribution network, which increases the cost of such a system. The protection of the distribution network would also then be reliant on a single main protection relay. This has the disadvantage that protection of the system could be lost due to communication failure or faulty sensing equipment.

The various types of renewable DG sources (e.g. solar PV, wind or biomass) behave differently under fault conditions [33]. Different protection schemes and technical requirements need to be addressed based on the different technologies to ensure that protection of the generation plant, as well as the distribution network, is maintained at all times.

2.3.5 Power system stability

An increase in the contribution of energy generation from DG sources increases the probability of protection issues. This could lead to sections of the power system experiencing the effects of multiple DG plants tripping and could potentially create a situation where load demand is far greater then generation capacity available. A situation such as this creates instabilities within the power system [19].

Power system stability is a very important aspect that needs to be taken into account as instabilities within the power system could result in prolonged system outages or power quality issues. The introduction of DG sources, such as solar PV, which implement inverters as opposed to rotating electrical machines, reduces the overall power system inertia. This affects the power systems ability to react and compensate for faults within the network or other severe changes in system operation [34].

Stability issues are a concern in power systems at the transmission and sub-transmission network levels. Power system stability will become more of a concern at the distribution network level with the integration of more and more renewable energy generation sources. Power system stability of low-voltage reticulation networks is not a concern and therefore does not have major impact on reticulation network planning, design and operation with DG sources present. It is, however, still relevant as DG sources lower down within the power system do have an influence on transmission networks higher up in the power system.

2.3.6 Effect on power system operation

The integration of DG not only effects technical aspects of the power system, it also effects the way in which power systems can be operated. The integration of DG needs to be implemented in such a way that maximum benefit is derived. Power system parameters, such as voltage, also need to be maintained within specific limits set out in the relevant regulations.

2.3.6.1 Active network management

Conventional distribution networks are designed based on the “fit and forget” principle [35], [36], [37] which implies that minimal management of the distribution network is required. active network management (ANM) is the process of actively monitoring, controlling and managing the distribution network, to which DG sources are connected to ensure that all network components operate within all continuous and emergency capacities or ratings [35].

DNOs currently strictly limit the connection of DG to avoid the negative effects of high penetration levels on distribution network operating parameters [36]. To achieve high levels of DG penetration, and to extract maximum benefit from the implementation of DG, active network management is required [38]. This is done to ensure system operating conditions are within all of the prescribed limits [35].

One of the most integral parts of ANM is the estimation of network states [38] to determine the control action required to ensure that the network operating conditions are within stipulated limits. ANM entails the control and real-time management of DG units and other devices within distribution networks [35]. These include generation dispatch, transformer tap positions and reactive power compensation equipment set points [38].

One of the main system parameters that affects the level of DG penetration that can be achieved within a network is the permissible voltage limits [24]. The main challenge associated with the control schemes for active voltage control is the estimation of voltage states throughout the distribution network. This challenge is due to the size of typical distribution networks and low observability because of low levels of system monitoring [35].

There are three main schemes of coordinated voltage management, namely centralised distribution management systems (DMS), local voltage controllers and advanced automatic voltage control (AVC) relays [39]. The first scheme (centralised DMS) makes use of a centralised controller which implements a supervisory control and data acquisition (SCADA) system that collects measurements from remote terminal units (RTU's) located at strategic points in the network. This information is then transferred to the DMS [39]. The state estimation algorithm then determines the voltage levels at all nodes. The voltage levels are used to determine the required control action based on target values. This would then be used to determine if the voltage set points of the AVC relays should be changed, if online generation output should be altered or if network configurations should be changed to maintain the optimum state of the network [39].

The second scheme (local voltage control) is more applicable to a localised DG unit connected to the distribution network [39]. Local voltage control also implements state estimation to estimate a range of possible voltages for all nodes within the network under control [39].

The third scheme (advanced AVC relay) only makes use of measurements at a substation level and resemblance of load patterns on the various feeders of the substation to previously measured load patterns [39]. The advanced AVC relay method estimates the generation output based on the local measurement of the feeder to which the DG is connected [39]. Coordinated management of voltage levels at substations and curtailment of energy generation from DG units are the most efficient solutions to incorporating large amounts of DG into the distribution networks, without significant investments required for system upgrades [35].

2.3.6.2 Island operation of distributed generation

Islanding occurs when a section of an electrical network that has DG connected to it, is electrically isolated from the remainder of the power system and continues to be energised by the DG source [40]. The disconnection of DG units is required to prevent islanding as it has technical and safety issues that can result from DG operating in island mode [40].

International standards [41] do not allow for the island operation of DG units for a variety of technical and safety issues. Line workers' safety, inadequate system earthing, altering of system fault levels, out-of-phase reclosing and limited voltage or frequency control are the main concerns associated with the island operation of DG units [40].

Allowance of DG units to operate in island mode can improve security of supply within the distribution network to which they are connected [19], [40]. Islanding operation also has economic benefits for the DG source owner's due to the additional electricity sales generated during island operation [40].

2.3.7 Economic benefits of distributed generation

Network planning and design not only entails overcoming technical aspects to ensure the most suited solution is implemented, economic aspects of the power system also need to be taken into account. The main economic aspect that DG affects would be the cost associated with energy losses within the power system, as well as economic investments required for network upgrades or expansions.

The introduction of DG can reduce system operation costs by reducing system energy losses, reduce capital costs related to system upgrades required by deferring investments as well as reduced depreciation of assets. The reduction of environmental penalties related to emissions also reduces the cost and increases competitiveness in open electricity markets resulting in lower electricity tariffs [35].

2.4 CHAPTER SUMMARY

The introduction of DG into distribution networks is altering networks from passive networks with unidirectional power flow to active networks with bi-directional power flow. The altering of network behaviour has resulted in requirements for more network information as well as control intensive network topologies such as smart grids or micro-grids.

The development of modern network topologies is not only due to the changing of how the system behaves, it is also required for overcoming several technical issues related to the integration of DG into the power system. There are many technical issues related to the integration of DG to the distribution network; however, the main areas of concern are voltage related issues as well as protection related issues.

Many of the technical issues can be resolved through the integration of DG at the optimal location within the network as well as optimal system sizing. Placement and sizing of DG to overcome a variety of technical concerns has been demonstrated via a number of optimisation techniques each with its own merit. There is; however, not one solution that fits all the possible configurations and optimisation still needs to be done on a case by case basis.

Addressing protection related concerns with the development of new protection schemes is critical for the efficient and safe implementation of DG within the power system. These concerns are unique to the configuration of the network and also need to be addressed on a case by case basis.

The inclusion of DG into the distribution networks poses many technical concerns; however, if these technical concerns are addressed the advantages that DG provides to the network, technically as well as economically, are favourable. Despite the vast amount of research conducted on the effects of DG relating to operational, technical and economic issues within the power system, there seems to be a lack of research conducted on commercial reticulation networks as well as low-voltage networks.

With an increased awareness on environmental issues, as well as security of supply to industry, it is predicted that there will be an increased integration of DG into such networks and this presents the need to understand the effects of DG particular to these types of networks. This would ensure that planning, design, implementation and operation are done effectively and safely.

CHAPTER 3 HYPOTHETICAL STUDY

3.1 CHAPTER OVERVIEW

Chapter 3 presents the results obtained for the hypothetical study that was conducted on a commercial retail reticulation network developed, to study the effects of varying levels of DG penetration on load and network parameters. Section 3.2 provides detail on the information used and input to develop the reticulation network model as well as the relevant load parameters of interest for the study. Section 3.3 presents the base case results obtained, where sections 3.4 and 3.5 presents the results for the centralised DG scenario and de-centralised DG scenario respectively. Section 3.6 concludes the chapter.

3.2 NETWORK MODEL INPUT PARAMETERS

To develop the hypothetical commercial retail reticulation network model, a number of parameters had to be determined and this was done by referring to relevant literature or making certain assumptions based on common industry practise. Developing the hypothetical study began with load modelling and determining suitable load demand profiles for each of the customers used in the study.

3.2.1 Load modelling

Load demand profiles depict the nature of how electricity demand varies over a given period, and is a function of the facility (i.e. residential, commercial or industrial) as well as human behaviour within the facility.

Different types of electricity consumers have different characteristic load demand profiles and associated load models. How each of the different consumers utilises electricity results in differing load parameters, such as diversity and load factor, which are representative of the load type. It was important that the correct load demand profiles were utilised for the hypothetical study. This ensured that the load parameters and the effect of DG integration on load parameters were representative for the load type associated with each of the commercial electricity consumers.

Different load modelling techniques have been found to have an impact on the results obtained when conducting energy loss analysis on DG integration into a distribution network [42]. Load modelling techniques have further been found to play an important role in power system analysis and have an impact on PV generation planning [43]. Load variations have also been seen to affect optimal sizing of DG sources [44]. It is therefore important to accurately model load demand behaviours with suitable mathematical models for this study.

There are three different load types that define load behaviour in relation to the supply voltage; namely constant power, constant current, or constant impedance [45]. Studies have been conducted investigating the impact of different load models on solar PV generation planning within the distribution networks [43] and it was found that the impact of the incorrect load models on results obtained could be significant [11], [43], [46].

Electrical loads that are voltage dependent loads are residential, industrial and commercial electricity consumers [11]. This implies that load power varies as function of the supply voltage. Voltage dependant loads can be mathematically expressed by (3.1) and (3.2) [47].

$$P = P_o V^{\alpha} \tag{3.1}$$

$$Q = Q_o V^{\beta} \tag{3.2}$$

where:

- α = active power exponent;
- β = reactive power exponent;

- P_o = active power operating point; and
- Q_o = reactive power operating point.

Parameters α and β in (3.1) and (3.2) have been found to range between the values given in Table 3.1 for commercial loads [47]. The values of the parameters are dependent on season and time of the day.

Table 3.1 Commercial static load model parameters

α	β	**Condition**
1.25	3.50	Summer/Day
0.99	3.95	Summer/Night
1.50	3.15	Winter/Day
1.51	3.40	Winter/Night

When studying the effects of DG within commercial retail reticulation networks, incorrect modelling techniques could have a significant impact on the results, as observed in similar studies for other network types. The significance of load modelling techniques, together with the fact that commercial electricity users are voltage dependent loads, resulted in the need for a voltage dependent load model to be used. It was therefore important that representative load model parameters and load demand profiles were used to assess the impact of DG on load parameters, for commercial retail customers.

To develop load models for each of the customers within the hypothetical commercial retail reticulation network; load demand profiles for a typical day of operation for each of the customers had to be established. To simplify the analysis, and limit the number of assumptions input into the network model, a total of five commercial customers were modelled as part of the reticulation network.

To accurately estimate building electricity consumption, significant detail is required of the building under study. Capturing or obtaining the required information is a time-consuming exercise [48]. It was therefore more practical in this scenario to utilise publicly available data for commercial retail building’s load consumption and demand profiles to develop typical load models for this study [49], [50]. Unfortunately, all publicly available sources are of commercial retail facilities based in the United States of America (USA). Differences are expected between commercial retail load demands taken for facilities in the USA, when compared to commercial retail facilities in South Africa. This would be due to the difference in building material used in the two countries as well as the fact that the USA is a developed country and South Africa is still a developing country. Due to the lack of publicly available measured load data for commercial retail customers within South Africa, utilising commercial retail load demand data from facilities in the USA was the best alternative to basing simulated load demand profiles on purely assumed load demand profiles, resulting in more reliable results for the hypothetical study. These results could be compared to the case study results (Chapter 4), which are based on a commercial retail facility in South Africa.

Based on the two commercial building load demand databases available [49], [50] it was found that only one database [50] was best suited for developing a normalised load demand profile, as this source contained an hourly load schedule. A typical weekday hourly load demand profile was developed by utilising hourly load schedule information. The data was normalised to obtain a per unit or normalised load demand profile, as seen in Figure 3.1 The normalised load demand profile was then scaled accordingly to obtain the expected load demand profile for each customer. Each customer’s load demand profile was based on the normalised load demand profile given in Figure 3.1, with each being slightly altered. The load demand profiles were altered such that the maximum coincident demand of each customer did not occur at the same hour of the day, and were also of different magnitudes. This was done to introduce variability into the study and all modifications were based on what would be expected in a real-life scenario.

In addition to introducing variations into the study by implementing differing load demand profiles, different maximum load demands for each of the customers was assumed. Two different maximum load demands were selected; one to represent a mid-size commercial retail customer and a second to represent a larger sized commercial retail customer. The maximum load demand for each type of commercial retail customer was based on 75% of the main supply circuit breaker rating for the customer. The main supply circuit breaker rating was assumed to be 63A three-phase for mid-size customers and 80A three-phase for larger size customers, as these are standard circuit-breaker ratings and commonly used in industry. This equates to a maximum load demand of 30.8kW and 39.14kW for the mid-size and larger size commercial retail customers respectively. All customers were assumed to operate at a power factor of 0.95 lagging.

Once the expected maximum load demand had been determined for each customer, and load demand profiles were generated, the load demand profiles were input into the commercial reticulation network model for each of the customers.

The load model parameters implemented for (3.1) and (3.2) were selected to be for a summers' day, and are given in Table 3.2. These parameters were used as inputs for (3.1) and (3.2) and incorporated into the load models.

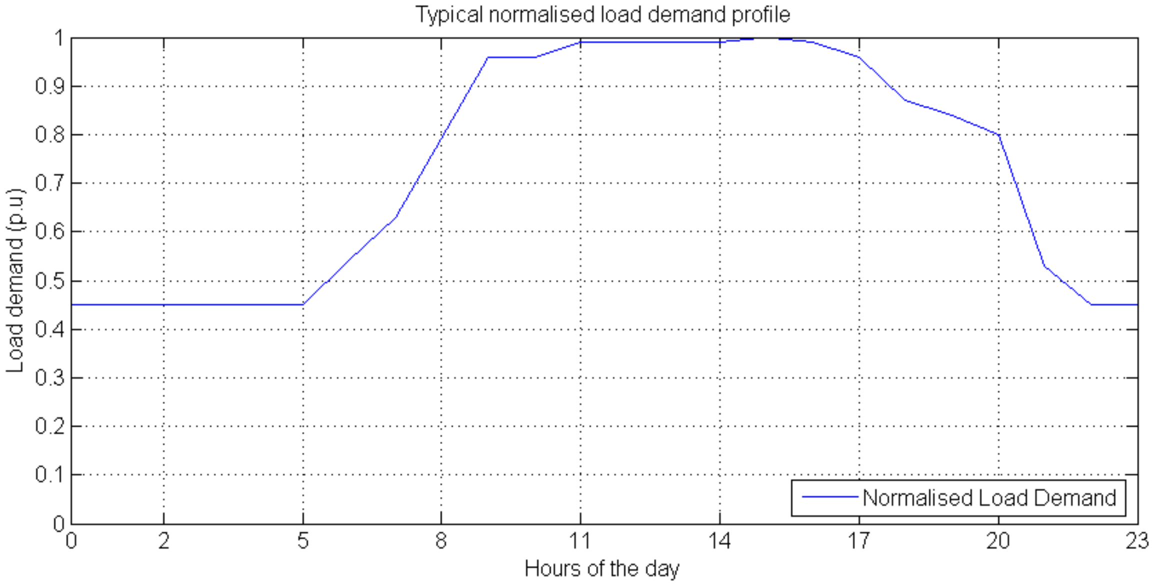

Figure 3.1. Normalised commercial retail customer hourly load demand profile

Table 3.2 Commercial static load model parameters

α	**β**	**Condition**
1.25	3.50	Summer/day

3.2.2 Suitable DG source

The DG source selected to be integrated into the commercial retail network was a solar PV system. Solar PV is a common type of renewable energy DG source being implemented by electricity consumers around the world. The capacity of new solar PV systems installed around the world increase by 50% in 2017 [51]. Assuming DG would be implemented by means of solar PV would therefore be a realistic representation. The declining cost of solar PV systems, as well as its modular nature, makes it suitable for most applications and scalable for the customers’ electrical demand.

Due to the nature of the renewable energy source that solar PV systems harvest (solar energy), solar PV system generation profiles are distinctive. The per unit solar PV generation profile that was modelled and scaled according to theoretically determined capacity can be seen in Figure 3.2.

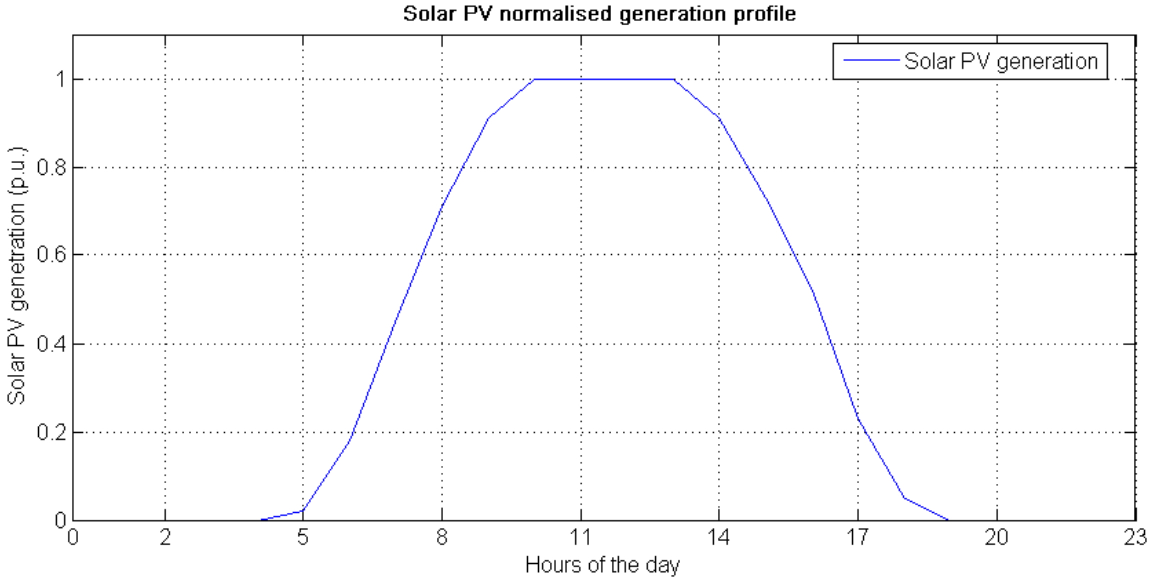

Figure 3.2. Normalised solar PV generation profile

3.2.2.1 Introduction of the DG source

The introduction of the DG source into the reticulation network was done in two different scenarios; namely, centralised and de-centralised scenarios. The definition of each of the scenarios is given in section 3.2.2.1.1 and 3.2.2.1.2 respectively.

3.2.2.1.1 Centralised DG scenario

In the centralised DG scenario a DG source was introduced into the reticulation network at the main low-voltage supply point to the commercial retail reticulation network. The DG source capacity was varied, from zero to the maximum coincident load demand at the busbar it was connected to. This was done to understand the effect of DG and penetration levels on the various load and network parameters under investigation.

3.2.2.1.2 De-centralised DG scenario

The second scenario (de-central DG) was to introduce the DG source further downstream within the reticulation network and to vary the penetration level based on the maximum load demand of the respective customer to which it was connected.

3.2.3 Reticulation network model

Once the load modelling was complete, the next step was to develop a reticulation network model to conduct the required analysis and obtain results. To analyse the impact of varying load demand over a specific period and DG output, quasi-dynamic load flow simulation studies were conducted. The studies were conducted over a 24-hour period.

3.2.3.1 Network topology

A number of studies have implemented standard Institute of Electrical and Electronic Engineers (IEEE) test networks to conduct the required analyses [42], [52]-[54] to determine the effect of DG on a number of network parameters. These test networks are mainly transmission and distribution systems which are high-voltage systems. They are therefore not representative of commercial retail reticulation networks, as a commercial retail reticulation network is typically a low-voltage network. There are also standard low-voltage network test systems available [55]; however, these low-voltage reticulation test networks contain several hundred nodes. These are therefore more representative of larger scale reticulation networks rather than a network containing five customers. The test networks are therefore not representative of a commercial retail reticulation network, as it is expected that a commercial retail reticulation network would contain significantly fewer nodes based on the number of customers assumed.

It was for this reason that a hypothetical reticulation that is more representative of the commercial retail reticulation under question was developed based on suitable information, available literature and certain assumptions based on industry standards and common practice.

To develop the hypothetical reticulation network model, a number of network component parameters needed to be determined. The information to be obtained or assumed in order to develop the model was:

- Supply transformer capacity ratings and parameters such as impedance; and
- Size and length of supply cables to each of the customers.

3.2.3.2 Reticulation network component parameters:

Due to the small number of customers modelled within the commercial retail reticulation network, a low capacity distribution transformer was selected. The total combined coincident demand of the five customers is approximately 165kW. Operating at an assumed power factor of 0.95 lagging results in a total load demand of approximately 174kVA. This value was used to arrive at a standard supply transformer capacity of 315kVA. The capacity and other relevant transformer parameters that were used as inputs for the network model are indicated in Table 3.3.

Table 3.3 Supply transformer parameters

HV rating (kV)	LV rating (V)	Capacity (kVA)	No load losses (W)	Full load losses (W)	Impedance (%)	Vector group
11	415	315	720	3,800	5.00%	Dyn11

Supply transformer parameters such as no-load losses, full load losses and percentage impedance were based on parameters for a 315kVA, 11/0.415kV distribution transformer outlined in South African National Standard (SANS) 780 [56]. These transformer parameters were then input into the two-winding transformer model within DIgSILENT Power Factory.

Based on the maximum load demand for each of the customers, a standard cable size was selected to supply each of the customers from the distribution transformer. The cable sizing was done by taking the voltage-drop limit of 5% at maximum load demand and proposed length for each supply cable into account. The standard cable size that was selected was a 25mm^2, 4 core copper conductor, 600/1000V rated cable. The cable parameters that were used as inputs for each of the feeder cable network elements are indicated in Table 3.4.

Table 3.4 Feeder cable parameters

Cable size (mm^2)	**Current rating: ground (A)**	**Impedance (Ω/km)**
25	119	0.8749

The length of each of the supply cables was assumed and varied in length to add additional variability in the network model. The length of each of the feeder cables is given in Table 3.5.

Table 3.5 Customer feeder cable length

Customer No.	**Feeder cable length (m)**
1	50
2	100
3	150
4	200
5	250

3.2.4 Analysis

Once the reticulation network model was developed, quasi-dynamic load flow simulation studies were conducted to determine the following:

- Combined coincident load demand for the entire network;
- Voltage profiles at each of the relevant nodes;
- Current flow within each of the network branches; and
- Thermal loading of equipment.

Once the required load flow simulation studies were conducted and network parameters (supply voltage) were determined, post-processing of results was done to determine the various load parameters for each of the DG scenarios at varying penetration levels.

3.3 BASE CASE SCENARIO RESULTS

The base case scenario is defined as the operating scenario of the commercial retail reticulation network with no DG source present. The definition of the various load parameters under consideration and the results obtained for the base case scenario are given in section 3.3.1 and 3.3.2 respectively.

Figure 3.3 presents the single line diagram (SLD) of the hypothetical commercial retail network, outlining the topology, and main reticulation network components. From Figure 3.3 it can be seen that the network is radial in topology and consists of five sub-distribution boards, supply each customer.

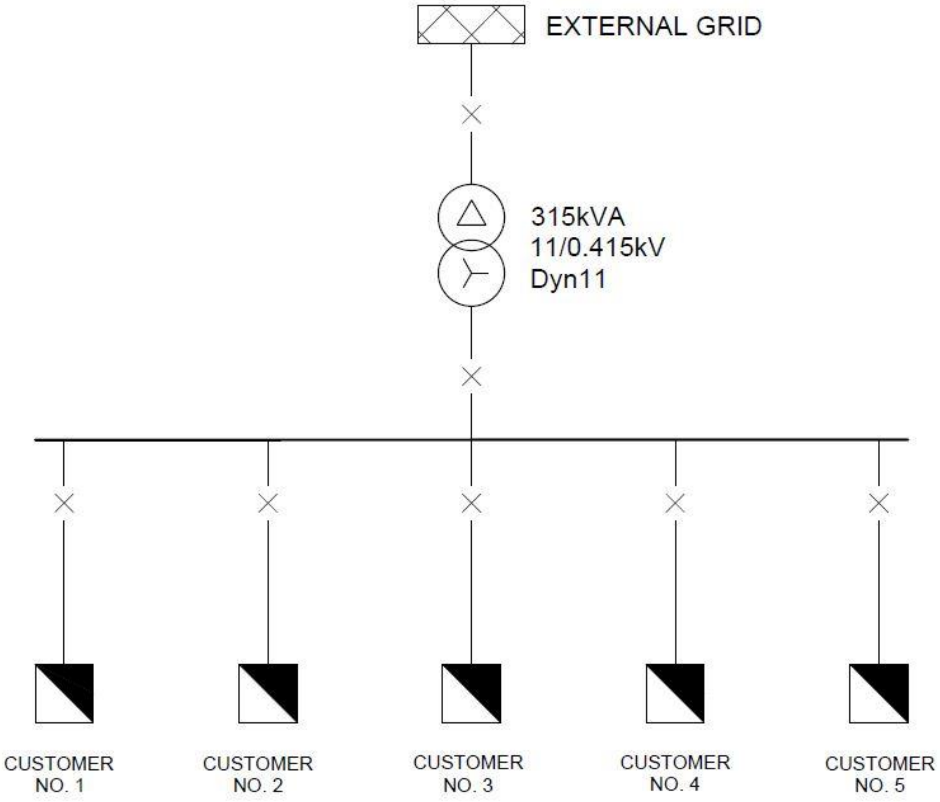

Figure 3.3. Hypothetical commercial retail reticulation network single line diagram

3.3.1 Load parameter definitions

The load parameters investigated with their associated definitions and formulas are given in Table 3.6. There is a total of eight load parameters under investigation for this study.

Table 3.6 Definitions and formula of load parameters under investigation

Load Parameter	Definition	Formula
Coincident demand	Maximum combined demand for a composite group of loads.	-
Demand factor	The ratio of the maximum demand of a system to the total connected load of the system.	$\frac{Coincident\ demand}{\sum connected\ load}$
Utilisation factor	The ratio of maximum demand of a system to the rated capacity of the system.	$\frac{Coincident\ demand}{Rated\ capacity}$
Load factor	The ratio of average load over a designated period of time to the peak load occurring during the period.	$\frac{Average\ load}{Coincident\ demand}$
Diversity factor	The ratio of the sum of individual maximum demands of the various customers of a system to the maximum demand of the entire system.	$\frac{Maximum\ non-coincident\ demand}{Maximum\ coincident\ demand}$
Coincidence factor	The ratio of the maximum coincident demand for a group of consumers to the sum of the maximum demands of the individual consumers comprising the group both taken at the same point in time.	$\frac{Maximum\ coincident\ demand}{Maximum\ non-coincident\ demand}$
Load diversity	The difference between the maximum non-coincident demand and the maximum diversified demand	$(Maximum\ non-coincident\ demand) - (Maximum\ coincident\ demand)$
Loss factor	The ratio of average power loss to peak power loss during a specified period. The coefficient k was taken as 0.1557 for commercial loads [57].	$k(load\ factor) + (1-k)(load\ factor)^2$

3.3.2 Load parameters

Based on the load demand profiles developed for each of the five customers, together with network component parameters used as inputs for the network model, the base case load parameter results were obtained. The results are tabulated in Table 3.7.

Table 3.7 Base case (No DG source integrated) load parameter results

Load parameter	Result
Coincident demand	165kW
Demand factor	0.72
Utilisation factor	0.56
Load factor	0.713
Diversity factor	1.004
Coincidence factor	0.996
Load diversity	0.6kW
Loss factor	0.54

The results presented in Table 3.7 are the base case results for the different load parameters of the composite load as seen by the external network (external grid as indicated in Figure 3.3). These will be used as the basis for comparison to determine how DG of varying penetration affects load parameters. The composite load demand profile at the transformer low-voltage busbar can be seen in Figure 3.4, the maximum coincident demand of 165kW can be noted to occur around 14:00.

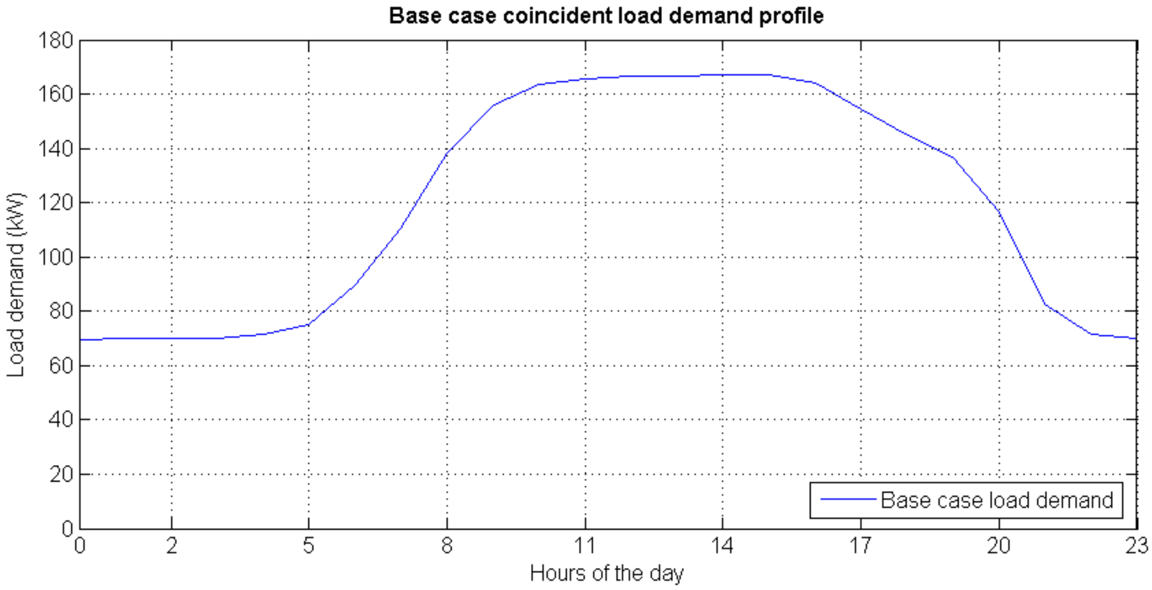

Figure 3.4. Base case load demand profile

Transformer percentage loading (based on a 315kVA capacity transformer) can be seen in Figure 3.5, the maximum percentage loading of the supply transformer is 56.4% which relates to the utilisation factor stated in Table 3.7. The maximum percentage transformer loading occurs at the same point in time that the maximum coincident demand occurs.

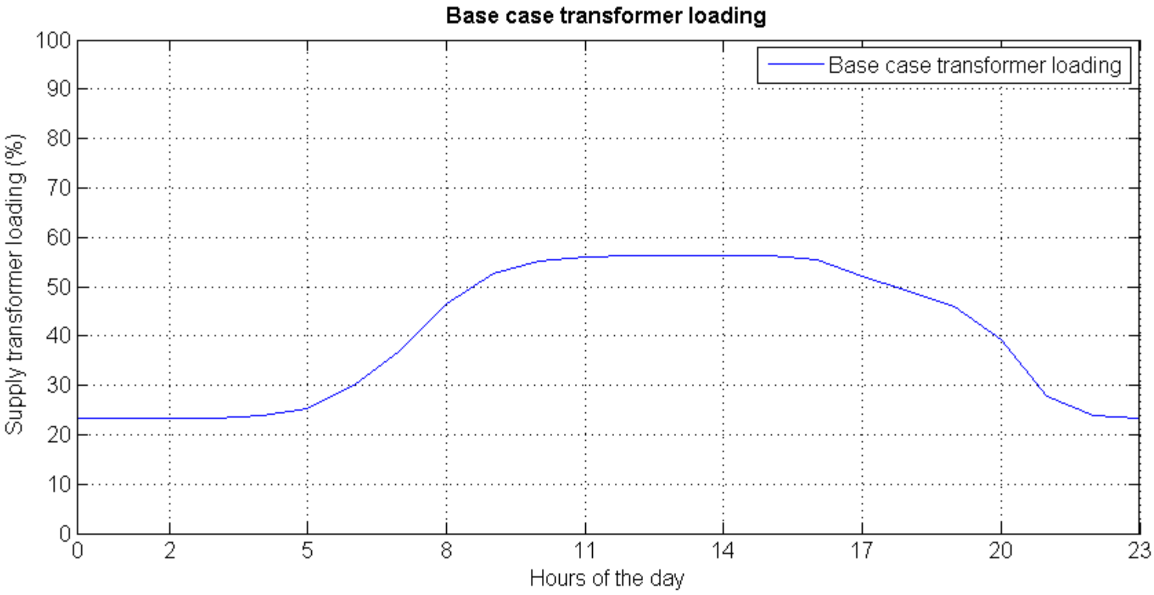

Figure 3.5. Base case transformer percentage loading

3.3.3 Network parameters

Supply voltage varies inversely to load demand and transformer loading, due to the higher current drawn by the system at peak demand. As a result of the higher current drawn by the system, a greater voltage-drop occurs. The minimum supply voltage is therefore observed at the same point in time as maximum coincident demand. The variation of supply voltage for the base case can be seen in Figure 3.6. The maximum and minimum voltages for the base case are 0.994p.u. and 0.985p.u. respectively.

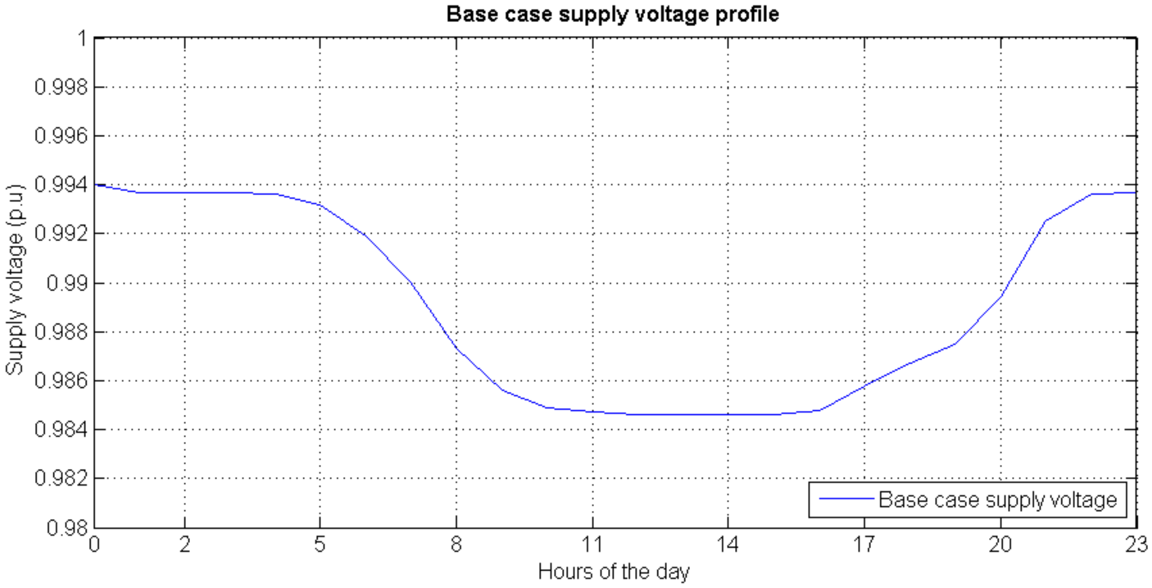

Figure 3.6. Base case supply voltage profile

3.4 CENTRALISED DG SCENARIO RESULTS

To determine the effect that DG has on load and network parameters, the next step in the analysis was to introduce a DG source into the reticulation network. The DG source capacity was varied to determine the effect that the penetration level has on load and network parameters.

The DG source was modelled as being connected to the main low-voltage busbar common to all the customer feeders as this is the central location of the network, this can be seen in the SLD given in Figure 3.7. The DG capacity selected was based on a percentage of maximum load demand as obtained in the base case results (167kW). The DG penetration levels investigated are indicated in Table 3.8.

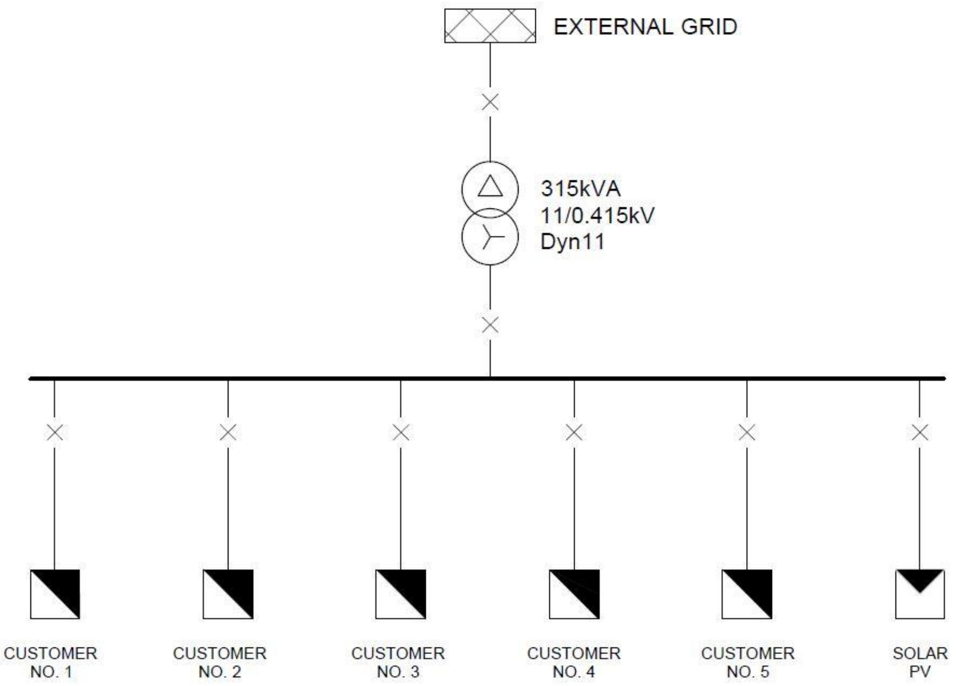

Figure 3.7. Single line diagram with central DG source

Table 3.8 Solar PV penetration levels and capacities modelled

Percentage penetration	Solar PV capacity (kWac)
10%	16.50
15%	24.75
20%	33.00
25%	41.25
50%	82.50
75%	123.75
100%	165.00

It should be noted that the capacities of the solar PV system modelled within the reticulation network are theoretical capacities only, and are not all practically achievable. This is due to solar PV system components, such as inverters, only being manufactured in discrete sizes. Although not practically achievable, these theoretical capacities assisted in gaining valuable insight on how the introduction of DG can affect the reticulation network and load parameters.

3.4.1 Load parameters

The introduction of a DG source alters the load demand profile as seen by the external network and not the individual customers load demand which results in a change in load parameters. The manner in which the introduction of a solar PV DG source alters the coincident load demand profile for the entire load can be seen in Figure 3.8. The variation in transformer loading (which is directly related to the coincident load demand) for varying levels of DG penetration can be seen in Figure 3.9.

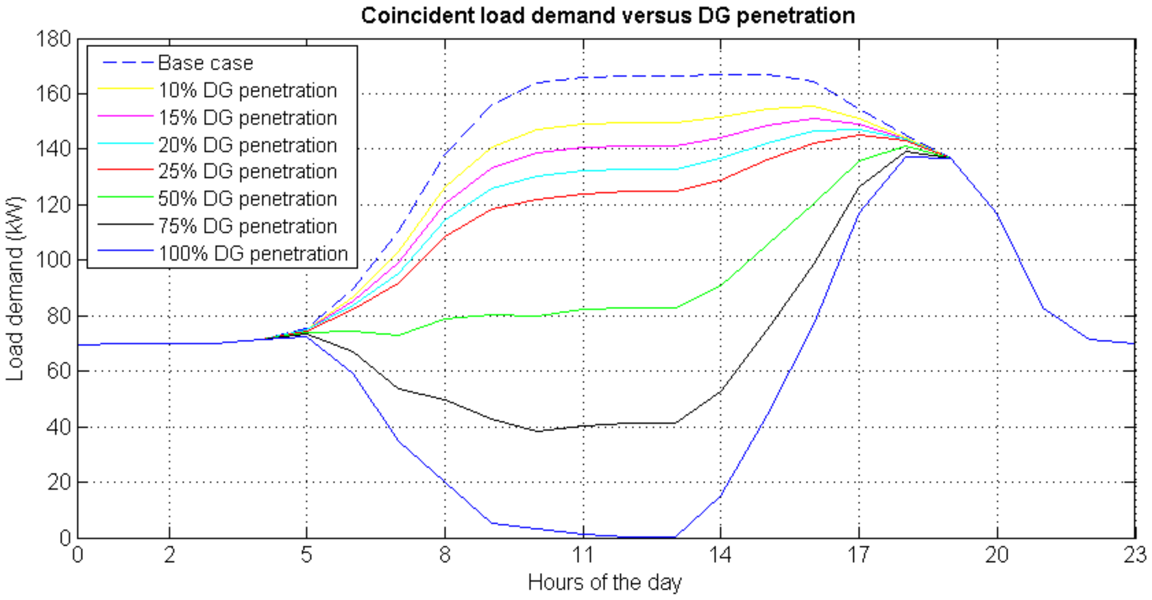

Figure 3.8. Coincident load demand versus DG penetration

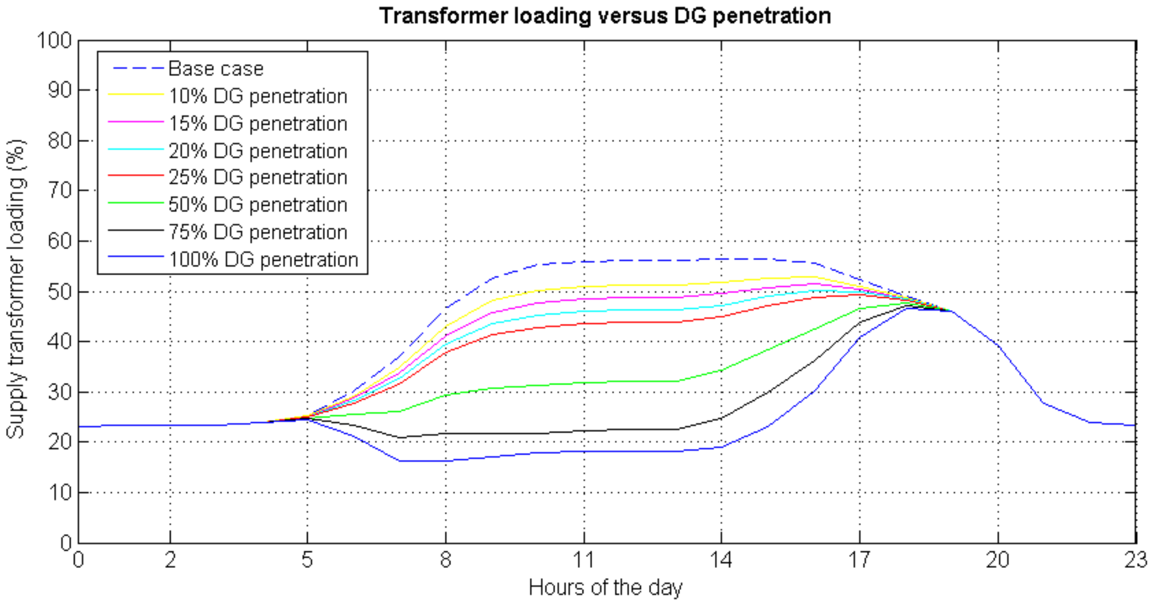

Figure 3.9. Transformer percentage loading versus DG penetration

The results obtained for the various load parameters at varying levels of DG penetration are presented in Table 3.9. A short discussion on the results obtained is given in section 3.4.1.1.

Table 3.9 External load parameters versus percentage DG penetration for central scenario

	Load Parameter							
%	Coincident demand	Demand factor	Utilisation factor	Load factor	Diversity factor	Coincidence factor	Load diversity	Loss factor
0	165.0	0.72	0.56	0.713	1.004	0.996	0.60	0.54
10	153.7	0.67	0.53	0.726	1.078	0.928	12.00	0.56
15	149.3	0.65	0.51	0.728	1.111	0.900	16.50	0.56
20	145.4	0.63	0.50	0.727	1.140	0.877	20.40	0.56
25	143.6	0.63	0.49	0.715	1.155	0.866	22.20	0.54
50	139.5	0.61	0.48	0.628	1.191	0.840	26.60	0.43
75	137.6	0.60	0.47	0.527	1.209	0.827	28.80	0.32
100	135.7	0.59	0.47	0.428	1.228	0.814	31.00	0.22

3.4.1.1 Discussion

From the results presented in Table 3.9, it can be seen the introduction of the solar PV DG source does result in the altering of load parameters as seen by the external network. The largest variation in load parameters (compared to the base case) can be seen at high levels of DG penetration. The most noticeable reductions were seen in coincident demand, load factor and loss factor. Not only did the introduction of the DG source result in a reduced coincident load demand (maximum demand), it also resulted in the maximum load demand occurring later in the day, this can be seen in Figure 3.8.

Load factor, on the other hand, did not monotonically decrease with an increase in DG penetration. Load factor was noted to increase between 0% DG penetration to 15% DG penetration. This is as a result of the maximum demand decreasing at a higher rate compared to the average load, and results in an increased ratio of average load to maximum demand. From 15% DG penetration onwards, load factor deceased with increase in DG penetration. Loss factor, being a function of load factor, varied in a similar manner.

As can be seen from Figure 3.9, the transformer percentage loading does not reduce to 0% whereas the coincident load demand (seen in Figure 3.8) can be seen to reduce to 0kW at 100% DG penetration. The reason for the transformer loading not reducing to 0% is as a result of the external network supplying the reactive power (kVAr) requirements of the load demand, whereas the DG source is supplying all of the real power (kW) requirements. This would result in the reticulation network appearing to have a poor power factor; however, this is not the case.

3.4.2 Network parameters

The variation in supply voltage versus DG penetration can be seen in Figure 3.10. The increase in DG penetration can be seen to improve the supply voltage profile from the base case.

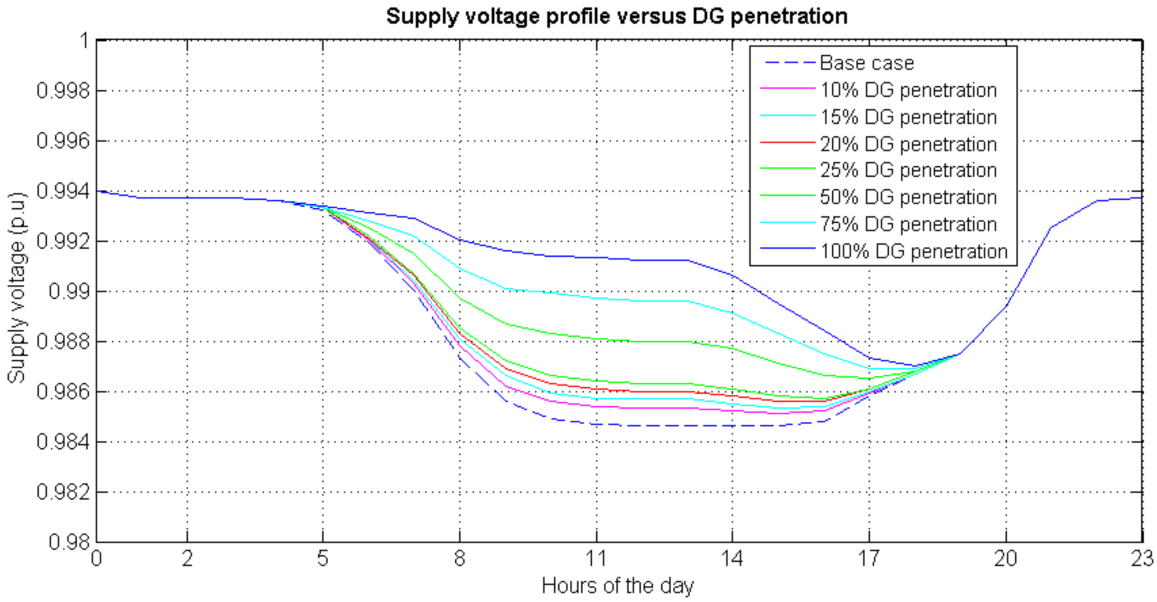

Figure 3.10. Supply voltage profile versus DG penetration

The variation in supply voltage maximum and minimum values is seen in Table 3.10. The minimum supply voltage for higher DG penetration levels can be seen to increase, when compared to the base case.

The increase in supply voltage was only noted for the minimum supply voltages which occurred during peak demand periods. The increase in minimum supply voltages was, however, not significant.

Table 3.10 Supply voltage maximum and minimum level for varying levels of DG penetration

	Supply voltage (per unit)	
Percentage penetration	**Minimum voltage**	**Maximum voltage**
0%	0.984	0.994
10%	0.985	0.994
15%	0.985	0.994
20%	0.985	0.994
25%	0.985	0.994
50%	0.986	0.994
75%	0.987	0.994
100%	0.987	0.994

3.5 DE-CENTRALISED DG SCENARIO RESULTS

Another possible scenario that was investigated is how load and network parameters were altered from the integration of a solar PV DG source connected to a single customers' local distribution board, referred to as the de-central DG scenario. The DG source capacity was varied, based on the selected customers load demand, to determine the effect that this has on load and network parameters.

The DG source was modelled as being connected to customer number five, the network SLD for this scenario can be seen in Figure 3.11. The reason customer number five was selected was because the feeder cable to customer number five was assumed to be longest in length, and any voltage concerns are expected to arise on the longest feeder length rather than the shorter lengths.

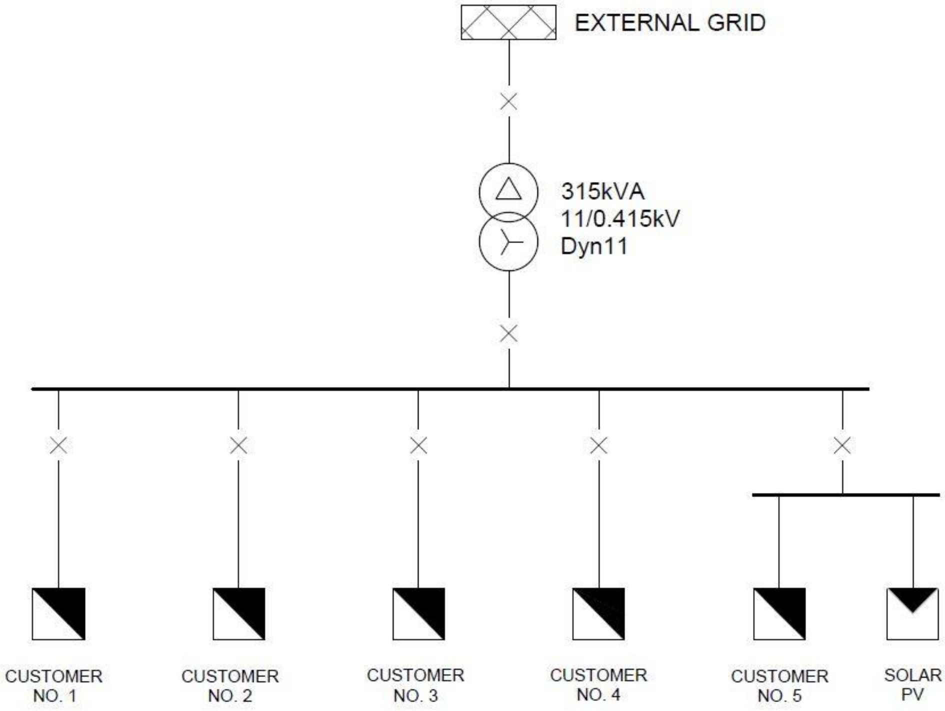

Figure 3.11. Single line diagram with de-central DG source

The DG capacity selected was based on a percentage of maximum load demand for customer number five (29.6kW). The DG penetration levels investigated are indicated in Table 3.11.

Table 3.11 De-centralised DG penetration levels and capacities modelled

Percentage penetration	**Solar PV capacity (kWac)**
10%	2.96
15%	4.44
20%	5.92
25%	7.40
50%	14.80
75%	22.20
100%	29.60

3.5.1 Load parameters

The introduction of a DG source alters the load demand profile for the single customer, and this has an impact on the overall load demand for the commercial retail reticulation network. This results in a change in load parameters for that specific customer but no effect is observed by the remaining four customers. How the introduction of solar PV DG source alters the coincident load demand profile for entire network can be seen in Figure 3.12. The variation in feeder cable loading for varying levels of DG penetration can be seen in Figure 3.13.

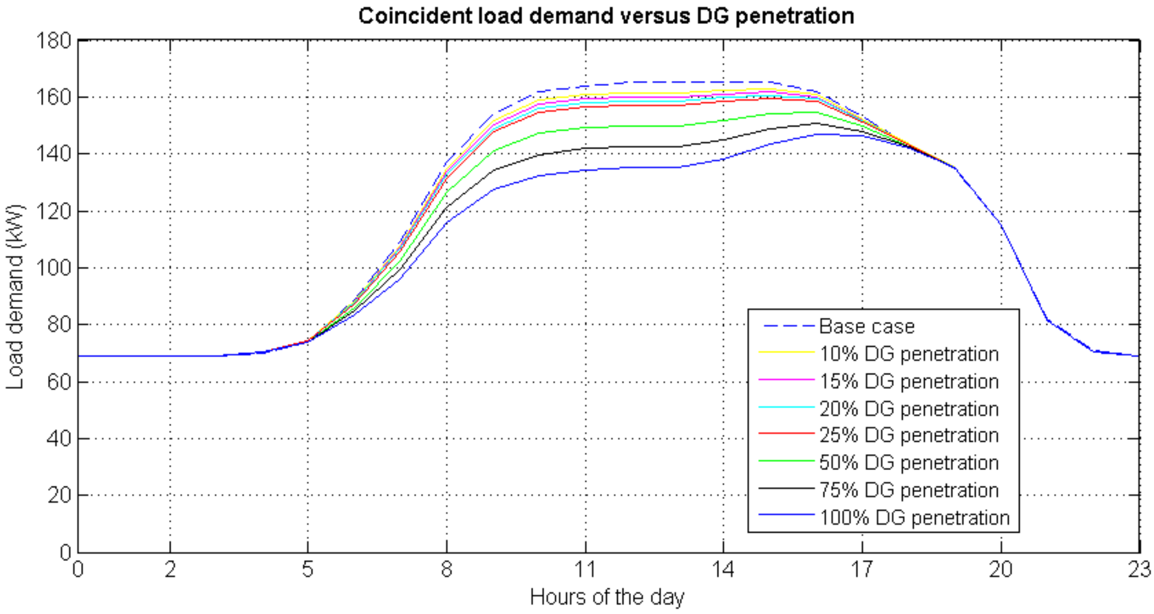

Figure 3.12. Coincident load demand versus de-central DG penetration

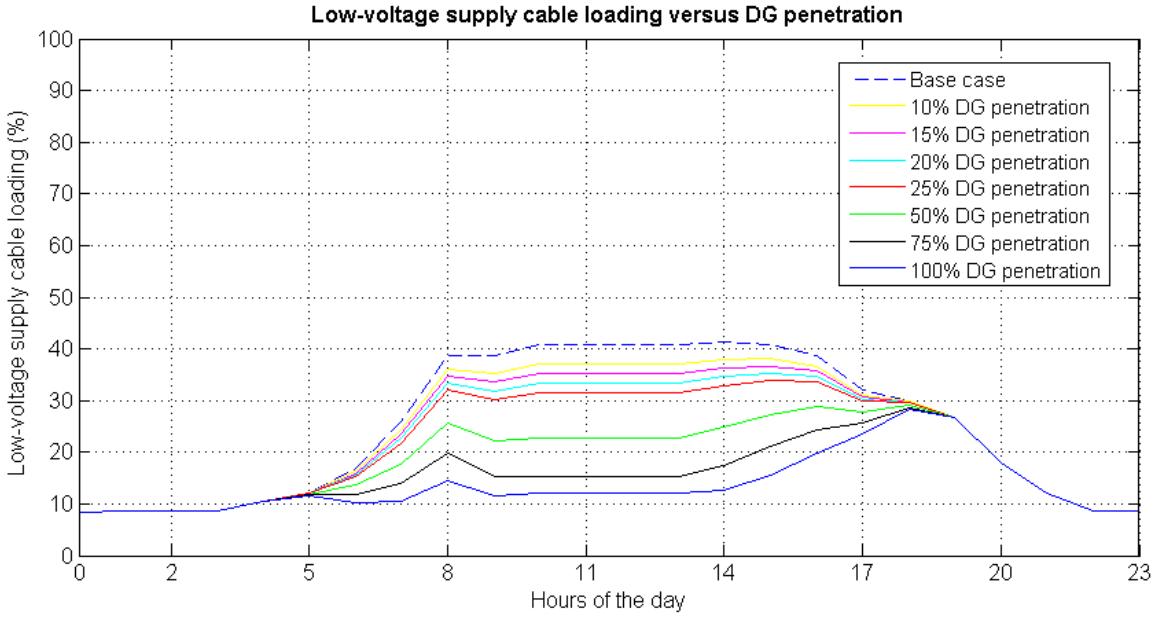

Figure 3.13. Customer No. 5 low-voltage feeder percentage loading versus DG penetration

The results obtained for the various load parameters at varying DG penetration levels are presented in Figure 3.12. A short discussion on the results obtained is given in section 3.5.1.1.

Table 3.12 External load parameters versus percentage DG penetration for de-central scenario

	Load Parameter							
%	Coincident demand	Demand factor	Utilisation factor	Load factor	Diversity factor	Coincidence factor	Load diversity	Loss factor
0	165.0	0.72	0.564	0.7131	1.004	0.996	0.6	0.540
10	162.7	0.71	0.556	0.7165	1.002	0.998	0.3	0.545
15	161.6	0.70	0.553	0.7180	1.001	0.999	0.2	0.547
20	160.4	0.70	0.549	0.7198	1.002	0.998	0.3	0.549
25	159.3	0.69	0.546	0.7213	1.003	0.997	0.4	0.551
50	154.6	0.67	0.530	0.7262	1.015	0.985	2.3	0.558
75	150.4	0.65	0.517	0.7272	1.041	0.960	6.2	0.559
100	146.4	0.64	0.505	0.7282	1.067	0.937	9.8	0.561

3.5.1.1 Discussion

Based on the results presented in Table 3.12, it can be seen that the introduction of the solar PV system at a de-central location does effect load parameters for the entire load, as seen by the external network. Load parameters such as coincident demand, demand factor, and utilisation factor decreased with increase in DG parameters. Load parameters such as load factor and loss factor increased with increasing DG penetration.

3.5.2 Network parameters

The variation in supply voltage profile versus DG penetration can be seen in Figure 3.14. The increase in DG penetration can be seen to improve the supply voltage profile from the base case.

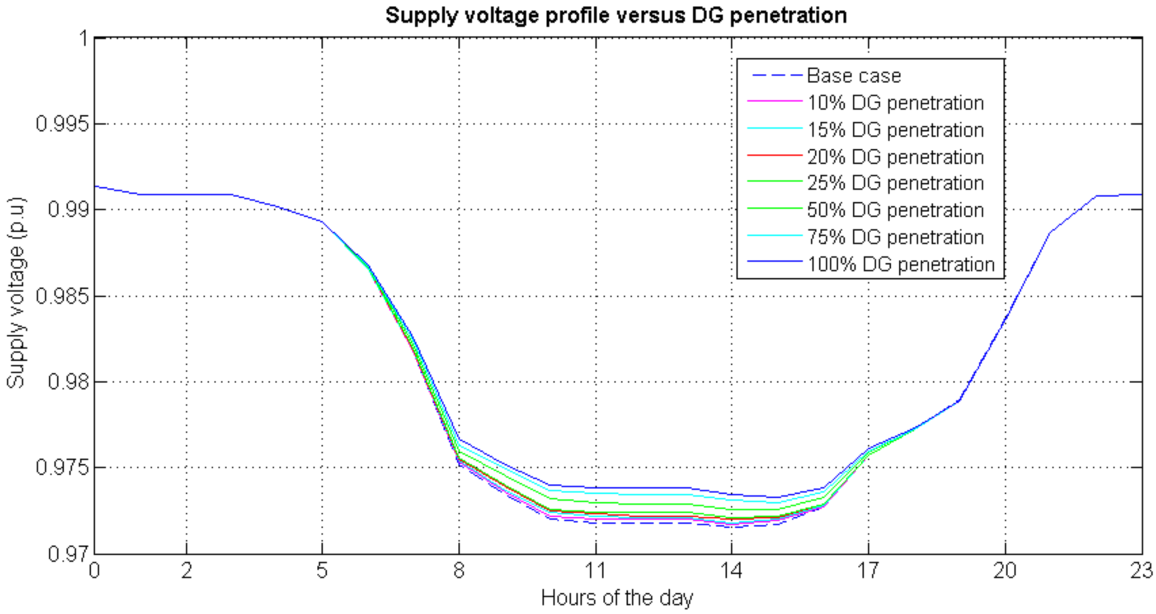

Figure 3.14. Customer no. 5 supply voltage profile versus DG penetration

The variation in supply voltage maximum and minimum voltages can be seen in Table 3.13. The minimum supply voltage for higher DG penetration levels can be seen to increase, when compared to the base case.

The increase in supply voltage was only noted for the minimum supply voltages which occurred during peak demand periods. The increase in minimum supply voltages was, however, not significant.

Table 3.13 Customer no. 5 supply voltage maximum and minimum level for varying levels of DG penetration

	Supply voltage (per unit)	
Percentage penetration	**Minimum voltage**	**Maximum voltage**
0%	0.972	0.991
10%	0.972	0.991
15%	0.972	0.991
20%	0.972	0.991
25%	0.972	0.991
50%	0.973	0.991
75%	0.973	0.991
100%	0.974	0.991

3.6 CHAPTER SUMMARY

From the hypothetical study conducted it is apparent that the introduction of a solar PV DG source into a commercial retail reticulation network has an impact on the load parameters of the composite load, as seen as by the external network. Load parameters were effected in both DG scenarios; central and de-central. The load parameters that were most significantly affected, in the central DG scenario, were load factor, diversity factor and therefore coincidence factor, load diversity as well as loss factor.

In the de-central DG scenario, load parameters as seen by the external network for the composite load were not significantly affected; however, load parameters such as load factor and loss factor increased with an increase in DG penetration. These results are also in alignment with the increase in these load parameters, for the central DG scenario, for low levels of DG penetration.

Network parameters, such as supply voltage, for both the central and de-central DG scenario were not significantly affected for varying levels of DG penetration.

CHAPTER 4 CASE STUDY

4.1 CHAPTER OVERVIEW

Chapter 4 presents the results obtained for the case study that was conducted to confirm the results obtained for the hypothetical study. The case study was based on a network in service with available load metered data. Section 4.2 provides detail on the information gathered and input to develop the reticulation network model. Section 4.3 provides detail on the DG source integrated into the reticulation network. Section 4.4 presents the base case results obtained, where sections 4.5 and 4.6 presents the results for the centralised DG scenario and de-centralised DG scenario respectively. Section 4.7 concludes the chapter.

4.2 METERED LOAD DATA AND EXISTING RETICULATION NETWORK INFORMATION

A case study was completed to verify and validate the results obtained in chapter 3. The study was based on an existing commercial retail park situated in Pretoria, South Africa. To accurately develop a network model along with the load demands for each of the electricity customers certain information was required. The information required was metered load demand data for each of the customers within the reticulation network as well as equipment ratings, capacities, size and configuration of the reticulation network in use. Section 4.2.1 and 4.2.2 provides further details on the information gathered to develop the network model for the case study.

4.2.1 Load modelling

To develop representative load models for each of the customers within the commercial retail reticulation network, recorded load demand information such as electricity demand, energy consumption and power factor over time was required.

The measured load data obtained was analysed to determine an average half-hourly load demand profile for each customer. This result was then used as the input to the load model for the customer within the DIgSILENT network model. In addition to the average load demand profile for each customer input to the DIgSILENT model, an average half-hourly power factor profile over the same period of operation was also used as an input.

4.2.1.1 Load demand data

The existing commercial retail park consists of 40 separate office units; refer to Table 4.1 for a complete list of the individual units. Most of the units are individually metered, there are however units for which there is no metered load demand data available. Metered load demand data for each of the units, with energy meters installed, was download from an online platform for the energy meters (Enermatics). Metering data downloaded was at a half-hourly time interval. There are situations where there is metered data available for a unit; however, the data was recorded as a zero value over the entire month. Metering data available covered a single month at a time from 2016.

There is a single three-phase meter (incoming meter, labelled Garsfontein Office Park (GOP) 3 phase) that measures the total load demand of the commercial retail park, this metering data was used as a check to determine if there are any errors in the data captured. It was found that there was a discrepancy between the total measured load demand versus the sum of each measured load demand per customer.

The error can be attributed to many different factors, such as:

- Measured load data was not available for each customer during the periods of analysis.
- The total measured load demand includes the network energy losses whereas the sum of individual customer load demands does not.
- There could have been an error with the energy meter, as some customers have a recorded zero load demand for an entire month.

The error between the main incoming meter data and the sum of individual meter data was in the order of approximately 25% of the total maximum load demand. To account for this large error in the load demand data, the error value for each measuring interval was divided by the number of customers that had recorded load demand of zero for the entire month. This value was then assigned to each of the customers.

Load demand data was analysed per month to minimise the amount of data that needed to be processed. Sample months from the year were selected. January and July were selected as these are during the summer and winter months respectively. As a result of the seasonal differences for which the data was analysed, variability in the load demand data was observable. This provided additional insight into the sensitivity of the effect of DG penetration on load parameters. These two months also happened to contain the lowest error between the incoming meter and sum of individual meters, therefore fewer assumptions were required when assigning the difference to respective customers.

Table 4.1 Unit numbers, description and meter numbers for each customer

Unit number	Unit description	Meter number
-	Incoming meter	GOP 3 phase
-	Guardhouse	GOP Guardhouse
1	Mustofin	GOP 001
2	Hans du Plessis	GOP 02
3	Dentist	GOP 03
4A	JPS & Associates	GOP 04A
4B	Dr Ferrerira Moinheiro	GOP 04B

Unit number	Unit description	Meter number
5	Dawie De Beer	GOP 05
6	Lemken	GOP 06
7	Mrumba HR Consulting	GOP 07
8	Haaks quantity surveyors	GOP 08
9	Nextera business communication	GOP 009
10	Niyakha group	GOP 10
11	Avico	GOP 11
011	Unknown	GOP 011
12	Absolut career personnel	GOP 12
13	Chris Botha Rekeningkundige Dienste	GOP 13
14	Unknown	GOP 14
15	ERS Excel Recovery Services	GOP 15
16	CTU training solutions - Academics & video studio	GOP 16
17	Myezo Environmental management services	GOP 17
18A	Garrun short term insurance	Unknown
18B	Garrun short term insurance	Unknown
18C	Modfin	GOP 18C
19	Umhlaba holding (pty) ltd	GOP 19
20	Unknown	GOP 20
21A	Ramulifho Inc	Unknown
21B	WLA specialist consulting engineers	Unknown
21C	Unknown	Unknown
22	SM Mare & Associate	GOP 22
23	Business engineering	GOP 23
24	Unknown	GOP 24
25	Multiprof	GOP 25
26	CTU training solutions - head office	GOP 026
27	Arch studio	GOP 27
28	Unknown	GOP 28
29	Unknown	GOP 29
30	Linda Lee Architectural design	GOP 30
31	Johan Erwee	GOP 31
32	Werner Prinsloo Prokureeurs	GOP 32
33	Battlefields	GOP 33

4.2.2 Reticulation network

The following information was obtained from an on-site inspection of the existing reticulation network:

- Location of main and sub distribution boards;
- Location of step-down transformer supplying the network;
- Size of each of the feeder cables from the main distribution board to the sub distribution boards;
- Network topology; and
- Circuit-breaker ratings of all incoming and outgoing circuit-breakers.

The above information was used to develop a network model for the reticulation network using DIgSILENT Power Factory simulation software, as was done for the hypothetical study. Not all of the required information to develop the network model was obtained from the on-site inspection. Certain assumptions therefore needed to be made to develop the network model, these assumptions were:

- Length of feeder cables; and
- Capacity and properties of the step-down transformer.

4.2.2.1 Length of feeder cables

The length of each of the feeder cables was determined using Google Earth by measuring the distance between the main distribution board and sub distribution boards. Assumptions with regards to the exact routing of the cables had to be made based on the facility layout, which included parking area and roadway layout, layouts of walk-ways and locations of distribution boards. The length of the main incoming feeder cable to the main distribution board was also determined from Google Earth. Again, an assumption regarding the routing of the cable had to be made. From the on-site inspection, the cable conductor cross-sectional area and type of cable feeding the main distribution board was not clearly identified, and therefore an additional assumption had to be made. The length, cable cross-sectional area and type of all the cables within the reticulation network are given in Table 4.2.

Table 4.2 Reticulation network cables properties and lengths

Source	**Destination**	**Type**	**Cross-sectional area**	**Assumed length**
Transformer	Main DB	Cu, 4 core, PVC/PVC/SWA/PVC	2 x 300mm^2	51m
Main DB	DB-M2	Cu, 4 core, PVC/PVC/SWA/PVC	95mm^2	31m
Main DB	DB-M3	Cu, 4 core, PVC/PVC/SWA/PVC	95mm^2	51m
Main DB	DB-M4	Cu, 4 core, PVC/PVC/SWA/PVC	95mm^2	51m
Main DB	DB-M5	Cu, 4 core, PVC/PVC/SWA/PVC	95mm^2	29m
Main DB	DB-M6	Cu, 4 core, PVC/PVC/SWA/PVC	95mm^2	28m
Main DB	DB-M7	Cu, 4 core, PVC/PVC/SWA/PVC	185mm^2	22m
Main DB	DB-M	Cu, 4 core, PVC/PVC/SWA/PVC	95mm^2	36m

It should also be noted that the cross-sectional area of the feeder cable between the step-down transformer and the main distribution board was assumed based on standard cable current carrying capacities, as the cable size was not visible during the site inspection. Based on the incoming circuit-breaker rating (1,250A) in the main distribution board, a cross-sectional area of 300mm^2 was selected; however, to continuously carry a current of 1,250A two parallel cables would be required.

4.2.2.2 Step-down transformer capacity and properties

The capacity of the transformer supplying the reticulation network was also not visible. The main incoming circuit-breaker is rated at 1,250A and a standard transformer rating of 1000kVA is capable of delivering a full load current of 1,391A at 415V. The rating of the step-down transformer was assumed based on the size of the incoming circuit-breaker within the down-stream main distribution board and selecting an industry standard transformer size. Based on this, a step-down transformer capacity of 1,000kVA was selected. The transformer property was assumed based on SANS 780 and is given in Table 4.3.

Table 4.3 Step-down transformer properties

HV rating (kV)	**LV rating (V)**	**Capacity (kVA)**	**No load losses (W)**	**Full load losses (W)**	**Impedance (%)**	**Vector group**
11	415	1000	1,900	9,500	5.00%	Dyn11

4.2.2.3 Network topology

A single line diagram of the reticulation network is given in Figure 4.1 and provides an overview of the reticulation network topology. From Figure 4.1 it can be seen that the network is radial in topology and consists of seven sub-distribution boards, supply each a number of different customers, listed in Table 4.1.

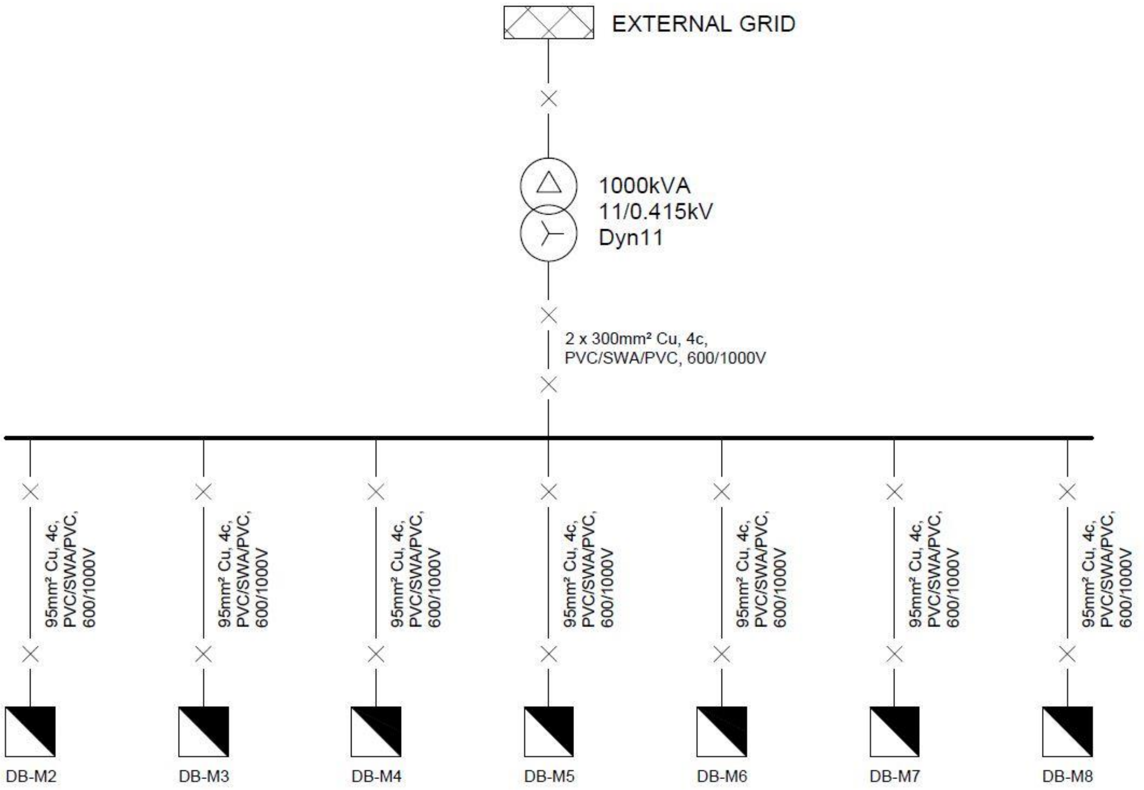

Figure 4.1. Case study reticulation network single line diagram

4.3 MODELLING OF DG SOURCE

Modelling of the solar PV DG source for the case study was done using the internal DIgSILENT Power Factory solar calculation function. The internal solar calculation required that the global positioning system (GPS) coordinates for the site be input, to perform the calculation. The built-in solar PV system block-type and standard PV module type (Sanyo Electric, HIT-240HDE4) were used to model the DG source. The solar PV system was set to operate at unity power factor.

The number of parallel inverters (each with ten modules per inverter) for each DG scenario was altered to increase the system capacity. This was done to arrive at a solar PV system capacity that is approximately equal to the DG percentage penetration required for each scenario. The exact percentage penetration value (i.e. 10% of 109.92kW) could not be achieved due to the discrete system capacity for solar PV modules.

As the maximum load demand is different for the two load demand scenarios (January 2017 and July 2016) the DG system capacities modelled for each of the scenarios was different. The DG system capacity modelled for the January 2017 and July 2016 load demand scenarios can be seen in Table 4.4 and Table 4.5 respectively.

Table 4.4 Centralised DG penetration levels and capacities modelled (Jan 2017 scenario)

Percentage penetration	**Solar PV capacity (kWac)**
10%	10.5
15%	17.6
20%	21
25%	28.1
50%	52.7
75%	82.6
100%	109

Table 4.5 Centralised DG penetration levels and capacities modelled (July 2016 scenario)

Percentage penetration	**Solar PV capacity (kWac)**
10%	14
15%	21
20%	26.3
25%	35.1
50%	68.5
75%	103.6
100%	137

4.4 BASE CASE SCENARIO RESULTS

The base case scenario is once again defined as the operating scenario of the commercial retail reticulation network without the inclusion of any DG sources. Two different load demand scenarios were considered such that seasonal variation in load demand could be taken into consideration. The two different time periods of captured load demand data covered the month of January 2017 and July 2016. These months were selected as they fall within the summer and winter seasons, for the southern hemisphere, respectively. Base case load parameters results, as well as network parameters, were obtained for each of the two scenarios and were used for comparison when DG sources were added to the reticulation network, for each scenario.

4.4.1 January 2017 load demand scenario

4.4.1.1 Load parameters

Based on the load demand data available for the month of January 2017 for the commercial retail park, together with the necessary assumptions made, the base case load parameter results were obtained. These are presented in Table 4.6.

Table 4.6 Base case (January 2017) load parameter results

Load parameter	Result
Coincident demand	109.92kW
Demand factor	0.068
Utilisation factor	14.02%
Load factor	0.465
Diversity factor	1.097
Coincidence factor	0.912
Load diversity	10.61kW
Loss factor	0.255

The results presented in Table 4.6 are the base case results for the load parameters of the composite load as seen by the external network, at the low-voltage busbar. These results were used as the basis for comparison to determine how DG of varying capacity affects load parameters for January 2017 scenario. The base case load demand profile at the transformer low-voltage busbar can be seen in Figure 4.2, a maximum coincident demand of approximately 110kW can be noted to occur around 13:00.

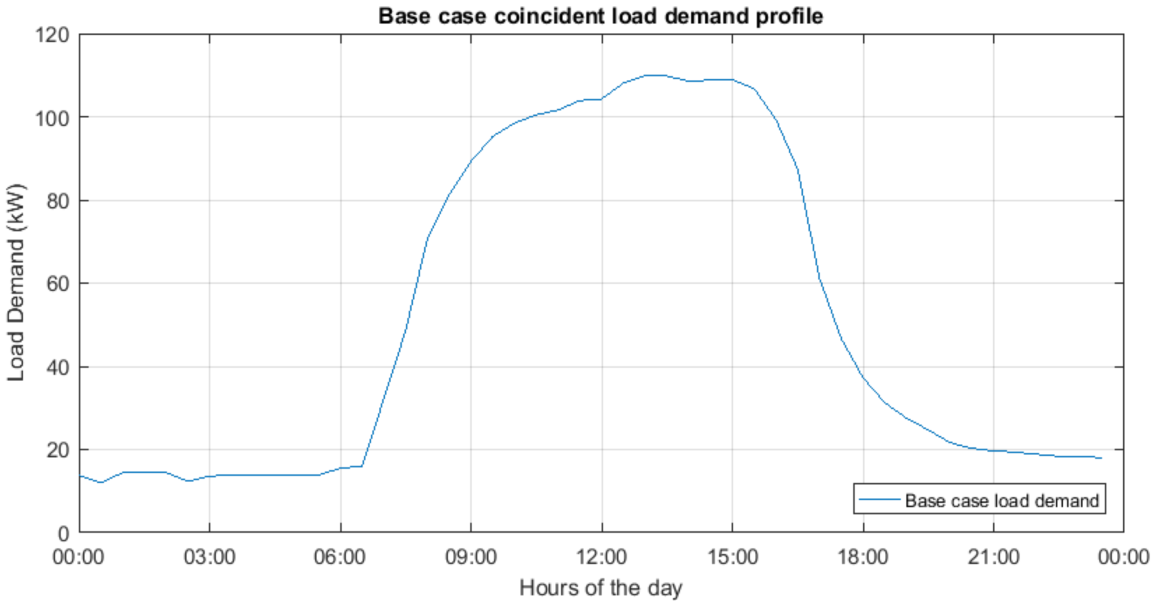

Figure 4.2. Base case load demand profile (Jan 2017 load demand data)

The transformer percentage utilisation or loading (based on 1,000kVA capacity) can be seen in Figure 4.3. The maximum percentage loading of the supply transformer is approximately 14%, which relates to the utilisation factor given in Table 4.6. The maximum percentage loading occurs at the same point in time that the maximum coincident demand occurs.

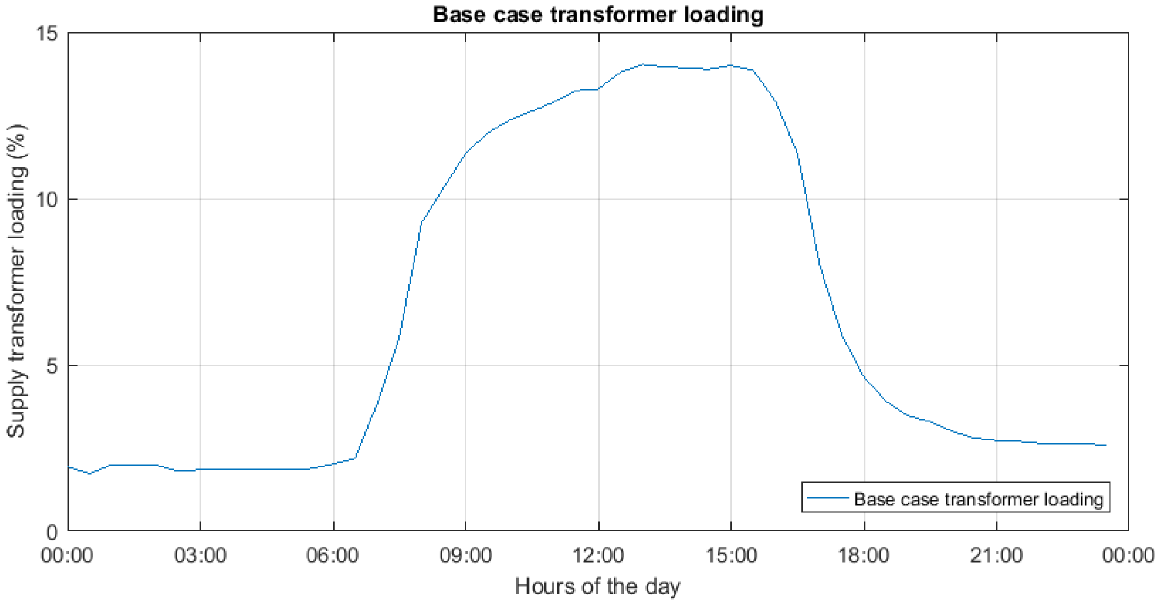

Figure 4.3. Base case transformer percentage loading (Jan 2017 load demand data)

4.4.1.2 Network parameters

The variation of supply voltage for the base case can be seen in Figure 4.4. The maximum and minimum voltages for the base case are approximately 1.037p.u. and 1.033p.u. respectively.

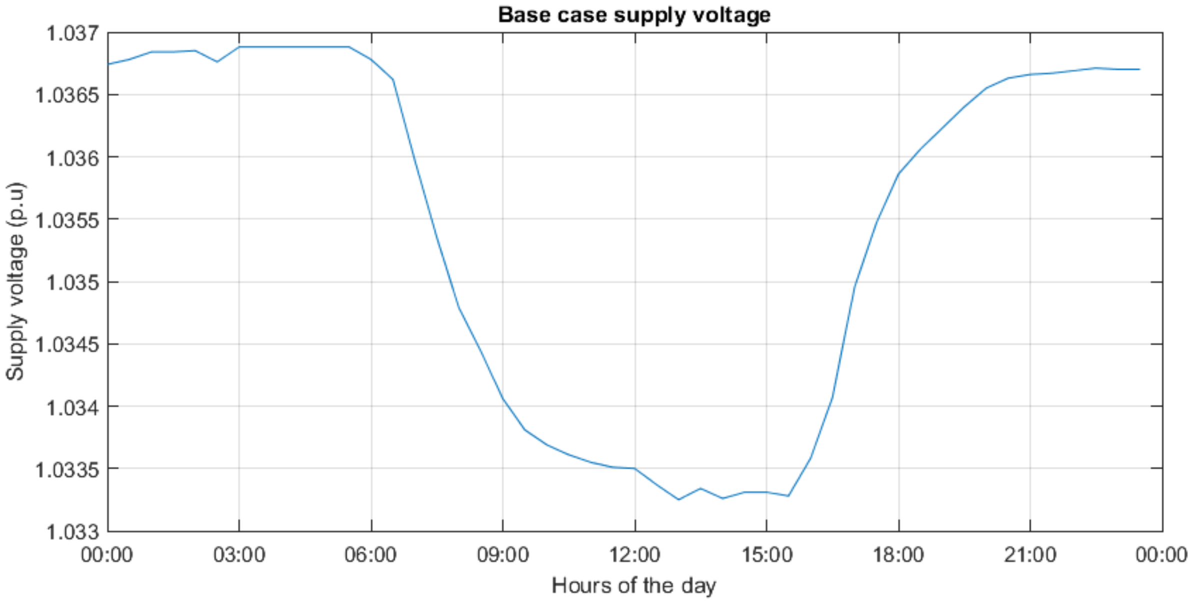

Figure 4.4. Base case supply voltage profile (Jan 2017 load demand data)

4.4.2 July 2016 load demand scenario

4.4.2.1 Load parameters

Based on the load demand data available for the month of July 2016 for the commercial retail park, together with the necessary assumptions made, the base case load parameter results were obtained. These are presented in Table 4.7.

Table 4.7 Base case (July 2016) load parameter results

Load parameter	Result
Coincident demand	137.27kW
Demand factor	0.085
Utilisation factor	18.51%
Load factor	0.424
Diversity factor	1.36
Coincidence factor	0.735
Load diversity	49.41kW
Loss factor	0.218

The results presented in Table 4.7 are the base case results for the load parameters (such as coincident demand, load factor and diversity factor) of the composite load as seen by the external network, at the low-voltage busbar. These results were used as the basis for comparison, to determine how DG of varying capacity affects load parameters for the July 2016 scenario. The load demand profile at the transformer low-voltage busbar can be seen in Figure 4.5, the maximum coincident demand of approximately 137kW can be noted to occur around 09:00.

By comparing Figure 4.2 and Figure 4.5, it can be seen that the load demand profiles for the two different months, and therefore seasons, have different trends. The load demand profile for January 2017 has a lower maximum coincident demand when compared to July 2016 (109.92kW versus 137.27kW respectively), which occurs after midday. The load demand profile for July 2016 has a higher maximum coincident demand, which occurs around 9:00. The difference in the load demand profiles also result in differing load parameters; such as demand factor.

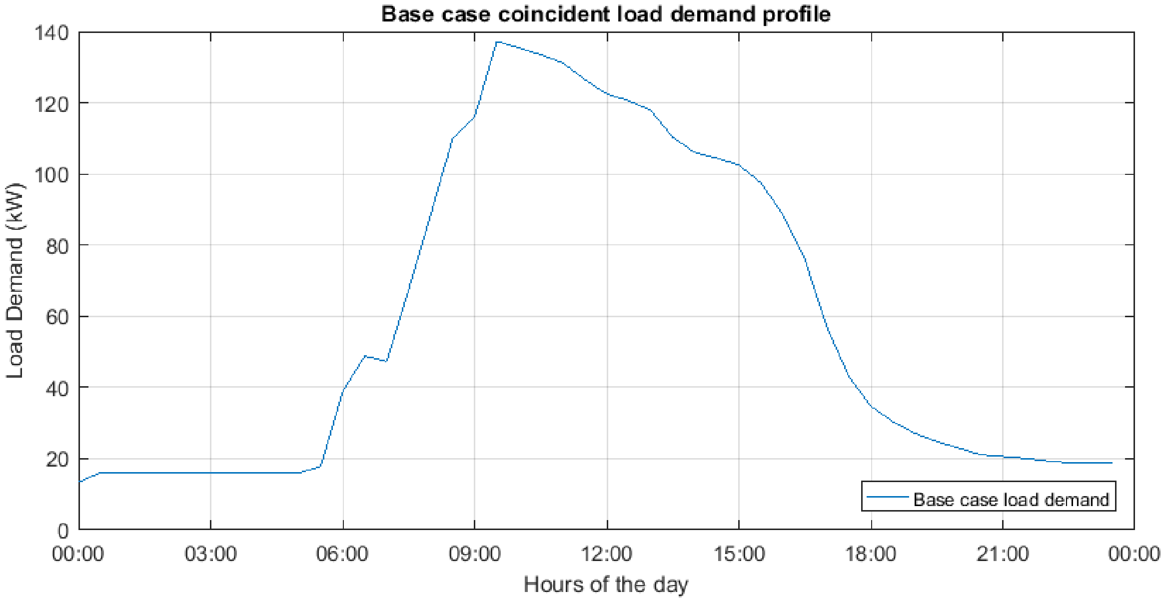

Figure 4.5. Base case load demand profile (July 2016 load demand data)

Transformer percentage loading for this scenario can be seen in Figure 4.6, the maximum percentage loading of the supply transformer is approximately 18% which relates to the utilisation factor stated in Table 4.7. The maximum percentage transformer loading occurs at the same point in time which the maximum coincident demand occurs.

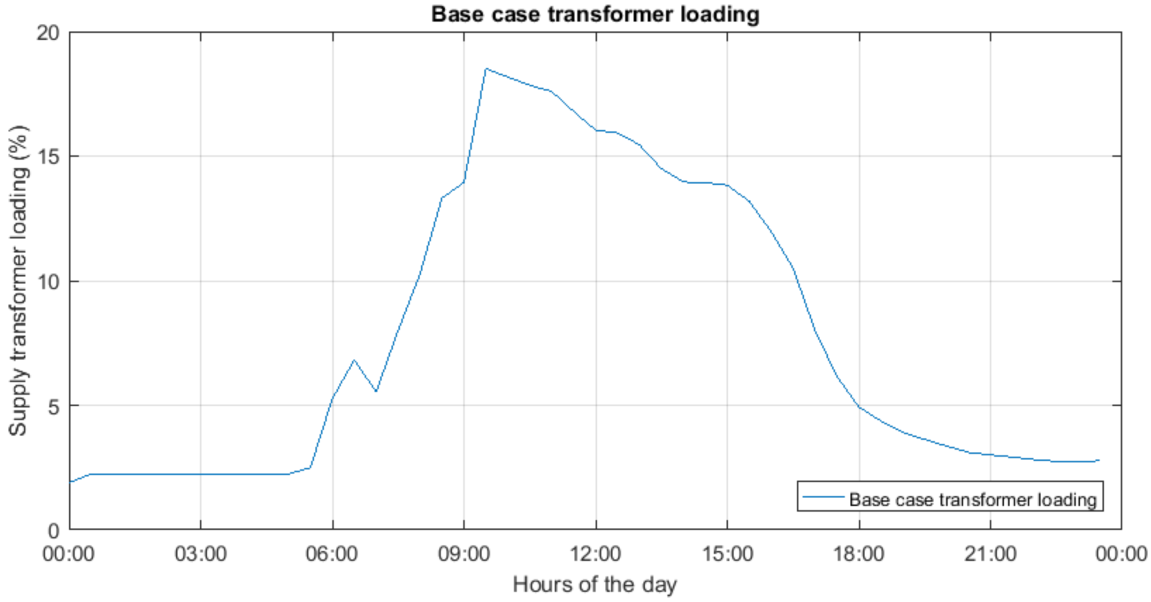

Figure 4.6. Base case transformer percentage loading (July 2016 load demand data)

4.4.2.2 Network parameters

The variation of supply voltage for the base case can be seen in Figure 4.7. The maximum and minimum voltages for the base case are 1.0368p.u. and 1.033p.u. respectively.

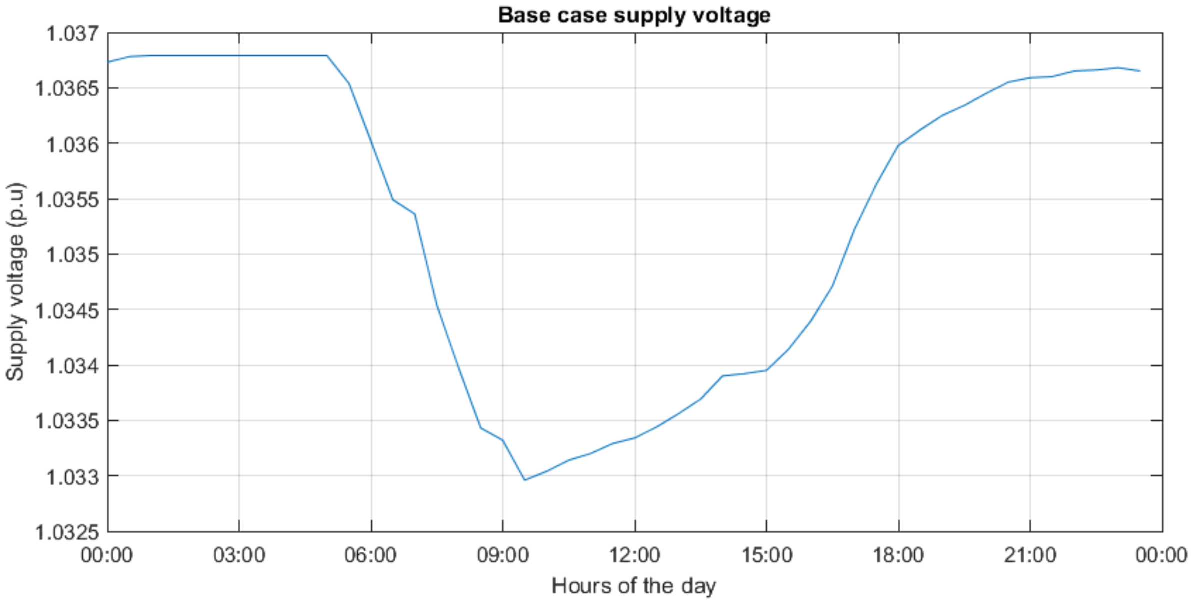

Figure 4.7. Base case supply voltage profile (July 2016 load demand data)

4.5 CENTRALISED DG SCENARIO RESULTS

To confirm the effect on load and network parameters from the introduction of a solar PV DG source, as noted in section 3.4, the same approach and methodology was applied to the two different load demand scenarios for the case study. The results obtained are presented in this section.

As was done for the hypothetical study, the DG source was modelled as being connected to the main low-voltage busbar common to all the customer feeders, as this is the central location of the network, this can be seen in Figure 4.8.

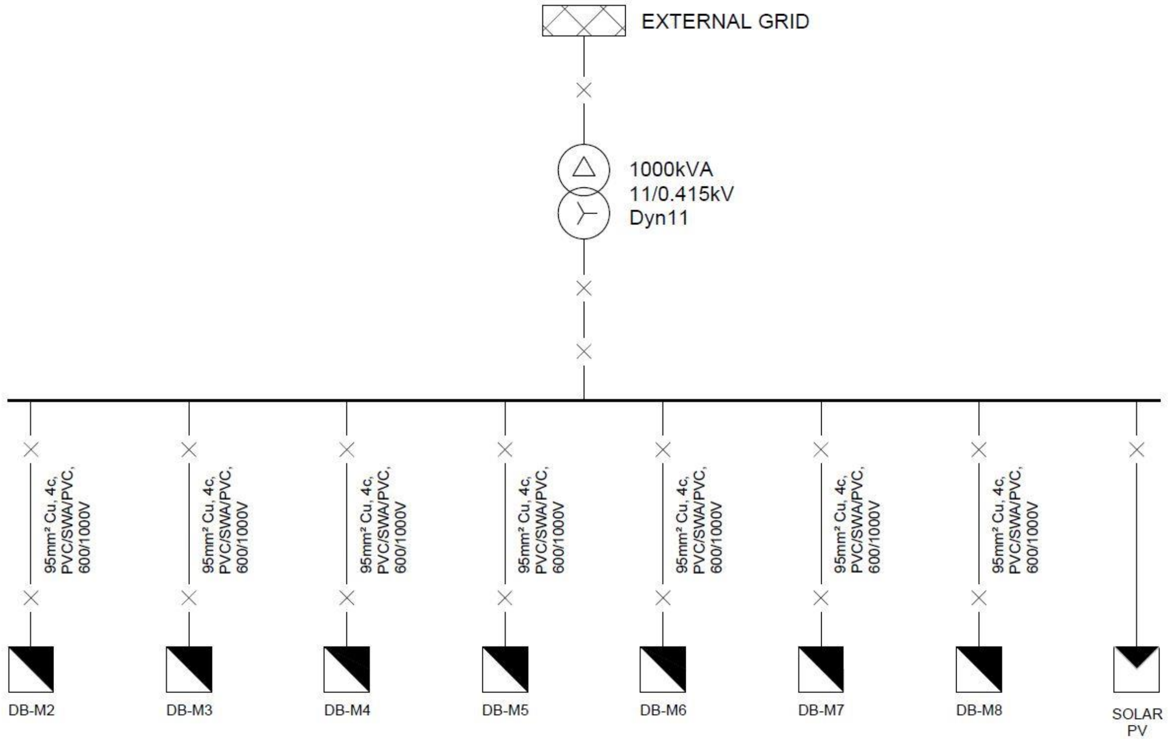

Figure 4.8. Case study central DG scenario single line diagram

4.5.1 January 2017 load demand scenario

The introduction of a solar PV DG source alters the coincident load demand profile for the entire load, as seen by the external network. This can be seen in Figure 4.9. The variation in transformer loading (which is directly related to the coincident load demand) for varying levels of solar PV penetration can be seen in Figure 4.10.

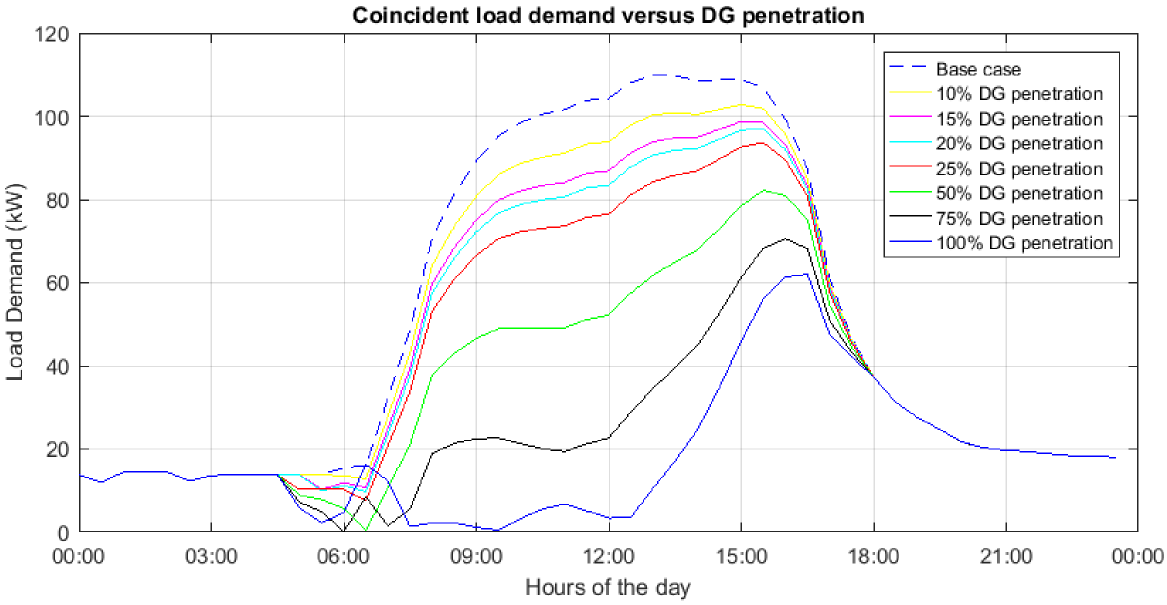

Figure 4.9. Coincident load demand versus DG penetration (Jan 2017 load demand)

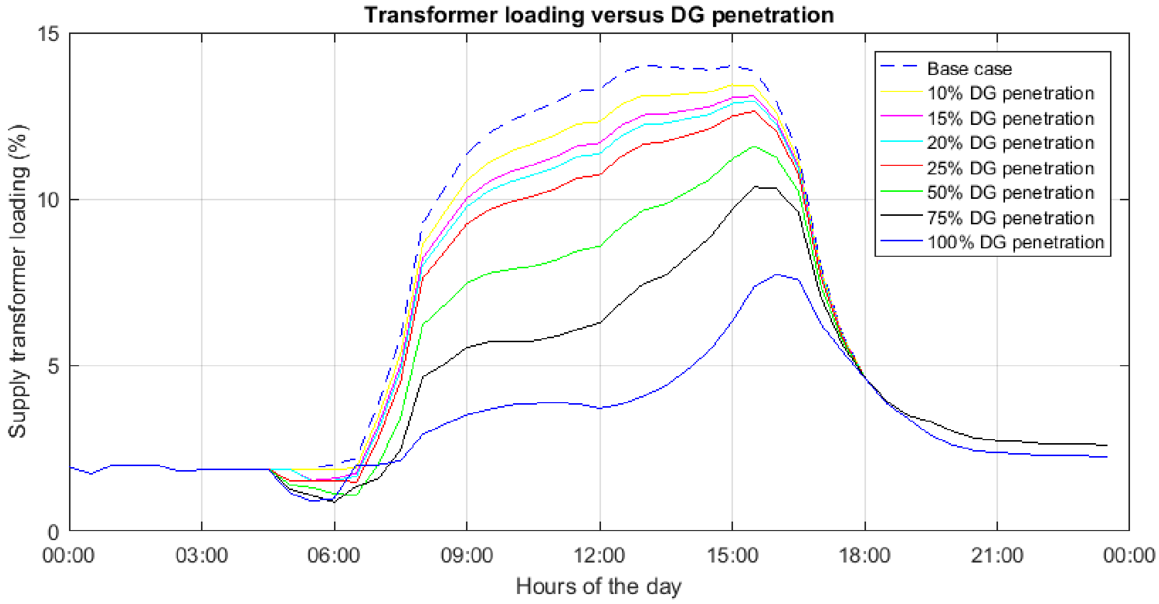

Figure 4.10. Transformer percentage loading versus DG penetration (Jan 2017 load demand)

4.5.1.1 Load parameters

The results obtained for the various load parameters at varying DG penetration levels for the January 2017 load demand scenario is given in Table 4.8. A short discussion on the results obtained is presented in section 4.5.2.1.1.

Table 4.8 Load parameters versus percentage DG penetration (Jan 2017 load demand)

	Load parameter							
%	Coincident demand	Demand factor	Utilisation factor	Load factor	Diversity factor	Coincidence factor	Load diversity	Loss factor
0	109.92	0.068	14.02	0.465	1.097	0.912	10.61	0.255
10	102.79	0.063	13.42	0.464	1.173	0.853	17.73	0.254
15	98.73	0.061	13.09	0.460	1.221	0.819	21.79	0.250
20	96.91	0.060	12.94	0.457	1.244	0.804	23.61	0.247
25	93.64	0.058	12.63	0.448	1.287	0.777	26.89	0.239
50	82.18	0.051	11.59	0.414	1.467	0.682	38.34	0.209
75	70.52	0.044	10.35	0.352	1.709	0.585	50.01	0.160
100	62.04	0.038	7.72	0.299	1.943	0.515	58.49	0.122

4.5.1.1.1 Discussion

From the results presented in Table 4.8, it can be seen that the introduction of the solar PV DG source does result in the altering of load parameters in a similar manner to the hypothetical study, as discussed in section 3.4.1.

Once again it can be seen that the introduction of DG at low levels of load penetration does not significantly alter load parameters, although an effect can be noted on load parameters. The largest variation in load parameters is seen at high levels of DG penetration.

The most noticeable reduction was seen in coincident demand, load factor, and loss factor. Not only did the introduction of the DG source result in a reduced coincident load demand (maximum demand), it also resulted in the maximum load demand occurring later in the day, this can be seen in Figure 4.9. This is in agreement with the results obtained from the hypothetical study.

The variation of load factor with DG penetration, on the other hand, was not in agreement with the hypothetical study. In the hypothetical study, an initial increase and then decrease was noted for load factor. The case study found that load factor continuously decreased with an increase in DG penetration level. This is explained in more detail in the discussion chapter; Chapter 5.

As can be seen from Figure 4.10, the transformer percentage loading does not reduce to 0% whereas the coincident load demand (seen in Figure 4.9) can be seen to reduce to 0kW, at 100% DG penetration. The reason for the transformer loading not reducing to 0% is due to the external network supplying the reactive power (kVAr) requirements of the load, whereas the DG source is supplying all of the real power (kW) requirements. This result is also in agreement with the result obtained from the hypothetical study.

4.5.1.2 Network parameters

The variation in supply voltage versus DG penetration, for the January 2017 load demand, can be seen in Figure 4.11. Increase in DG penetration can be seen to improve the supply voltage profile from the base case, although not significantly.

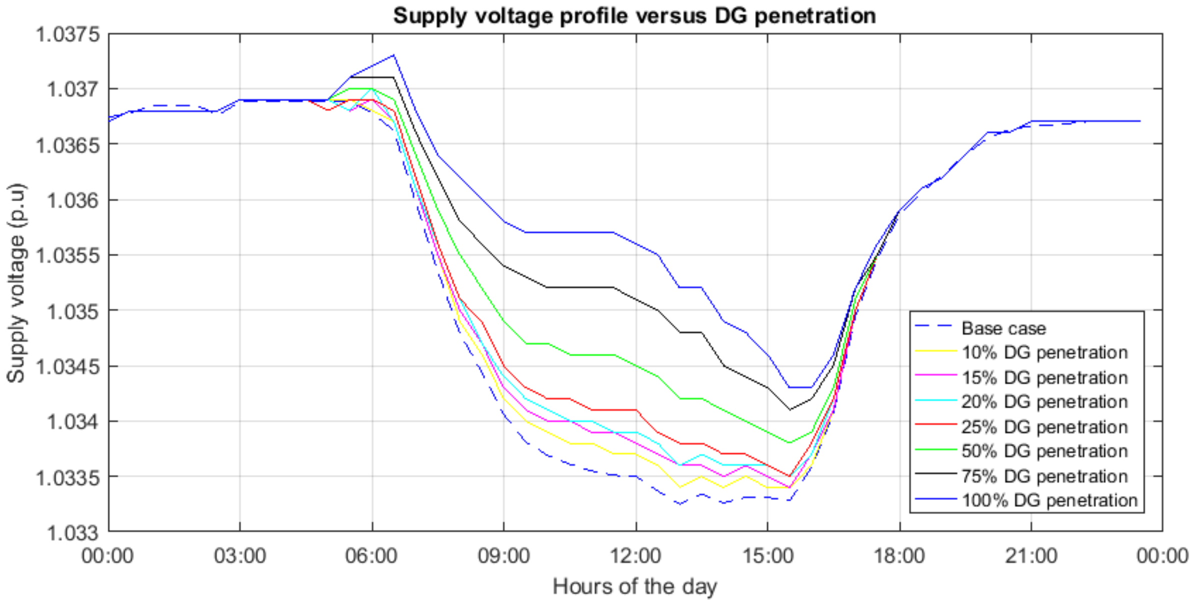

Figure 4.11. Supply voltage profile versus DG penetration (Jan 2017 load demand)

The variation in supply voltage maximum and minimum values can be seen in Table 4.9. The minimum supply voltage for higher DG penetration levels can be seen to improve, when compared to the base case.

The increase in supply voltage was only noted for the minimum supply voltages which occurrs during peak demand periods. The increase in minimum supply voltages was however, not significant. These results again confirm the results obtained in the hypothetical study, section 3.4.2.

Table 4.9 Supply voltage for varying levels of DG penetration (Jan 2017 load demand)

	Supply voltage (per unit)	
Percentage penetration	**Minimum voltage**	**Maximum voltage**
0%	1.0333	1.0369
10%	1.0334	1.0369
15%	1.0334	1.0369
20%	1.0335	1.0370
25%	1.0335	1.0369
50%	1.0338	1.0370
75%	1.0341	1.0371
100%	1.0343	1.0373

4.5.2 July 2016 load demand scenario

The variation in coincident load demand versus DG penetration, for the July 2016 load demand scenario can be seen in Figure 4.12. The variation in transformer loading for varying levels of solar PV penetration can be seen in Figure 4.13.

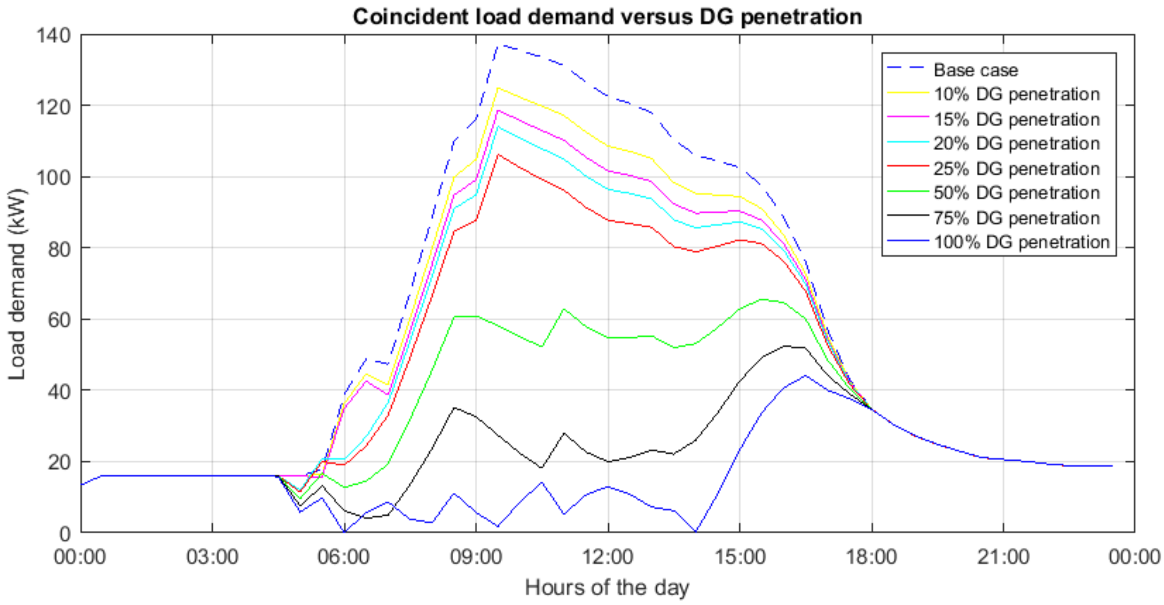

Figure 4.12. Coincident load demand versus DG penetration (July 2016 load demand)

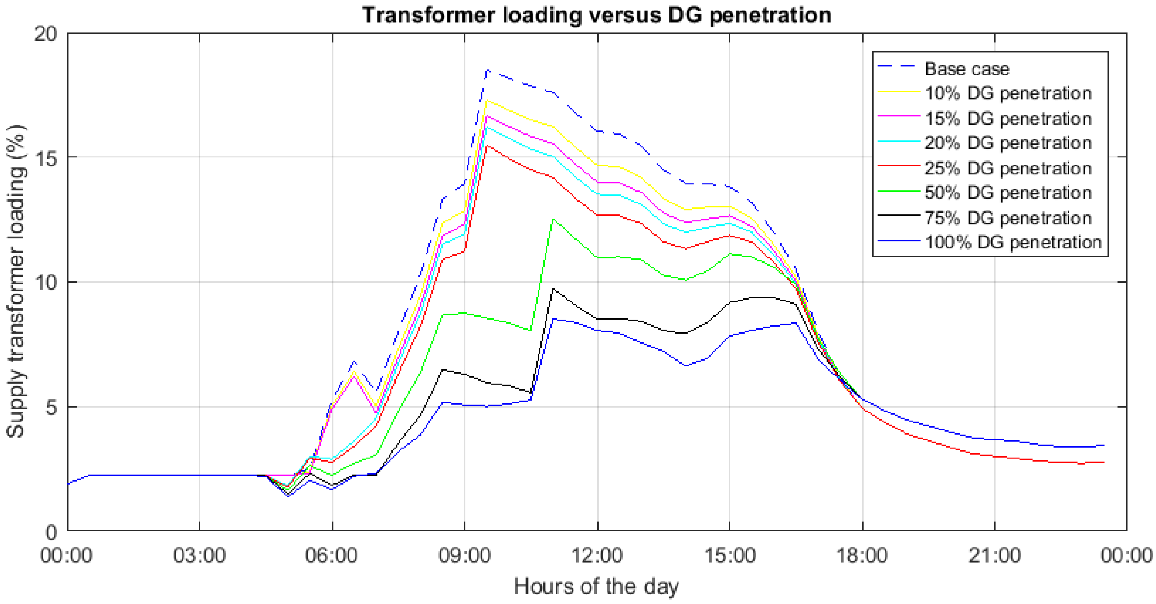

Figure 4.13. Transformer percentage loading versus DG penetration (July 2016 load demand)

4.5.2.1 Load parameters

The results obtained for the various load parameters at varying DG penetration levels are given in Table 4.10, for the July 2016 load demand scenario. A short discussion on the results obtained is presented in section 4.5.2.1.1.

Table 4.10 Load parameters versus percentage DG penetration (July 2016 load demand)

	Load parameter							
%	Coincident demand	Demand factor	Utilisation factor	Load factor	Diversity factor	Coincidence factor	Load diversity	Loss factor
0	137.27	0.085	18.51	0.424	1.360	0.735	49.41	0.218
10	124.89	0.077	17.29	0.430	1.495	0.669	61.78	0.223
15	118.67	0.073	16.67	0.434	1.573	0.636	68.00	0.226
20	113.99	0.070	16.22	0.432	1.638	0.611	72.68	0.225
25	106.21	0.066	15.48	0.437	1.758	0.569	80.47	0.229
50	65.57	0.040	12.55	0.528	2.847	0.351	121.10	0.318
75	52.36	0.032	9.74	0.446	3.565	0.280	134.31	0.237
100	44.12	0.027	8.52	0.377	4.231	0.236	142.56	0.178

4.5.2.1.1 Discussion

From the results presented in Table 4.10, it can be noted that the load factor varied in a similar manner to the hypothetical study as noted in section 3.4.1. Load factor increases for low levels of DG penetration and then decreases for higher levels of DG penetration. This is as a result of the coincident demand decreasing at a higher rate compared to the average load, and results in an increased ratio of average load to maximum demand.

The most noticeable reduction was seen in coincident demand, load factor, and loss factor. Not only did the introduction of the DG source result in a reduced coincident load demand (maximum demand), it also results in the maximum load demand occurring later in the day, this can be seen in Figure 4.12.

4.5.2.2 Network parameters

The variation in supply voltage versus DG penetration can be seen in Figure 4.11. The increased DG penetration can be seen to improve the supply voltage profile from the base case.

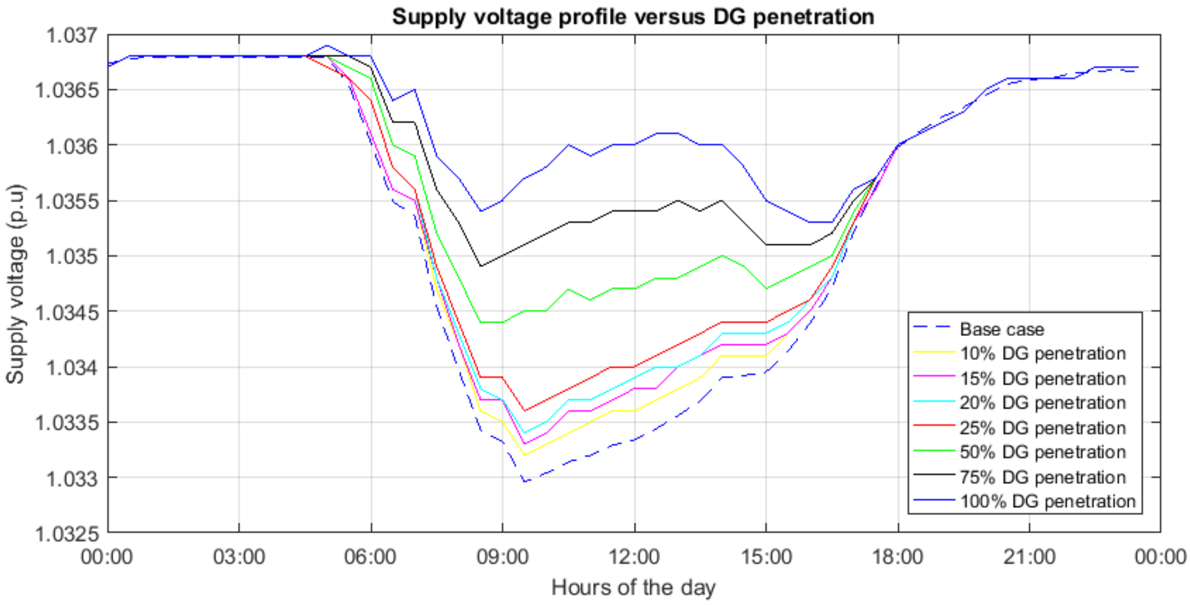

Figure 4.14. Supply voltage profile versus DG penetration (July 2016 load demand)

The variation in supply voltage maximum and minimum voltages can be seen in Table 4.11. The minimum supply voltage for higher DG penetration levels can be seen to increase, when compared to the base case.

The increase in supply voltage was only noted for the minimum supply voltages which occurred during peak demand periods. The increase in minimum supply voltages was however, not significant.

Table 4.11 Supply voltage for varying levels of DG penetration (July 2016 load demand)

	Supply voltage (per unit)	
Percentage penetration	**Minimum voltage**	**Maximum voltage**
0%	1.0330	1.0368
10%	1.0332	1.0368
15%	1.0333	1.0368
20%	1.0334	1.0368
25%	1.0336	1.0368
50%	1.0344	1.0368
75%	1.0349	1.0368
100%	1.0353	1.0369

4.6 DE-CENTRALISED DG SCENARIO RESULTS

As was done in the hypothetical study, a de-centralised DG scenario, for both load demand scenarios (January 2017 and July 2016), was investigated. The DG source was modelled as being connected to DB-M3, as seen in Figure 4.15. The reason DB-M3 was selected, was because this is the sub-distribution board with the highest load demand out of the seven. Sub-distribution board DB-M3 services five different customers.

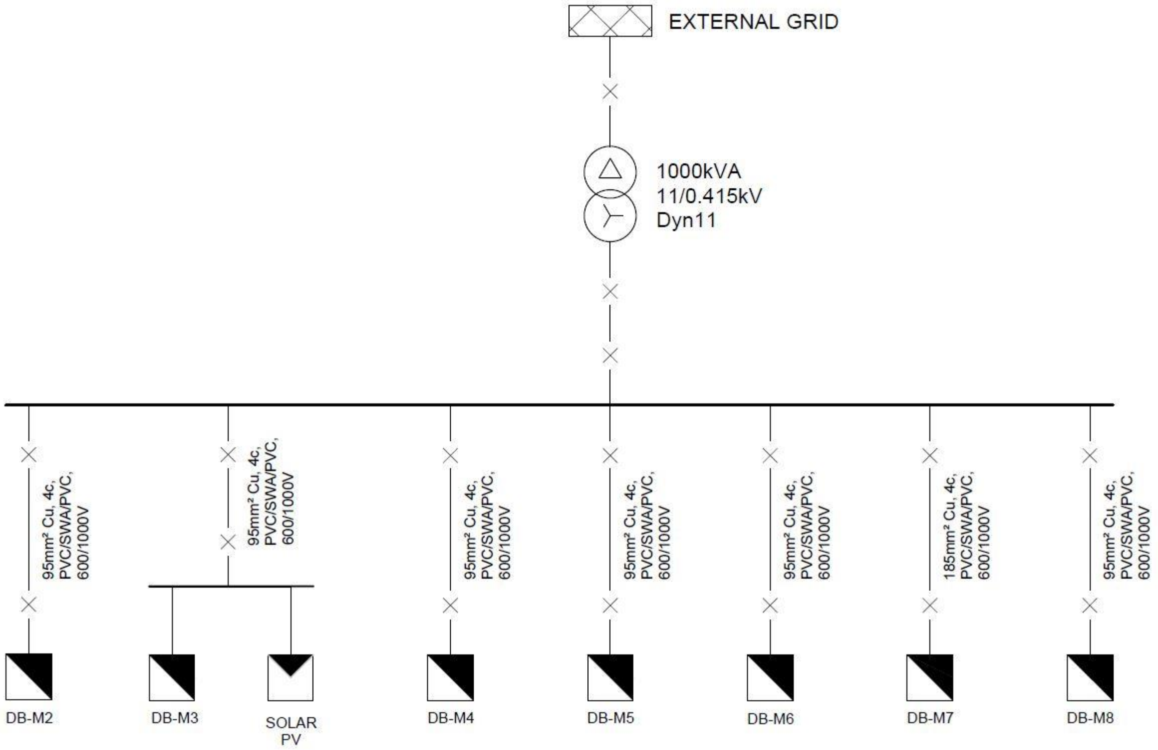

Figure 4.15. Single line diagram with de-central DG source (case study)

4.6.1 January 2017 load demand scenario

The DG capacity selected was based on a percentage of maximum load demand for DB-M3 (24.27kW) for the January 2017 load demand scenario. The percentage penetration levels and associated DG capacities simulated are given in Table 4.12. Due to the methodology of modelling the DG source, only discrete system capacities could be selected and therefore the DG capacity is not the exact percentage of the maximum load demand of DB-M3.

Table 4.12 De-centralised DG penetration levels and capacities modelled

Percentage penetration	**DG capacity (kWac)**
10%	1.75
15%	3.51
20%	5.26
25%	7.01
50%	12.27
75%	19.28
100%	24.54

For both the load demand scenarios (January 2017 and July 2016) the same capacity DG source was model. This is because, in a real-life scenario, the DG source capacity would not vary but rather a fixed capacity would be installed.

4.6.1.1 Load parameters

The introduction of a DG source alters the load demand profile for DB-M3, and in turn, the total load demand profile, which has an impact on load parameters. The manner in which the total load demand profile is affected can be seen in Figure 4.16. The variation in the supply transformer percentage loading for varying levels of DG penetration can be seen in Figure 4.17. The variation in feeder cable percentage loading for DB-M3, for varying levels of DG penetration, can be seen in Figure 4.18.

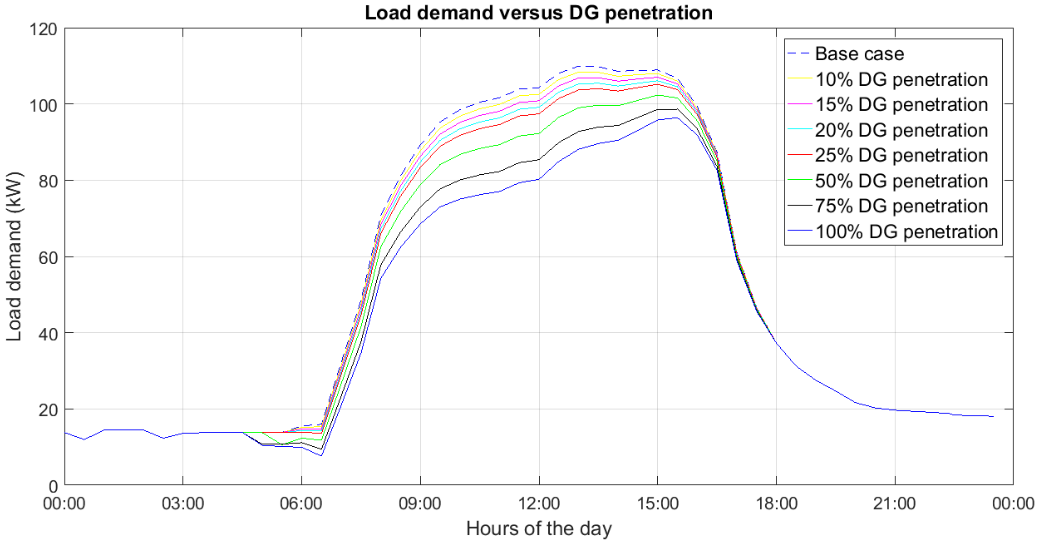

Figure 4.16. Coincident load demand versus de-central DG penetration (Jan 2017 load demand)

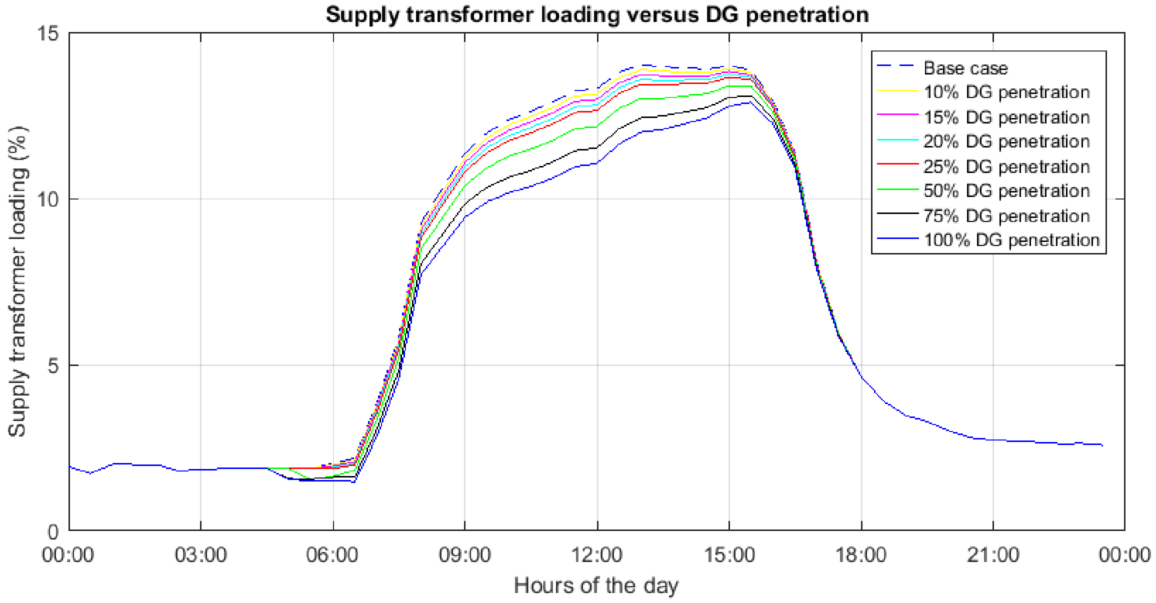

Figure 4.17. Transformer percentage loading versus de-central DG penetration (Jan 2017 load demand)

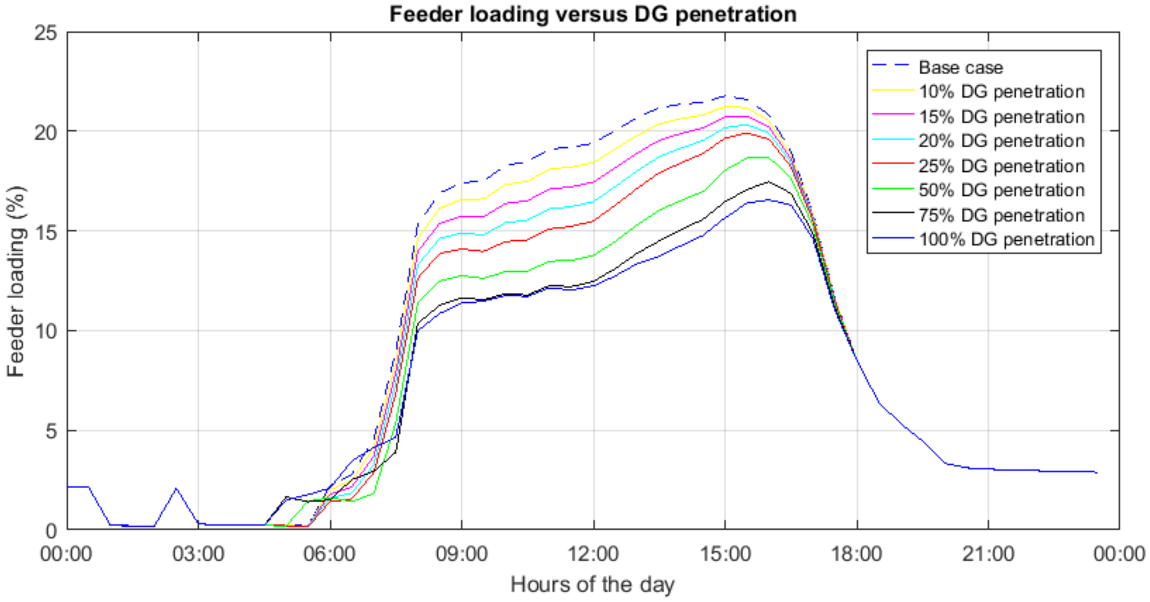

Figure 4.18. DB-M3 feeder cable percentage loading versus DG penetration (Jan 2017)

The results obtained for the various load parameters at varying DG penetration levels is presented in Table 4.13. A short discussion on the results obtained is presented in section 4.6.1.1.1.

Table 4.13 Load parameters versus percentage DG penetration for de-central scenario (Jan 2017)

	Load parameter							
%	Coincident demand	Demand factor	Utilisation factor	Load factor	Diversity factor	Coincidence factor	Load diversity	Loss factor
0	109.92	0.068	14.02	0.465	1.097	0.912	10.610	0.255
10	108.35	0.067	13.90	0.466	1.112	0.899	12.171	0.256
15	107.01	0.066	13.82	0.467	1.126	0.888	13.514	0.257
20	106.08	0.065	13.73	0.466	1.136	0.880	14.451	0.256
25	105.14	0.065	13.64	0.465	1.146	0.872	15.388	0.254
50	102.33	0.063	13.38	0.460	1.178	0.849	18.197	0.250
75	98.62	0.061	13.09	0.454	1.222	0.818	21.909	0.245
100	96.40	0.059	12.89	0.447	1.250	0.800	24.121	0.238

4.6.1.1.1 Discussion

Based on the results presented in Table 4.13, it can be seen that the introduction of the solar PV system at a de-central location does affect load parameters for the entire load. This agrees with the results observed in the hypothetical study. Coincident demand, demand factor, and utilisation factor all decreased with increase in DG penetration. Load factor and loss factor, on the other hand, increased to a certain percentage DG penetration after which they decreased. These results are not in agreement with the results obtained for the hypothetical study. This will be further elaborated on in the discussion chapter, Chapter 5.

4.6.1.2 Network parameters

The variation in supply voltage versus DG penetration can be seen in Figure 4.19. The increase in DG penetration can be seen to improve the supply voltage profile from the base case.

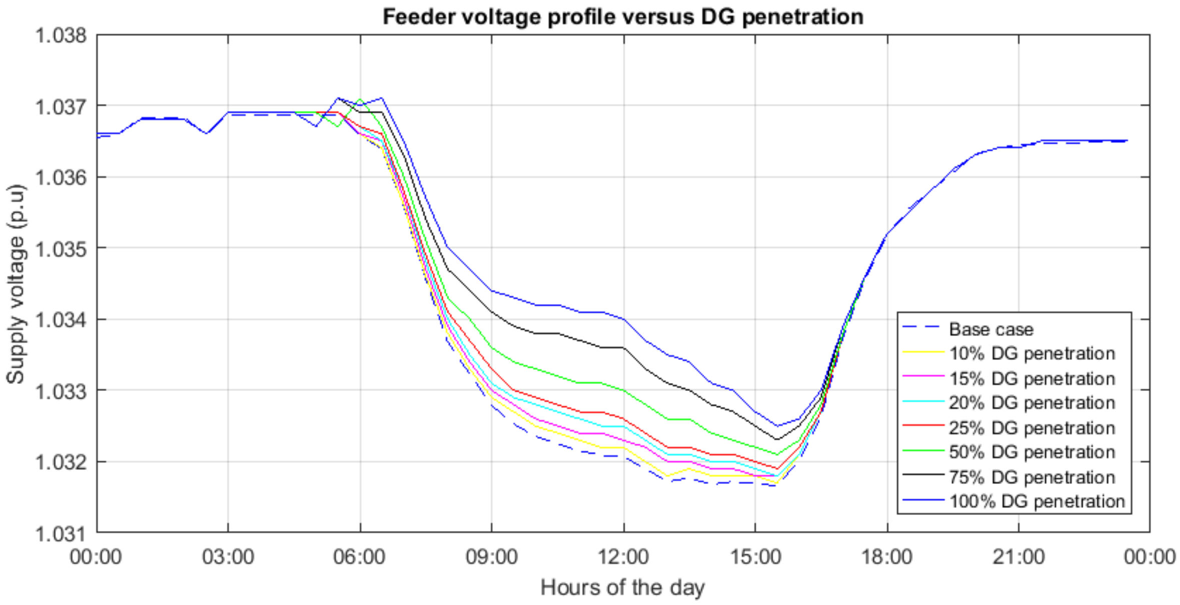

Figure 4.19. DB-M3 supply voltage profile versus DG penetration (Jan 2017)

The variation in supply voltage maximum and minimum voltages can be seen in Table 4.14. The minimum supply voltage for higher DG penetration levels can be seen to increase, when compared to the base case. The increase in supply voltage was only noted for the minimum supply voltages, which occurred during peak demand periods. The increase in minimum supply voltages was however, not significant.

Table 4.14 DB-M3 supply voltage for varying levels of DG penetration (January 2017)

	Supply voltage (per unit)	
Percentage penetration	**Minimum voltage**	**Maximum voltage**
0%	1.0317	1.0369
10%	1.0317	1.0369
15%	1.0318	1.0369
20%	1.0318	1.0369
25%	1.0319	1.0369
50%	1.0321	1.0371
75%	1.0323	1.0371
100%	1.0325	1.0371

4.6.2 July 2016 load demand scenario

The same analysis was conducted for the July 2016 load demand scenario as for the January 2017 scenario. The results obtained for the load parameters and network parameters are presented in sections 4.6.2.1 and 4.6.2.2 respectively.

4.6.2.1 Load parameters

The manner in which the total load demand profile was affected by the introduction of a DG source with varying capacity, for the July 2016 load demand scenario, can be seen in Figure 4.20. The variation in the supply transformer percentage loading for varying levels of DG penetration can be seen in Figure 4.21. The variation in feeder cable (supplying DB-M3) percentage loading, for varying levels of DG penetration, can be seen in Figure 4.22.

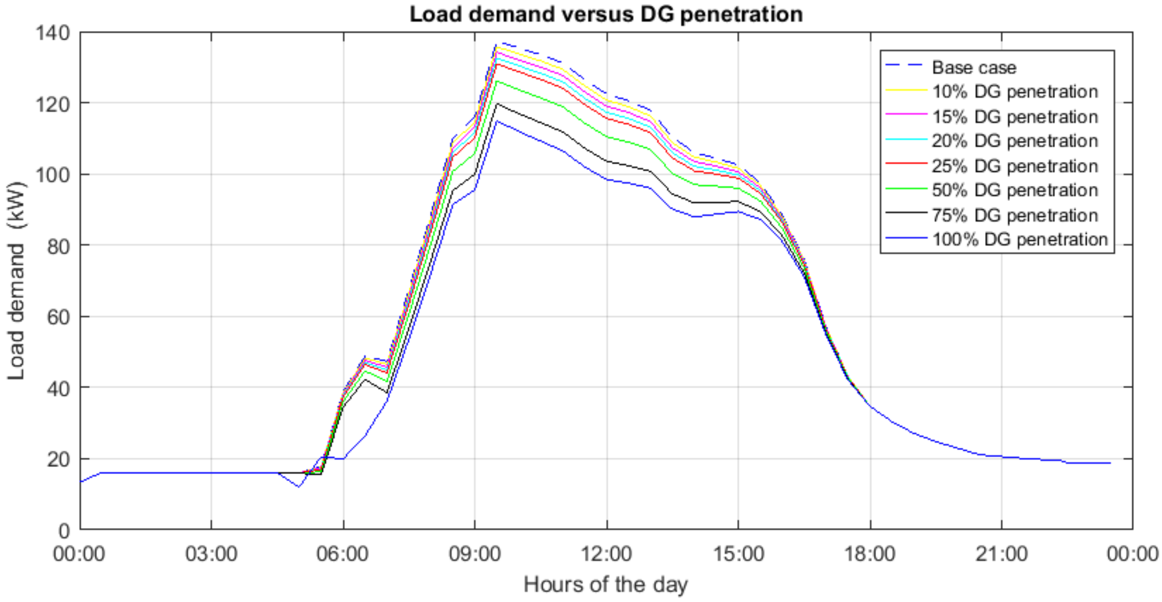

Figure 4.20. Coincident load demand versus de-central DG penetration (July 2016 load demand)

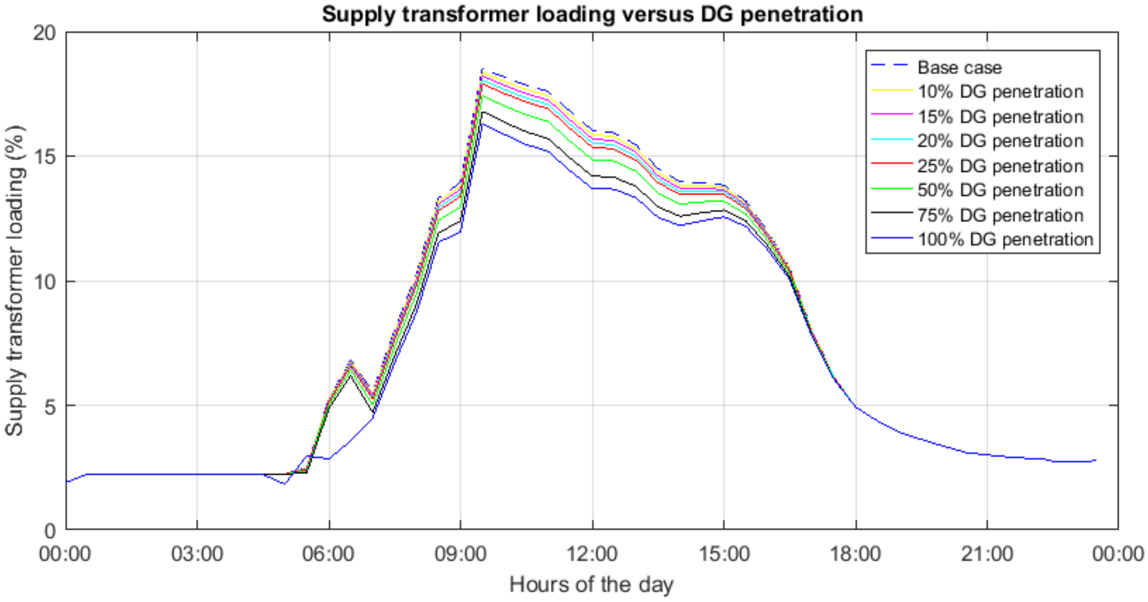

Figure 4.21. Transformer percentage loading versus de-central DG penetration (July 2016 load demand)

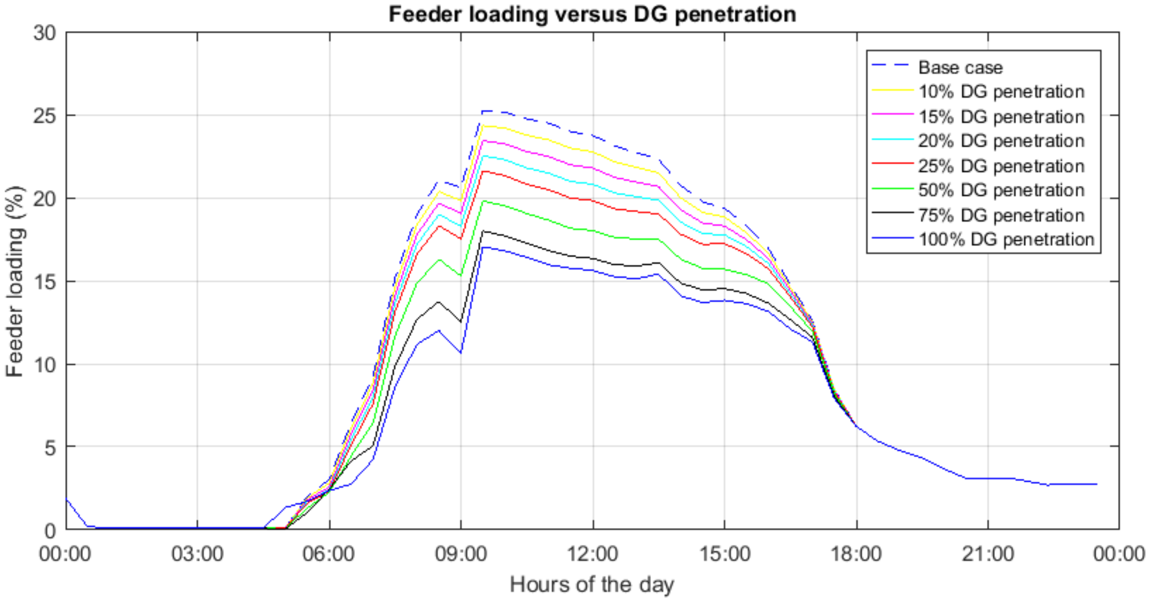

Figure 4.22. DB-M3 feeder cable percentage loading versus DG penetration (July 2016)

The results obtained for the various load parameters at varying DG penetration levels are presented in Table 4.15. A short discussion on the results obtained is presented in section 4.6.2.1.1.

Table 4.15 Load parameters versus percentage DG penetration for de-central scenario (July 2016)

	Load parameter							
%	Coincident demand	Demand factor	Utilisation factor	Load factor	Diversity factor	Coincidence factor	Load diversity	Loss factor
0	137.27	0.085	18.506	0.424	1.109	0.902	14.98	0.218
10	135.67	0.084	18.349	0.425	1.122	0.891	16.57	0.219
15	134.14	0.083	18.208	0.426	1.135	0.881	18.10	0.219
20	132.52	0.082	18.048	0.427	1.149	0.870	19.72	0.220
25	130.91	0.081	17.889	0.428	1.163	0.860	21.33	0.221
50	126.11	0.078	17.415	0.431	1.207	0.828	26.13	0.224
75	119.73	0.074	16.790	0.435	1.272	0.786	32.52	0.227
100	114.95	0.071	16.306	0.433	1.324	0.755	37.29	0.226

4.6.2.1.1 Discussion

Based on the results presented in Table 4.15, it can be seen that the introduction of the solar PV system at a de-central location does effected load parameters for the entire load. This is the same result as was observed in the hypothetical study. Coincident demand, demand factor, and utilisation factor decreased with an increase in DG penetration. Load factor and loss factor, on the other hand, increased with increasing DG penetration until a certain point, after which they decrease. This is in partial agreement with the results obtained for the hypothetical study, as well as for the January 2017 scenario.

4.6.2.2 Network parameters

The variation in supply voltage versus DG penetration can be seen in Figure 4.23. The increased DG penetration can be seen to improve the supply voltage profile from the base case.

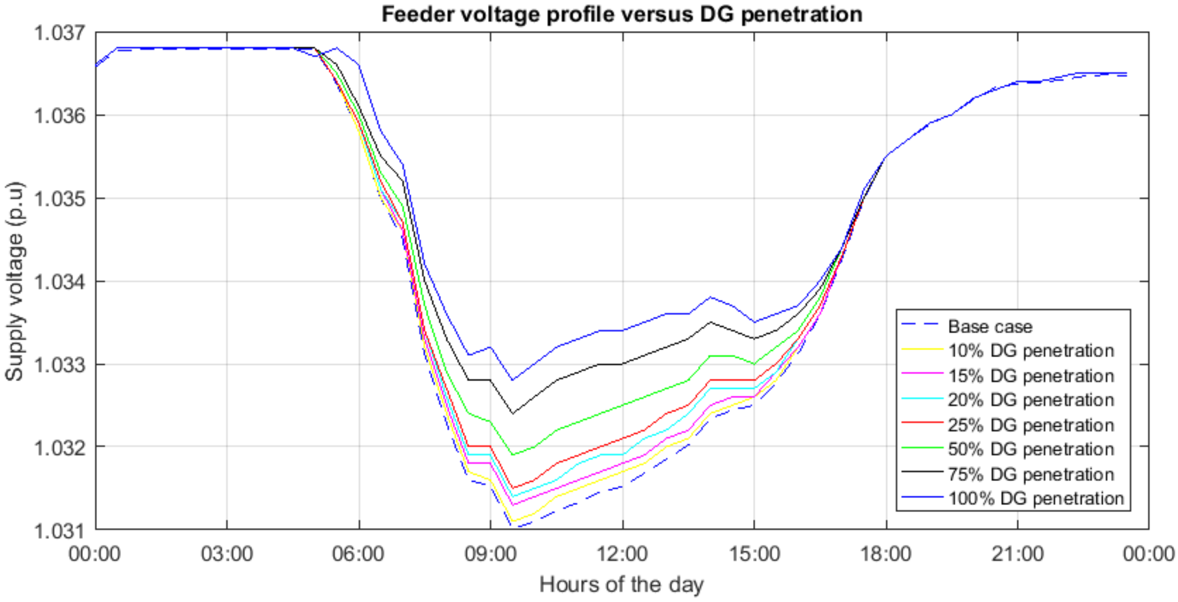

Figure 4.23. DB-M3 supply voltage profile versus DG penetration (July 2016)

The variation in supply voltage maximum and minimum values can be seen in Table 4.16. The minimum supply voltage for higher DG penetration levels can be seen to increase, when compared to the base case.

The increase in supply voltage was only noted for the minimum supply voltages; which occurred during peak demand periods. The increase in minimum supply voltages was however, not significant.

Table 4.16 DB-M3 supply voltage for varying levels of DG penetration (July 2016)

	Supply voltage (per unit)	
Percentage penetration	**Minimum voltage**	**Maximum voltage**
0%	1.0310	1.0368
10%	1.0311	1.0368
15%	1.0313	1.0368
20%	1.0314	1.0368
25%	1.0315	1.0368
50%	1.0319	1.0368
75%	1.0324	1.0368
100%	1.0328	1.0368

4.7 CHAPTER SUMMARY

From the results obtained for the two different load demand scenarios analysed, the results are generally in agreement with those obtained for the hypothetical study. It was found that the introduction of a solar PV DG source, at a central location within the network or at a de-central location, does have an effect on load and networks parameters.

The load parameters that were most significantly affected in the central DG scenario were coincident demand, load factor, diversity factor (and therefore coincidence factor), load diversity and loss factor.

In the de-central DG scenario, load parameters were not significantly affected; however, in some cases load factor and loss factor increased with an increase in DG penetration, as noted in the hypothetical study. These results are also in alignment with the increase in these load parameters (for the central DG scenario) for low levels of DG penetration in the July 2016 load demand case.

Network parameters, such as supply voltage, for both the central and de-central DG scenario were not significantly affected by varying levels of DG penetration. This is in agreement with the results obtained for the hypothetical study.

CHAPTER 5 DISCUSSION

5.1 CHAPTER OVERVIEW

The objective of this chapter is to discuss the results obtained for the hypothetical study and the case study. The results will be compared for validation and further analysed to determine the impact that varying levels of DG penetration has on load and network parameters. In addition to this, a conclusion will be made as to whether the impact on load and network parameters is great enough to warrant further investigation into determining suitable planning and design standards for reticulation networks containing varying levels of DG penetration.

5.2 HYPOTHETICAL STUDY

The impact of varying levels of DG penetration on load and networks parameters, for the hypothetical study, are further discussed in section 5.2.1 and 5.2.2 respectively.

5.2.1 Load parameters

The impact of varying levels of DG penetration on each of the load parameters under investigation are discussed below, for both the central and de-central DG scenarios.

5.2.1.1 Coincident demand

5.2.1.1.1 Central DG scenario

The impact of varying levels of DG penetration on coincident demand for the central DG scenario is given in Figure 5.1. The variation in DG penetration from 0% to 100% (0kW to

165kW installed capacity) of the maximum coincident demand only resulted in a reduction of the combined system coincident demand of approximately 18%. This is because of the solar PV DG source being unable to reduce the load demand beyond 18:00, due to the reduction of solar irradiation. The maximum coincident load demand has been shifted from 14:00 to around 18:00.

As can be noted from the altering of the coincident load demand profile (seen in Figure 3.8), the load demand profile is now more similar to a residential load demand profile, which has a higher maximum load demand in the evening. If the commercial facility were on a time-of-use tariff, it is possible that the average cost of the energy consumed by the facility would be higher for the high-levels of DG penetration compared to lower-levels. This would be because of the load shifting that occurs (for high-levels of DG penetration) and more energy being consumed during peak-demand charge periods, typically between 06:00 to 09:00 and 17:00 to 19:00. Overall, the facility would see a reduction in energy costs due to a portion of the facilities energy consumption being supplied by the solar PV system.

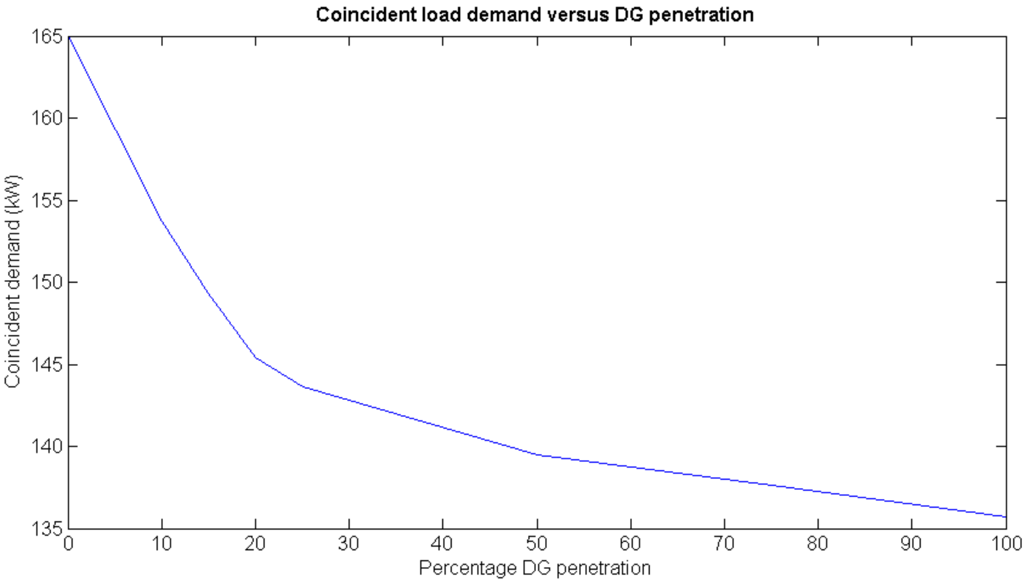

Figure 5.1. Coincident demand versus DG penetration (hypothetical study, central DG)

5.2.1.1.2 De-central DG scenario

The impact of varying levels of DG penetration on coincident demand for the de-central DG scenario is given in Figure 5.2. The variation in DG penetration from 0% to 100% (0kW to 29.6kW installed capacity) of the maximum coincident demand, for customer no. 5, resulted in a reduction of the combined system coincident demand of approximately 11%. The maximum de-central DG source capacity modelled was 29.6kW versus the 165kW modelled for the central DG scenario. The de-central DG scenario capacity is approximately 18% of the central DG scenario capacity; however, it results in approximately 58% of the reduction in coincident demand.

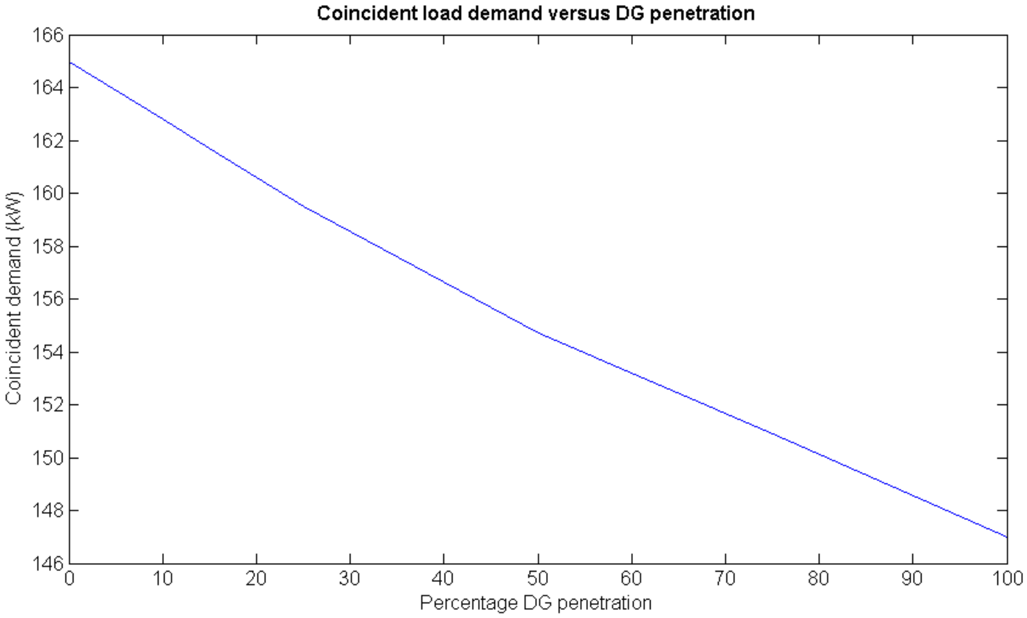

Figure 5.2. Coincident demand versus DG penetration (hypothetical study, de-central DG)

5.2.1.2 Demand factor

5.2.1.2.1 Central DG scenario

The impact of varying levels of DG penetration on demand factor for the central DG scenario is given in Figure 5.3. The variation in DG penetration from 0% to 100% of the maximum coincident demand resulted in a reduction of the combined system demand factor of approximately 18%, which is in line with the reduction of coincident demand.

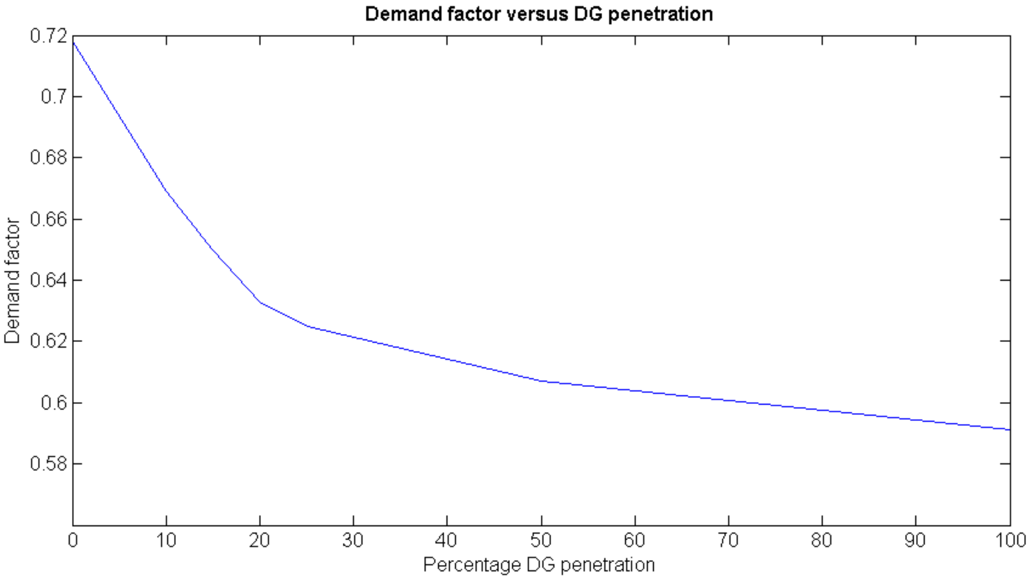

Figure 5.3. Demand factor versus DG penetration (hypothetical study, central DG)

5.2.1.2.2 De-central DG scenario

The impact of varying levels of DG penetration on demand factor for the de-central DG scenario is given in Figure 5.4. The variation in DG penetration from 0% to 100% of the maximum coincident demand resulted in a reduction of the combined system demand factor of approximately 11%, which is expected as demand factor is directly proportional to coincident demand and coincident demand decreased by approximately 11%.

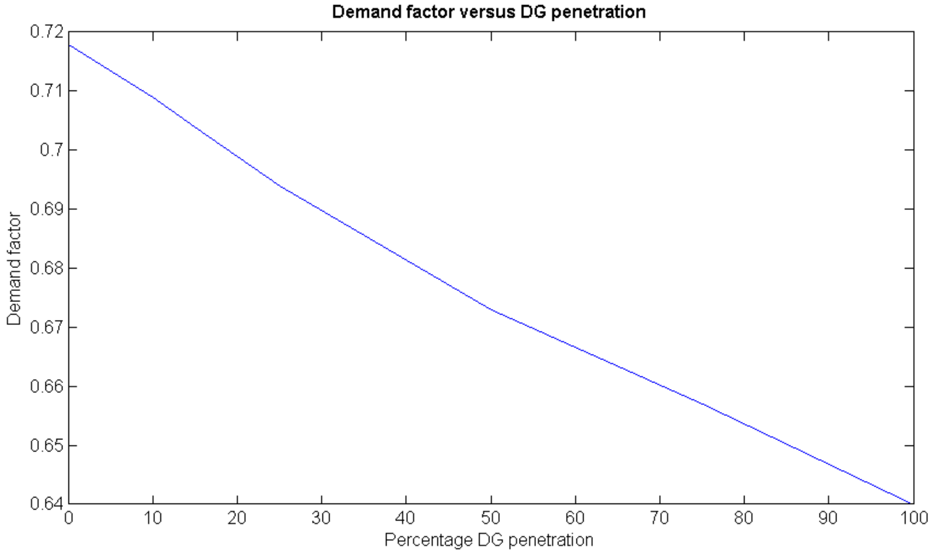

Figure 5.4. Demand factor versus DG penetration (hypothetical study, de-central DG)

5.2.1.3 Utilisation factor

5.2.1.3.1 Central DG scenario

The increase in DG penetration resulted in a reduction in the utilisation factor; which is approximately 17.5% for the central DG scenario. This can be noted from the decrease in utilisation factor with increase in DG penetration, seen in Figure 5.5. The reduction in transformer utilisation is because of the reduction in the coincident demand as well as a function of the placement and capacity of the DG source. If the DG source was integrated at the medium-voltage level of the reticulation (i.e. upstream of the transformer supplying the load) the transformer utilisation factor would not be impacted in such a manner. This would be due to the total load demand still being supplied through the transformers.

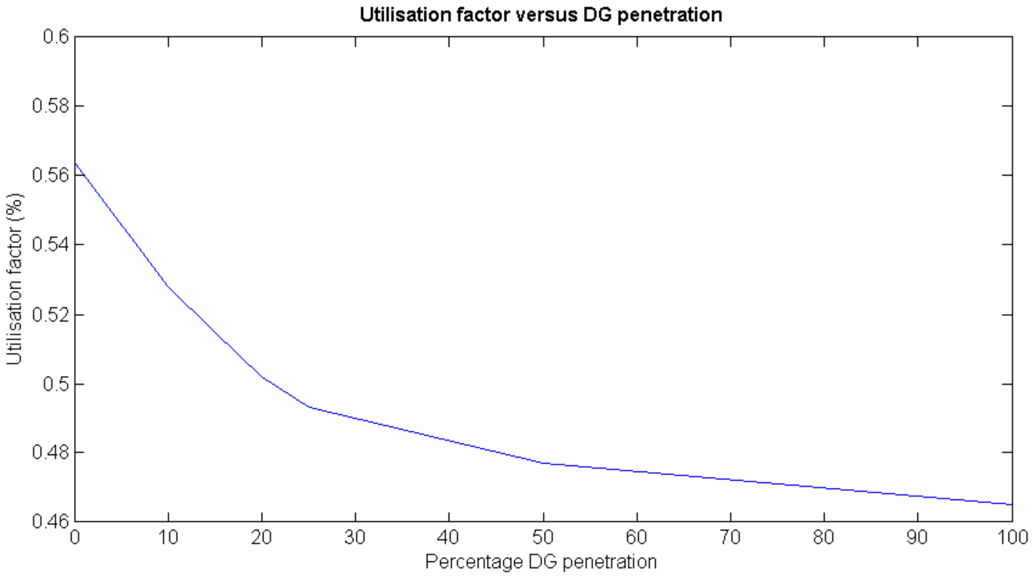

Figure 5.5. Utilisation factor versus DG penetration (hypothetical study, central DG)

5.2.1.3.2 De-central DG scenario

The reduction of utilisation factor of the supply transformer for the de-central DG scenario can be seen in Figure 5.6. The percentage reduction in utilisation factor is approximately 10%, which is again approximately 57% of the reduction noted for the central DG scenario. This is despite the fact that the DG source capacity for the de-central DG scenario was only 18% of the DG source capacity for the central DG scenario.

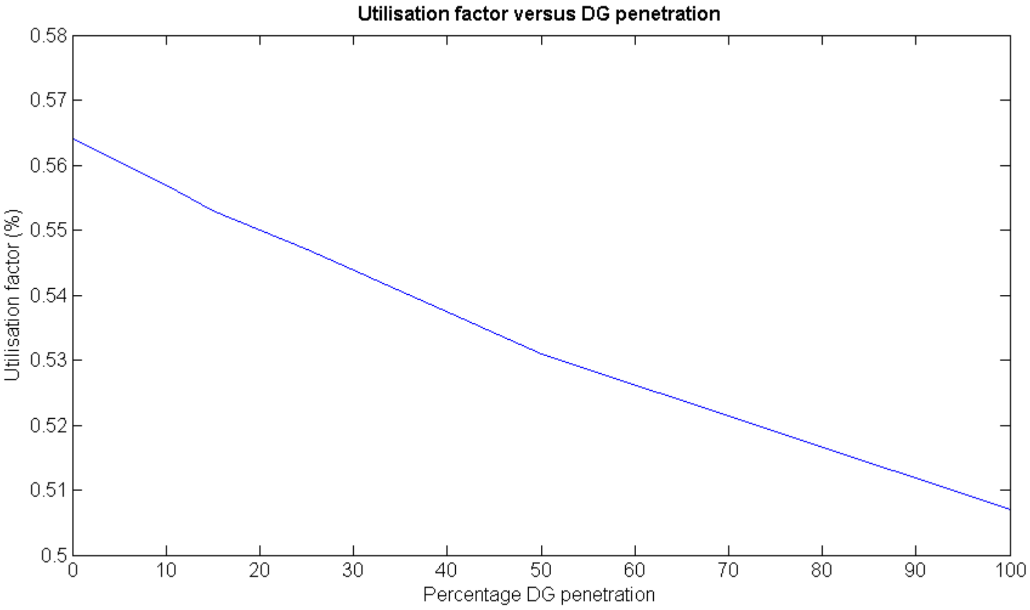

Figure 5.6. Utilisation factor versus DG penetration (hypothetical study, de-central DG)

5.2.1.4 Load factor

5.2.1.4.1 Central DG scenario

The variation of load factor with DG penetration is given in Figure 5.7, for the central DG scenario. Load factor did not monotonically increase or decrease with the increase in DG penetration. For lower levels of DG penetration load factor increased (up until 15%) and for higher levels of DG penetration load factor started to decrease. This is an interesting observation and demonstrates that the introduction of DG sources can be beneficial, as a higher load factor is an indication of a more constant load demand over time.

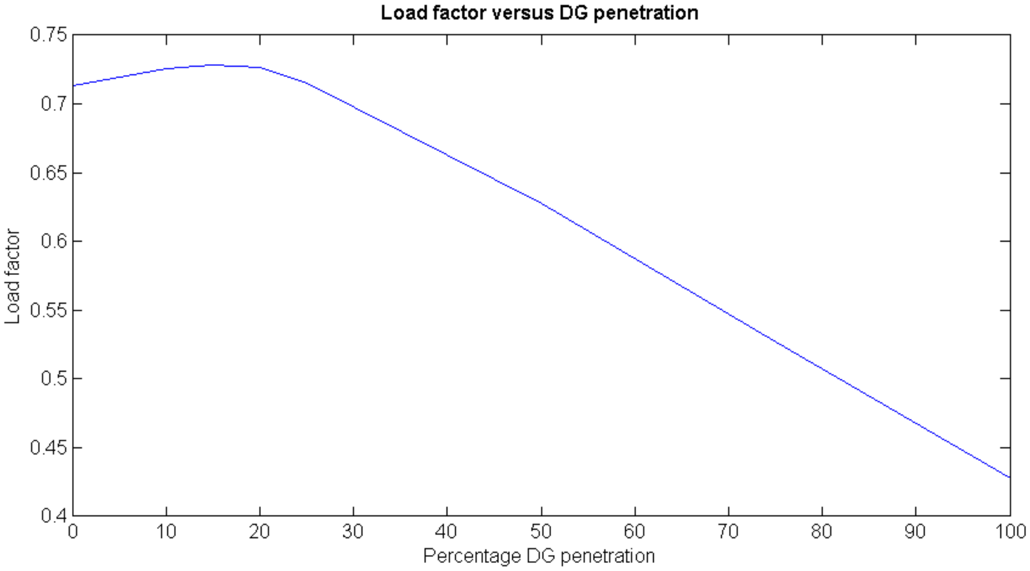

Figure 5.7. Load factor versus DG penetration (hypothetical study, central DG)

5.2.1.4.2 De-central DG scenario

Load factor versus percentage DG penetration for the de-central DG scenario is given in Figure 5.8. It can be noted that load factor continually increases with the increase in DG penetration, and this aligns with the initial increase noted for the central DG scenario seen in Figure 5.7. The increase in load factor is due to the greater decrease in coincident demand compared to the average load; which results in the ratio of the two being larger.

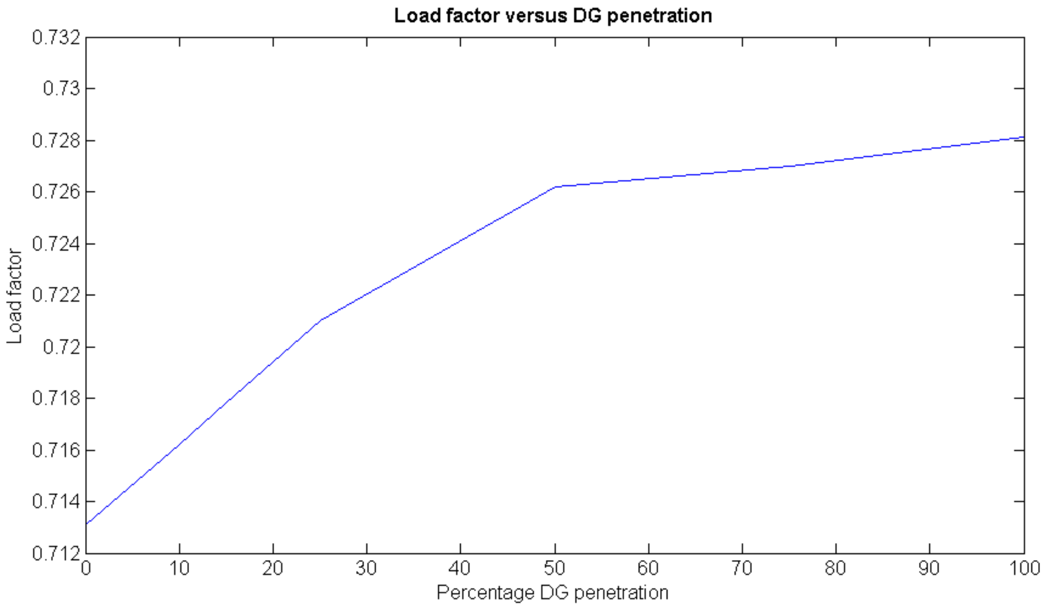

Figure 5.8. Load factor versus DG penetration (hypothetical study, de-central DG)

5.2.1.5 Diversity and coincidence factor

5.2.1.5.1 Central DG scenario

The variation in diversity factor versus DG penetration can be seen in Figure 5.9 for the central DG scenario. Diversity factor increased with the increase in DG penetration. This is due to the reduction in the coincident demand as seen in Figure 5.1, as the individual maximum demand of each customer was unchanged. Diversity factor increase by approximately 22%. Coincident factor, being the inverse of diversity factor, varied inversely to diversity factor, as seen in Figure 5.10.

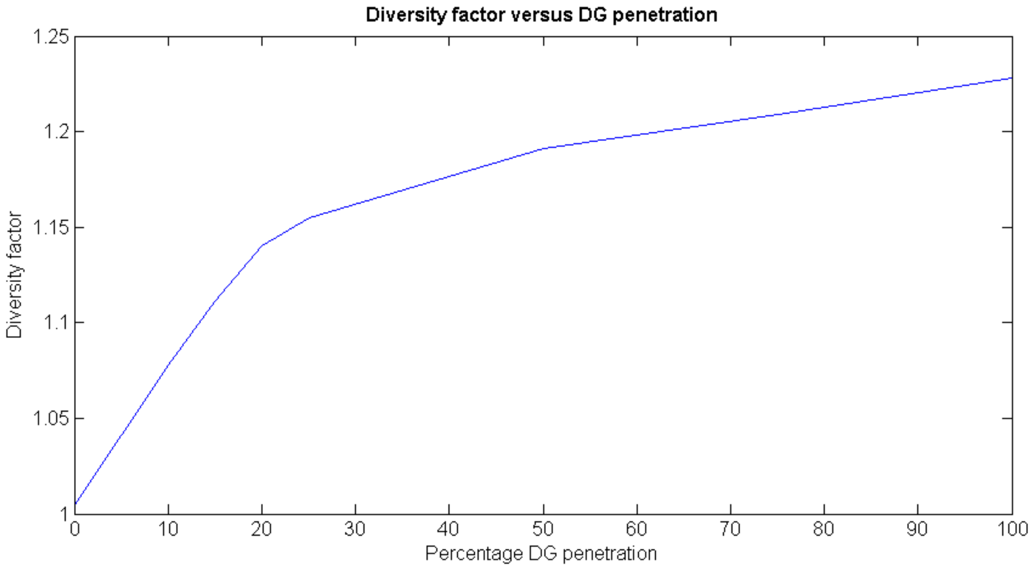

Figure 5.9. Diversity factor versus DG penetration (hypothetical study, central DG)

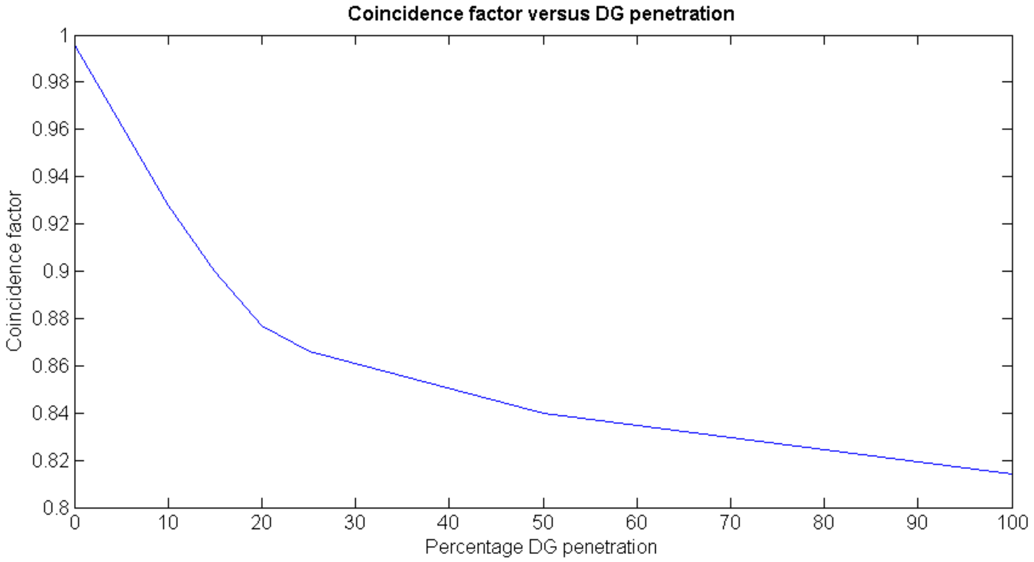

Figure 5.10. Coincidence factor versus DG penetration (hypothetical study, central DG)

5.2.1.5.2 De-central DG scenario

The variation of diversity and coincident factor versus DG penetration can be seen in Figure 5.11 and Figure 5.12 respectively, for the de-central DG scenario. The general trend for diversity factor was to increase with the increase of DG penetration. It should be noted that diversity factor initially decreases, as seen in Figure 5.11. Diversity factor increased by approximately 6%. Coincident factor, being the inverse of diversity factor, varied inversely to diversity factor, as seen in Figure 5.12. The increase in diversity factor and decrease in coincident factor is due to the reduction in the load demand for the single customer with the DG source connected.

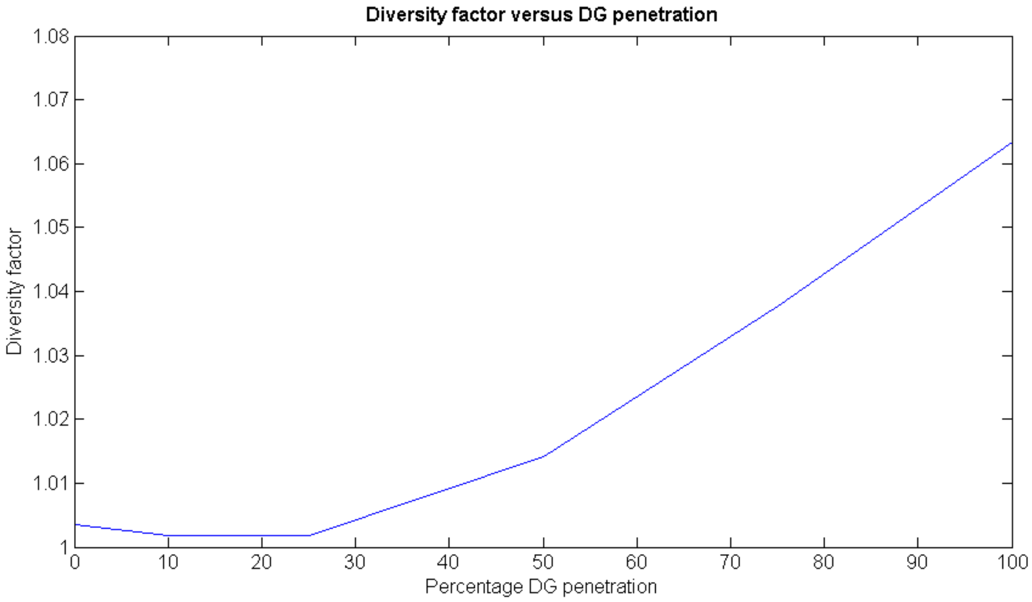

Figure 5.11. Diversity factor versus DG penetration (hypothetical study, de-central DG)

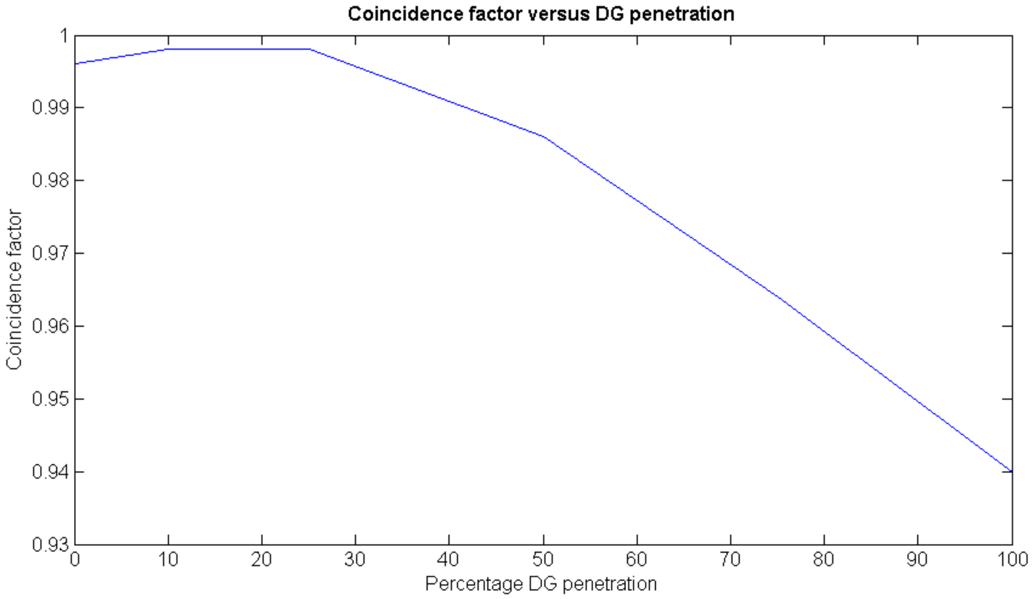

Figure 5.12. Coincidence factor versus DG penetration (hypothetical study, de-central DG)

5.2.1.6 Load diversity

5.2.1.6.1 Central DG scenario

Load diversity is a function of maximum coincident demand and maximum non-coincident demand. With the decrease in maximum coincident demand (as seen by the external network) there is an increase in load diversity with the increase in DG penetration. The impact of DG penetration on load diversity can be seen in Figure 5.13. The reason for the initially low load diversity was because all the load demand profiles for each of the customers were very similar, therefore the maximum coincident demand was similar to the sum of the individual maximum non-coincident demands. The difference between the maximum non-coincident demand and coincident demand was very small; however, this increased with the increase in DG penetration.

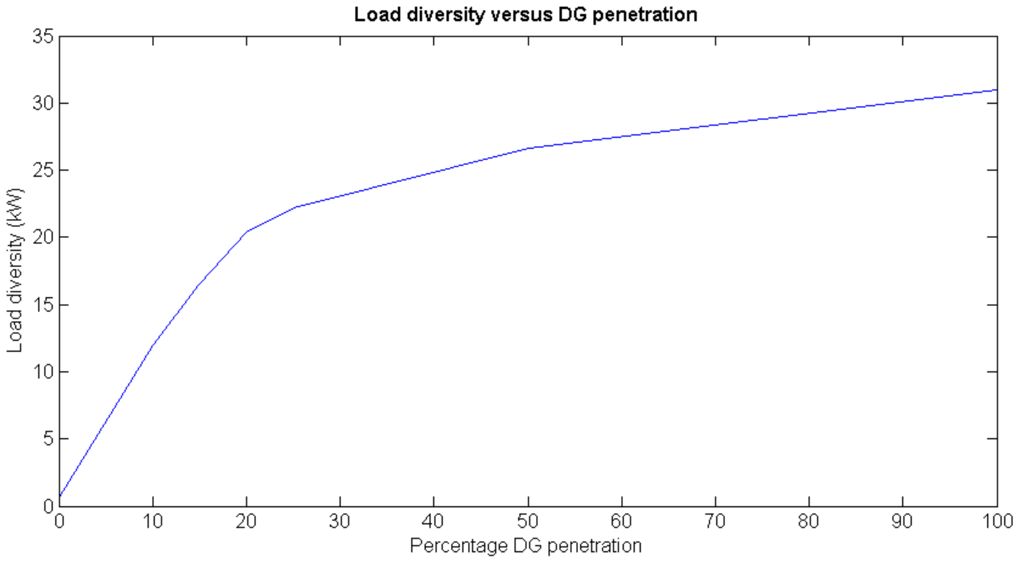

Figure 5.13. Load diversity versus DG penetration (hypothetical study, central DG)

5.2.1.6.2 De-central DG scenario

For the de-central DG scenario, at low-levels of DG penetration, load diversity was noted to slightly decrease with the increase in DG penetration. This can be seen in Figure 5.14. From Figure 5.14 it can be noted that for DG penetration levels above 25% there is an increase in in load diversity. This result is in agreement with the result seen for diversity factor.

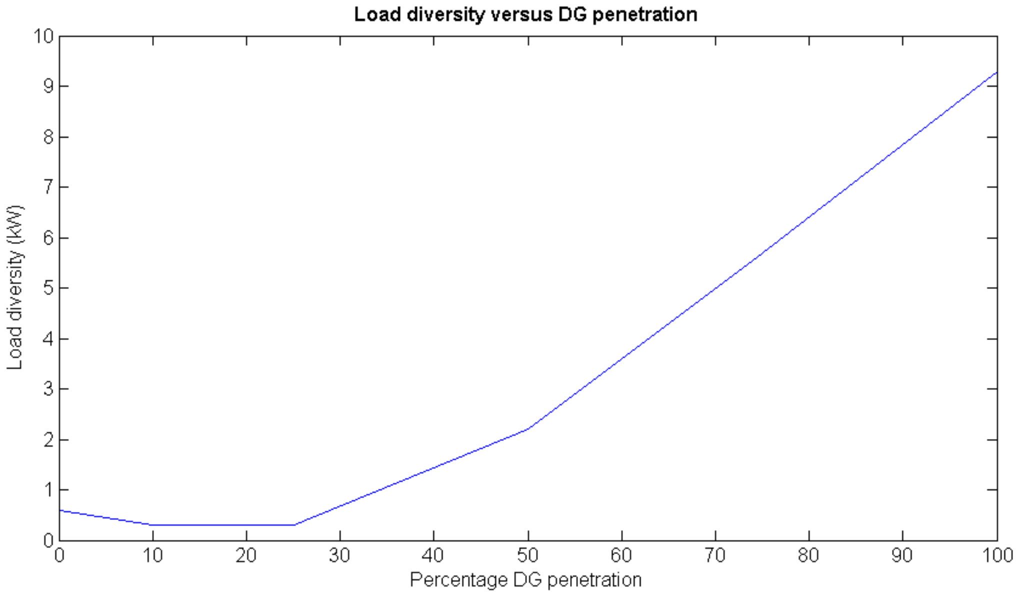

Figure 5.14. Load diversity versus DG penetration (hypothetical study, de-central DG)

5.2.1.7 Loss factor

5.2.1.7.1 Central DG scenario

Loss factor, being a function of load factor, varied in a similar manner. An initial increase for low levels of DG penetration and subsequent reduction for higher levels of DG penetration were observed. This can be seen in Figure 5.15. Loss factor decreased by approximately 59% from 0% DG penetration to 100% DG penetration. The initial increase in DG penetration is approximately 4%.

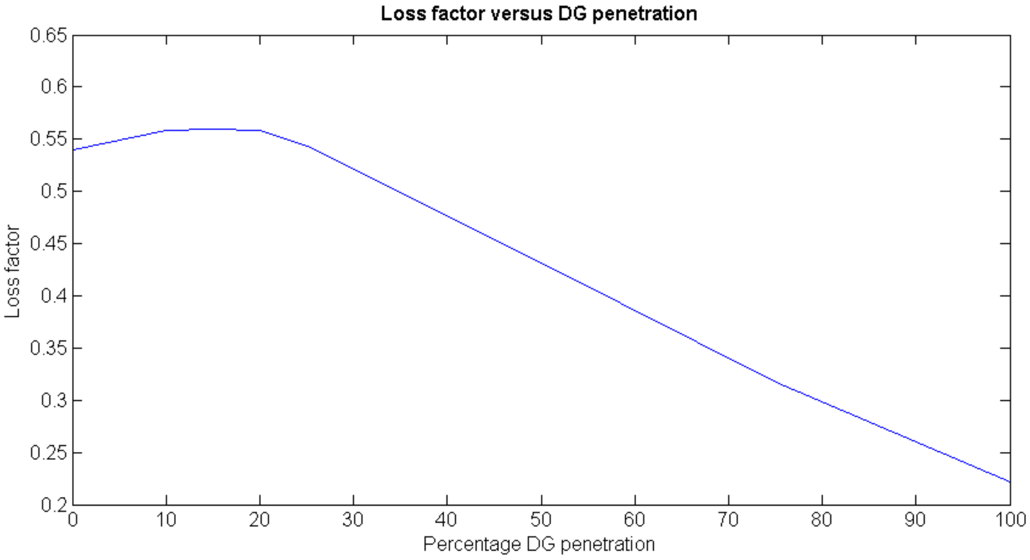

Figure 5.15. Loss factor versus DG penetration (hypothetical study, central DG)

5.2.1.7.2 De-central DG scenario

For the de-central DG scenario loss factor varied in a similar manner as load factor, as is expected. This can be seen in Figure 5.16 when compared to Figure 5.8. For this DG scenario, loss factor increased by approximately 4%, which is in line with the initial increase noted for the central DG scenario.

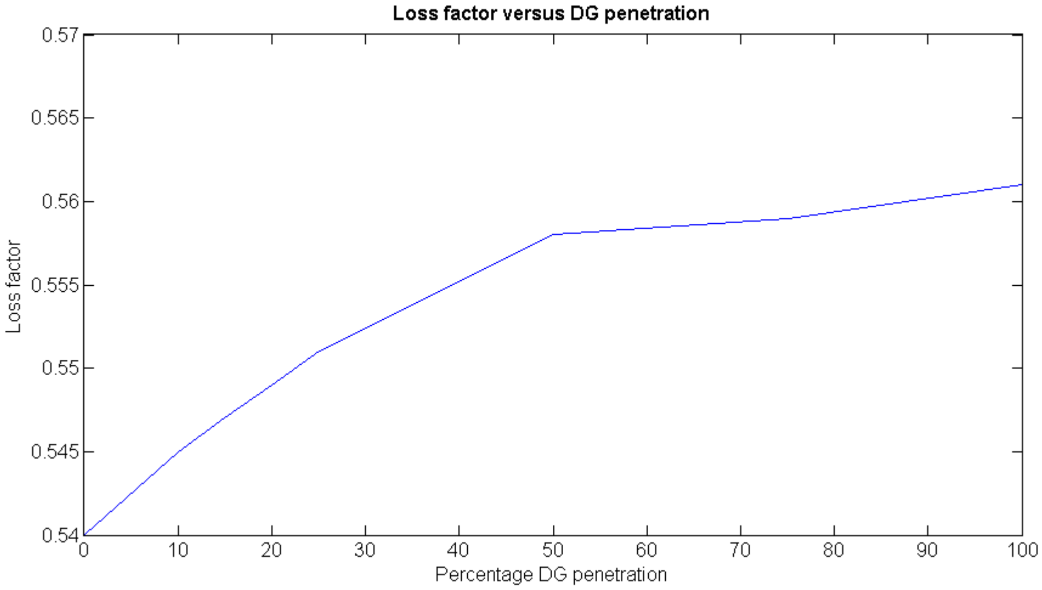

Figure 5.16. Loss factor versus DG penetration (hypothetical study, de-central DG)

5.2.2 Network parameters

The impact of varying levels of DG penetration on the supply voltage is discussed below, for both the central and de-central DG scenarios.

5.2.2.1 Central DG scenario

With the decrease in the maximum coincident demand, an increase in the minimum supply voltages can be expected. Minimum supply voltage occurs during peak demand periods. Supply voltage versus DG penetration can be seen in Figure 5.17. Although there is an improvement in minimum supply voltage, the increase was not significant for this specific case. This inherent effect of the introduction of a DG source does have benefits and could be used in situations where networks experience voltage problems.

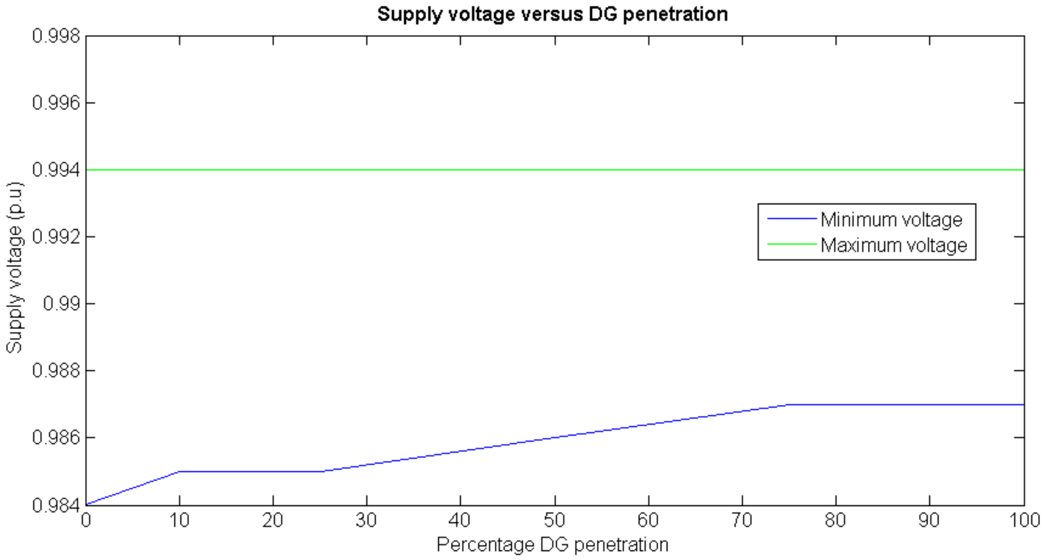

Figure 5.17. Minimum and maximum supply voltage versus DG penetration (hypothetical study, central DG)

5.2.2.2 De-central DG scenario

For the de-central DG scenario, the supply voltage magnitude at the supply transformer is less important and the supply voltage at the customer terminals is of greater importance. This is due to the fact that this parameter would be the most affected by the introduction of a DG source at this location. It is for this reason that the supply voltage at the customers' terminals were studied. The effect on supply voltage, for varying levels of DG penetration, can be seen in Figure 5.18. Similar to the central DG scenario, the effects are not significant.

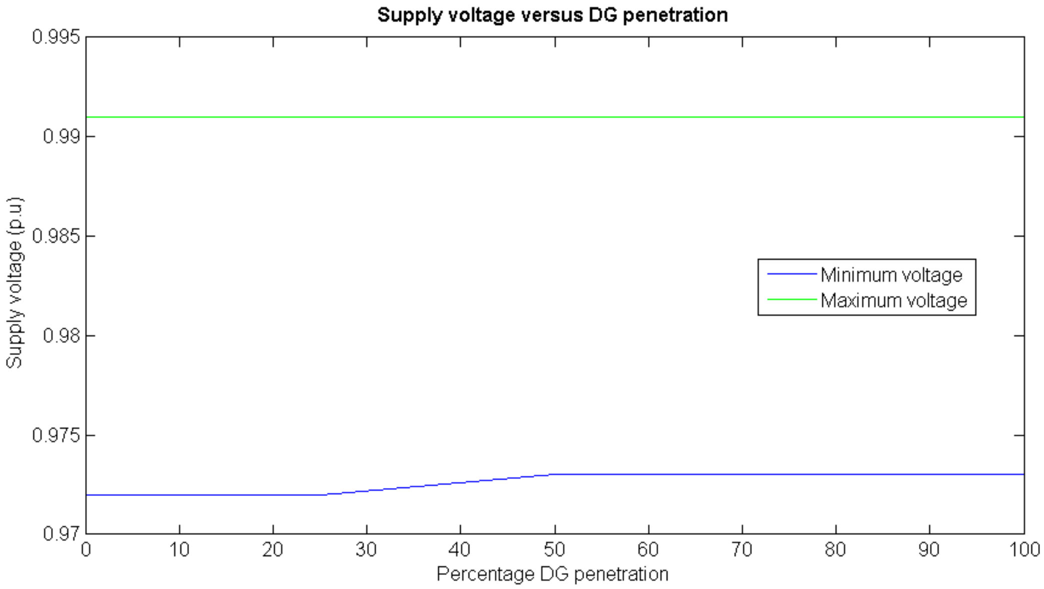

Figure 5.18. Minimum and maximum supply voltage versus DG penetration (hypothetical study, de-central DG)

5.3 CASE STUDY

A discussion of the results obtained for the case study for each of the load parameters and network parameters for the two different load demand scenarios (January 2017 and July 2016), as well as the different DG scenarios is given in the sections below.

5.3.1 Load parameters

The impact of varying levels of DG penetration on each of the load parameters under investigation are discussed below, for both the central and de-central DG scenarios, for the case study.

5.3.1.1 Coincident demand

5.3.1.1.1 Central DG scenario

The impact of varying levels of DG penetration on coincident demand for the central DG scenario, for both the January 2017 and July 2016 load demand scenarios, is seen in Figure 5.19. The variation in DG penetration from 0% to 100% (0kW to 110kW for January 2017 load demand scenario and 0 to 137kW for the July 2016 load demand scenario) of the maximum coincident demand, resulted in a reduction of the combined system coincident demand of approximately 44% for the January 2017 load demand scenario and 68% for the July 2016 load demand scenario. The percentage reduction in the coincident load demand is significantly larger compared to the hypothetical study. This would be due to the fact that there is more of an overlap between the solar PV generation profile and the load demand profile. The solar PV system therefore displaces more of the load demand when compared to the hypothetical study. This is because the load demand profile for the hypothetical study maintains a high demand for a longer period, before reducing in the evening, compared to the case study.

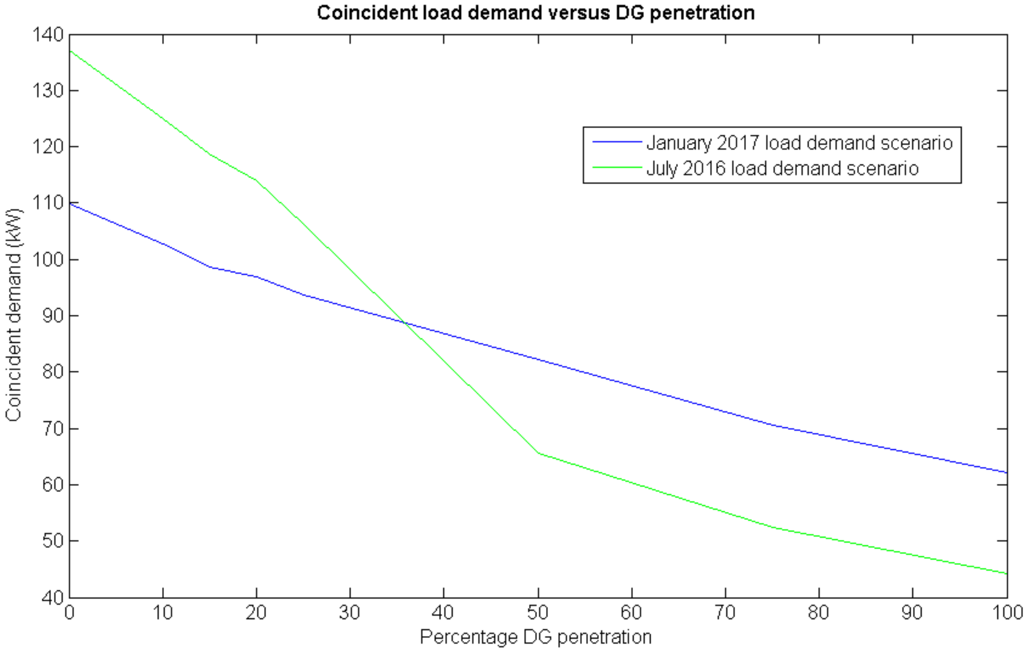

Figure 5.19. Coincident demand versus DG penetration (case study, central DG)

5.3.1.1.2 De-central DG scenario

The impact of varying levels of DG penetration on coincident demand for the de-central DG scenario is given in Figure 5.20. The variation in DG penetration from 0% to 100% (0kW to 24.54 kW installed capacity) of the maximum coincident demand resulted in a reduction of the combined system coincident demand of approximately 12% for the January 2017 load demand scenario and approximately 16% for the July 2016 load demand scenario. These percentage reductions are similar to the results obtained for the hypothetical study. This would be due to the DG source capacity being similar for both cases; 29.6kW for the hypothetical study and 24.54kW for the case study.

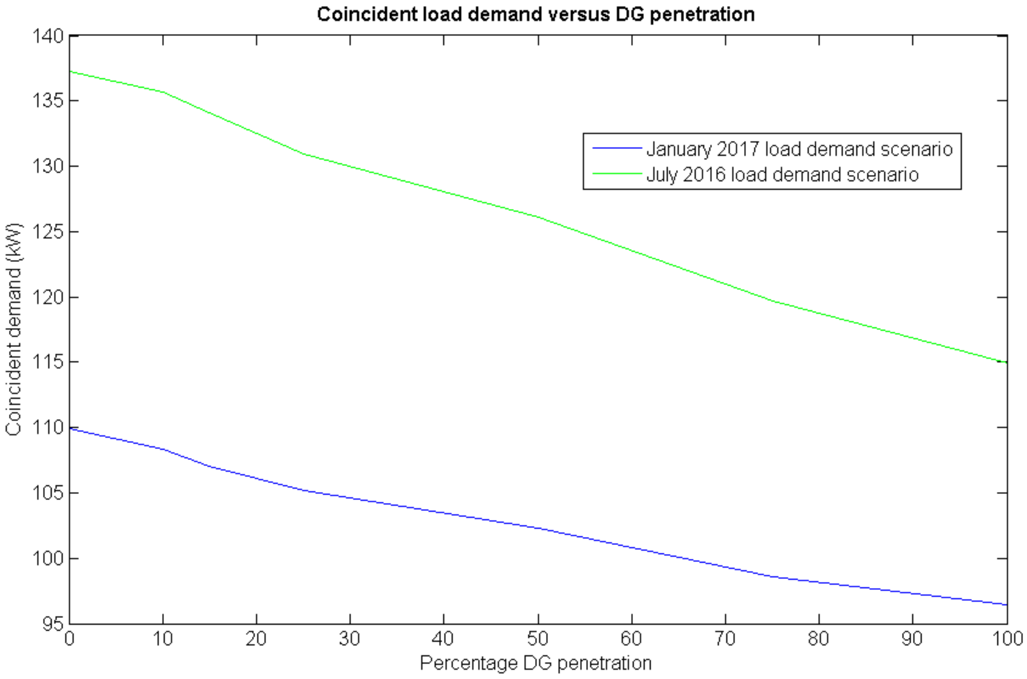

Figure 5.20. Coincident demand versus DG penetration (case study, de-central DG)

5.3.1.2 Demand factor

5.3.1.2.1 Central DG scenario

The variation of demand factor for increasing DG penetration levels for the central DG scenario is given in Figure 5.21. The increase in DG penetration from 0% to 100% of the maximum coincident demand resulted in a reduction of the combined system coincident demand of approximately 44% for the January 2017 load demand scenario and 68% for the July 2016 load demand scenario. The reduction in the demand factor noted in the case study is greater when compared to the hypothetical study. This is as a result of the greater reduction in coincident demand for the case study, as noted in section 5.3.1.1.

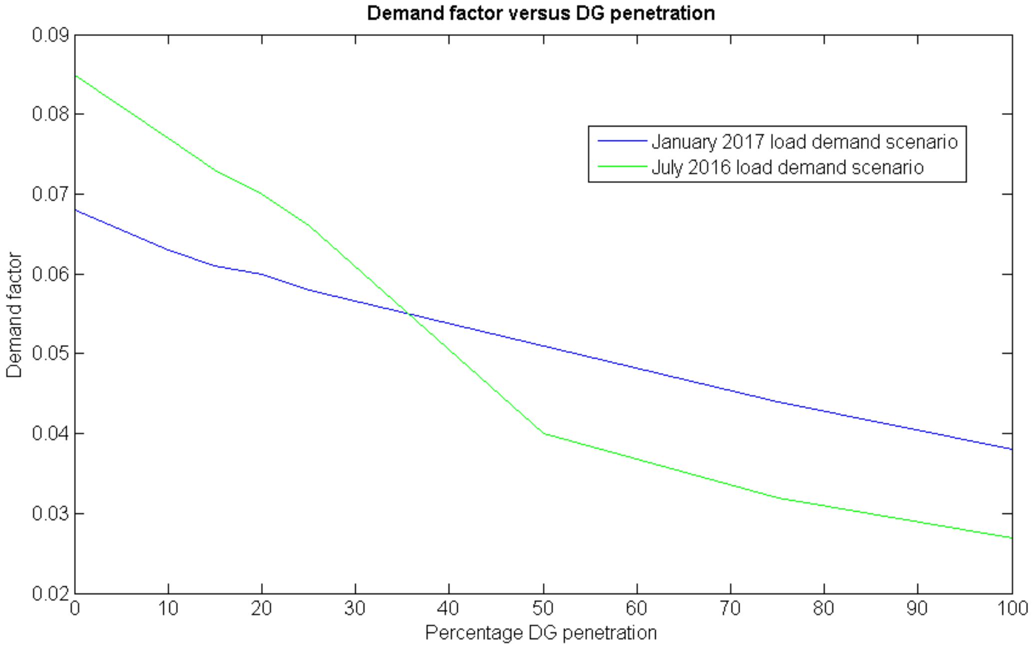

Figure 5.21. Demand factor versus DG penetration (case study, central DG)

5.3.1.2.2 De-central DG scenario

The variation of demand factor for increasing DG penetration levels for the central DG scenario is given in Figure 5.22. The increase in DG penetration from 0% to 100% of the maximum coincident demand resulted in a reduction of the combined system coincident demand of approximately 12% for the January 2017 load demand scenario and approximately 16% for the July 2016 load demand scenario. The reduction in the demand factor for this scenario aligns with the results obtained for the hypothetical study. This is because of the similar reduction in coincident demand for both the hypothetical study and case study (for this scenario) which is due to similar DG source capacities being integrated.

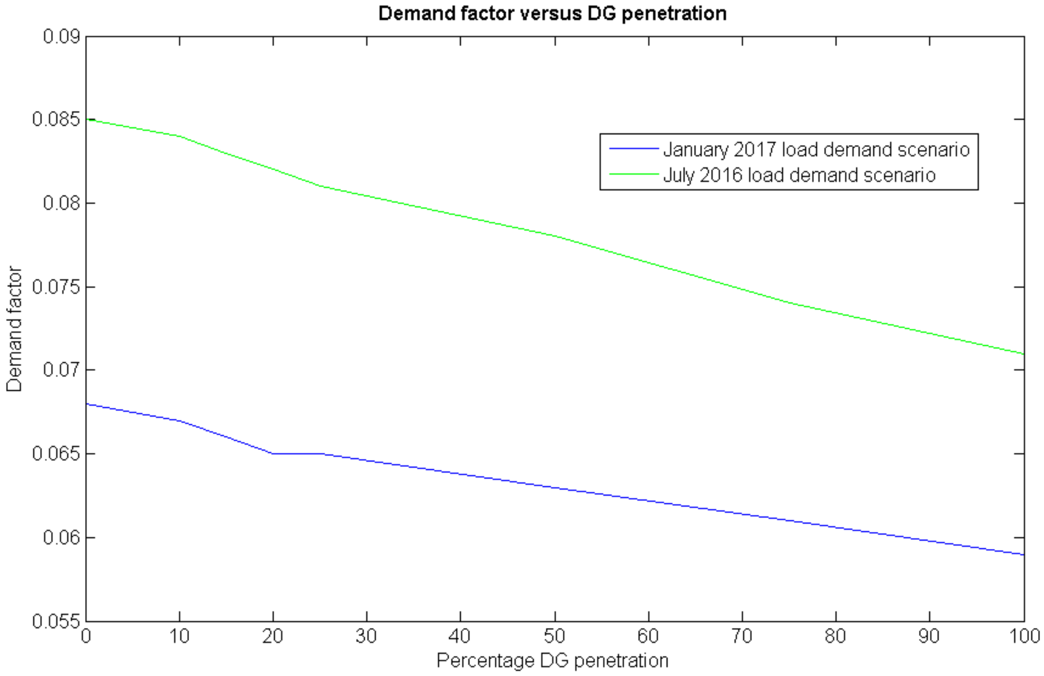

Figure 5.22. Demand factor versus DG penetration (case study, de-central DG)

5.3.1.3 Utilisation factor

5.3.1.3.1 Central DG scenario

The reduction in the transformer utilisation factor (1,000kVA transformer capacity) is approximately 45% for the January 2017 load demand scenario and 54% for the July 2016 load demand scenario, as noted in Figure 5.23. The reduction in utilisation factor is greater than the reduction noted in the hypothetical study. This is again because of the lower reduction in coincident demand for the hypothetical study compared to the case study.

The utilisation factor with the integration of a DG source with 100% load penetration significantly impacts the utilisation factor of the main supply transformer. Although the base case utilisation factor of the supply transformer is low (approximately 14% and 18% for January 2017 and July 2016 load demand scenarios respectively), the integration of the DG source with high penetration levels, in some cases, could justify the use of a smaller capacity transformer to supply the load demand.

If this were to be the approach followed in selecting transformer capacity, probabilistic analyses would need to be conducted where load demand requirements and reliability and availability of generation would need to be considered. This would need to be done to ensure that the transformer is not overloaded for long periods of time when there is no DG output. If this were the case, other methods such as load shedding or shifting might have to be implemented.

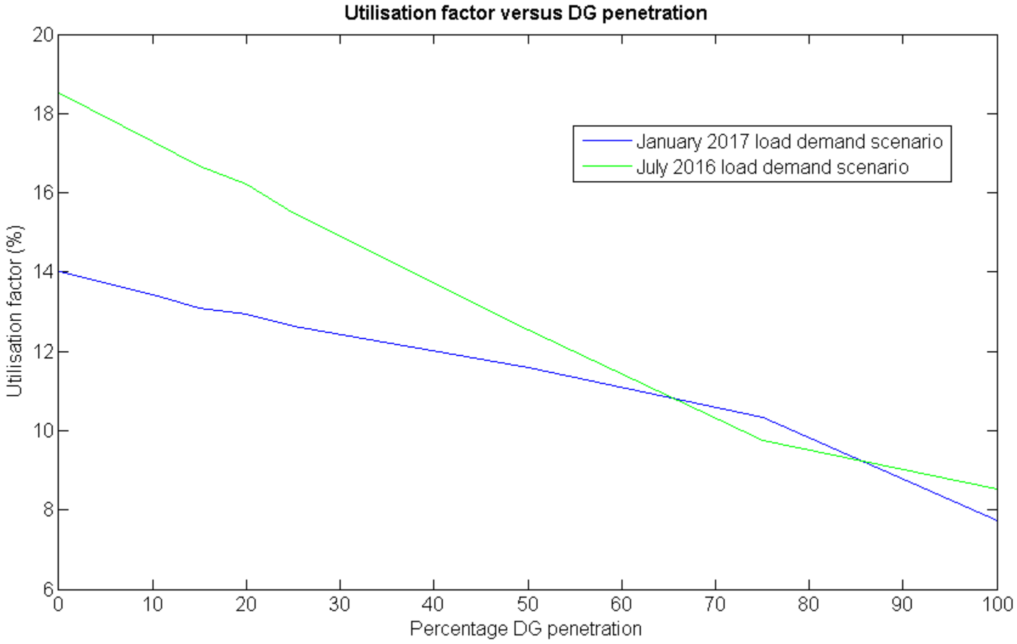

Figure 5.23. Utilisation factor versus DG penetration (case study, central DG)

5.3.1.3.2 De-central DG scenario

The reduction in the transformer utilisation factor for the de-central DG scenario is approximately 8% for the January 2017 load demand scenario and 12% for the July 2016 load demand scenario, as noted from Figure 5.24. The percentage reduction in the de-central DG scenario for the case study is aligned with the results obtained in the hypothetical study. Again, this is because of the similar reduction in coincident demand for both cases due to similar DG source capacities being integrated.

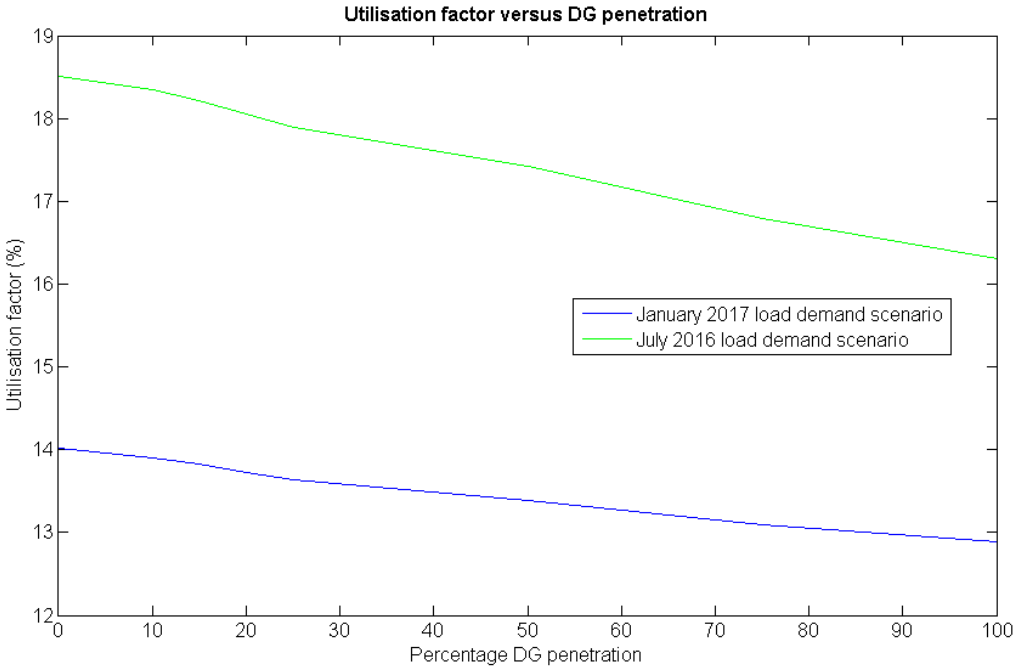

Figure 5.24. Utilisation factor versus DG penetration (case study, de-central DG)

5.3.1.4 Load factor

5.3.1.4.1 Central DG scenario

The variation of load factor with respect to DG penetration is given in Figure 5.25, for both load demand scenarios. Load factor did not monotonically increase or decrease with the increase in DG penetration for the July 2016 load demand scenario. For DG penetration levels between 0% and 50%, load factor increased. Beyond 50% DG penetration, load factor decreased. The results obtained for the variation of load factor for the July 2016 load demand scenario are more aligned with the results obtained for the hypothetical study than the January 2017 case. The load factor initially increased and then decreased after a certain DG penetration level. The increase in load factor is approximately 25% compared to the 2% increase noted for the hypothetical study. The larger variation in load factor for the case study is as a result of the greater reduction in coincident demand with increasing DG penetration.

For the January 2017 load demand scenario, load factor was noted to monotonically decrease with increase in DG penetration. This result is not aligned with the results noted for the hypothetical study as well as the July 2016 load demand scenario.

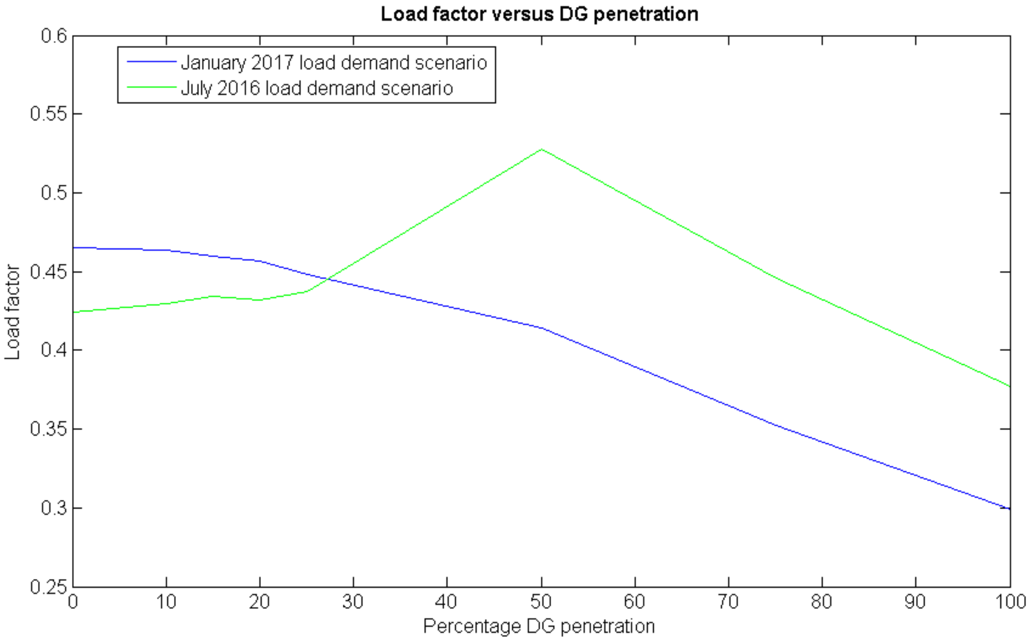

Figure 5.25. Load factor versus DG penetration (case study, central DG)

5.3.1.4.2 De-central DG scenario

Load factor versus percentage DG penetration for the de-central DG scenario is given in Figure 5.26. It can be noted that load factor continually increases with the increase in DG penetration for the July 2016 load demand scenario. For the January 2017 load demand scenario, the load factor only increases up to 15% DG penetration, and decreases thereafter.

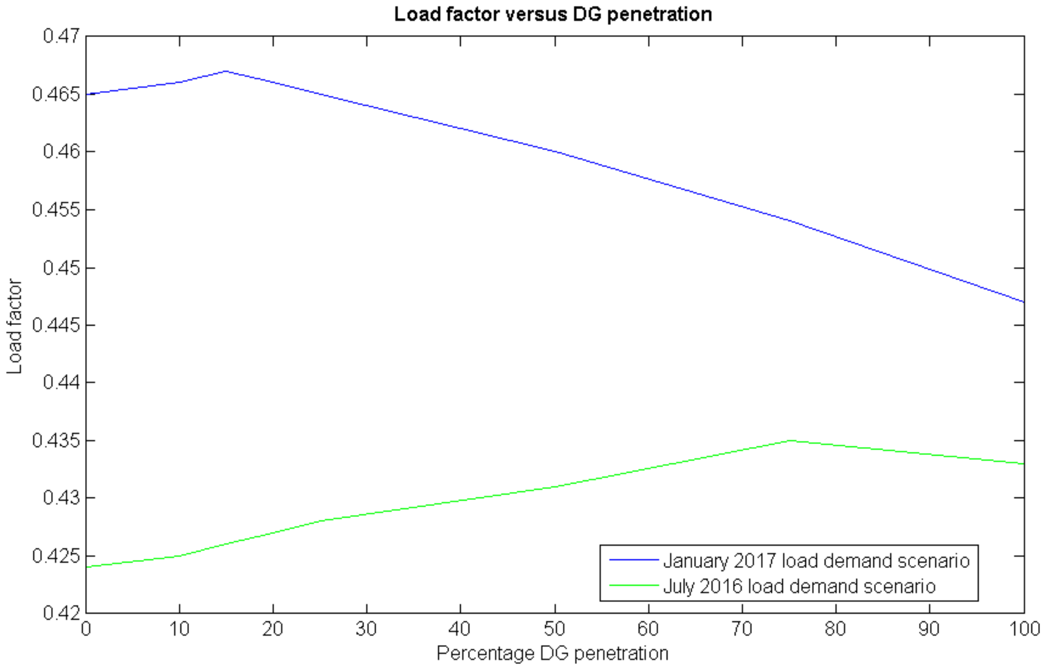

Figure 5.26. Load factor versus DG penetration (case study, de-central DG)

The results obtained for the July 2016 load demand scenario align with the results for the hypothetical study. For the January 2017 load demand scenario, load factor increases up to 10% DG penetration, after which it decreases. This differs from the hypothetical study due to the average load over the entire day exhibiting a greater reduction than the coincident demand, resulting in the decrease in load factor. This result indicates that a certain percentage of DG penetration results in an increase in load factor, for commercial retail loads.

5.3.1.5 Diversity and coincidence factor

5.3.1.5.1 Central DG scenario

The impact of increasing DG penetration on diversity factor for both load demand scenarios can be seen in Figure 5.27. Diversity factor increased with the increase of DG penetration. This is due to the reduction in the total system coincident demand, as seen in Figure 5.19, as there was no reduction in maximum non-coincident demand of each customer. The maximum non-coincident demand of each customer is unchanged as there is no effect of the DG source on the customer load demand requirement. Coincident factor, being the inverse of diversity factor, varied inversely, as seen in Figure 5.28. Diversity factor increased by approximately 77% for the January 2017 load demand scenario and 211% for the July 2016 load demand scenario. The increase in diversity for the case study is significantly larger than for the hypothetical study. This is as a result of the larger decrease in coincident demand for the case study.

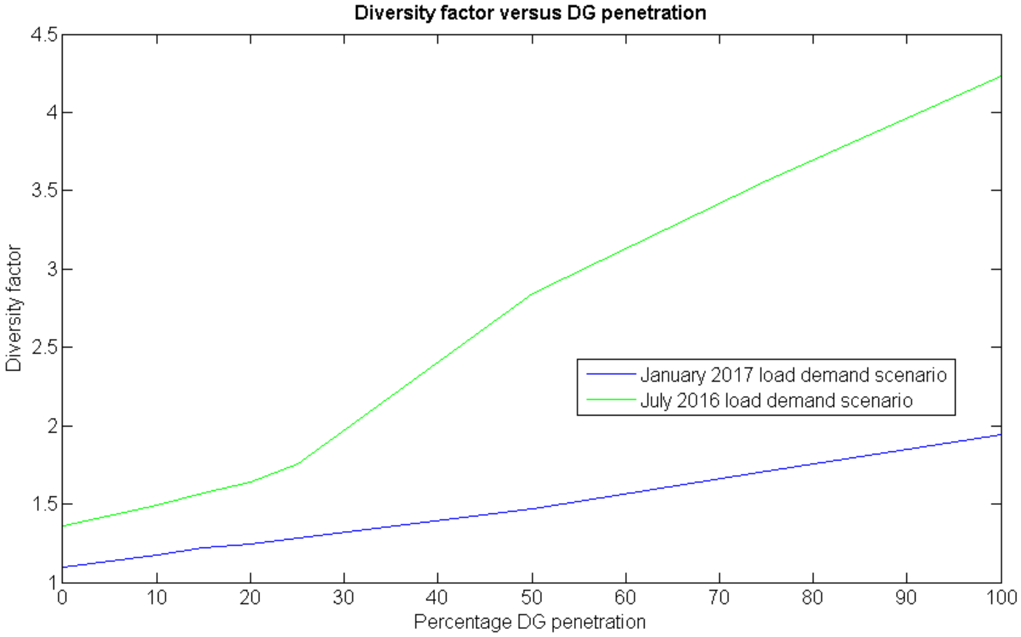

Figure 5.27. Diversity factor versus DG penetration (case study, central DG)

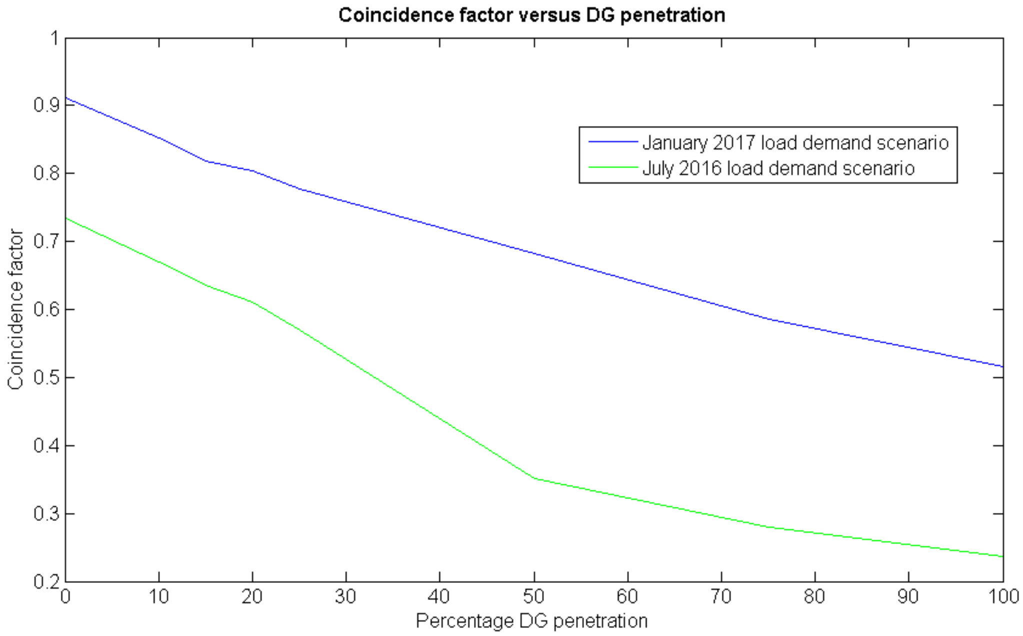

Figure 5.28. Coincidence factor versus DG penetration (case study, central DG)

5.3.1.5.2 De-central DG scenario

Diversity and coincident factor versus increasing DG penetration can be seen in Figure 5.29 and Figure 5.30 respectively. For the de-central DG scenario, the impact on diversity and coincidence factor are seen to be fairly small compared to the central DG scenario. This is due to the marginal decrease in the maximum coincident demand, which is as a result of relatively small DG capacity introduction, when compared to the total load demand. Diversity factor increased by 14% and 19% respectively for the January 2017 and July 2016 load demand scenarios. These results agree with the results obtained for the hypothetical study, although the increase in diversity factor for the hypothetical study was less. This again would be as a result of the lower reduction in coincident demand.

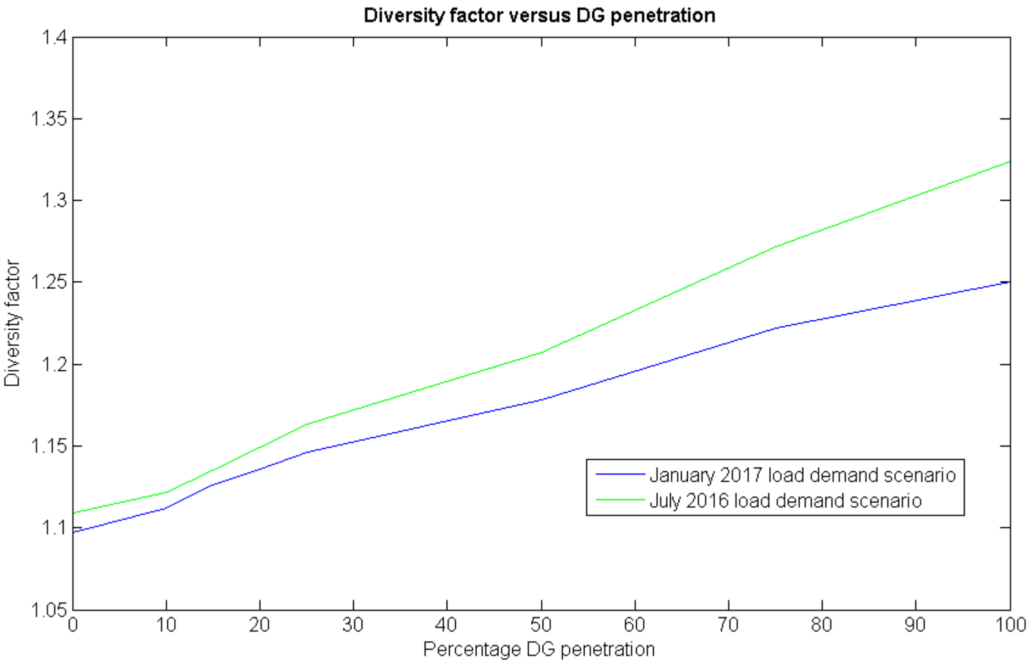

Figure 5.29. Diversity factor versus DG penetration (case study, de-central DG)

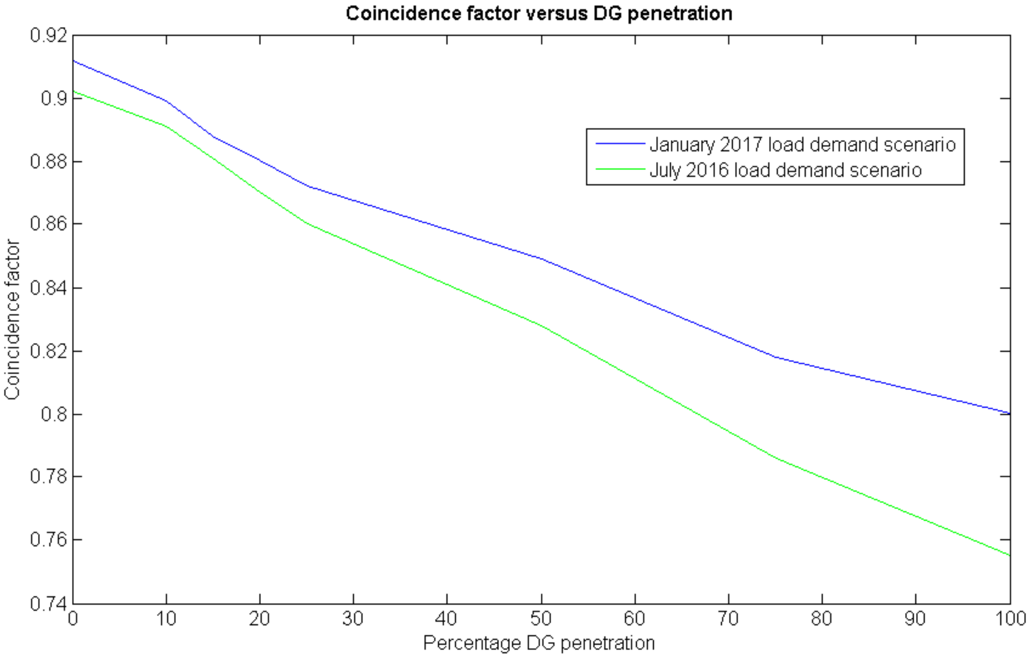

Figure 5.30. Coincidence factor versus DG penetration (case study, de-central DG)

5.3.1.6 Load diversity

5.3.1.6.1 Central DG scenario

Load diversity is a function of maximum coincident demand and maximum non-coincident demand. With the decrease in the maximum coincident demand (as seen by the external network) there is an increase in load diversity with the increase of DG penetration. This can be seen in Figure 5.31 for both the January 2017 and July 2016 load demand scenarios. The load diversity for the January 2017 load demand scenario increased by approximately 48kW and approximately 93kW for the July 2016 load demand scenario. Load diversity therefore increased by approximately 451% and 189% for the January 2017 and July 2016 load demand scenarios respectively.

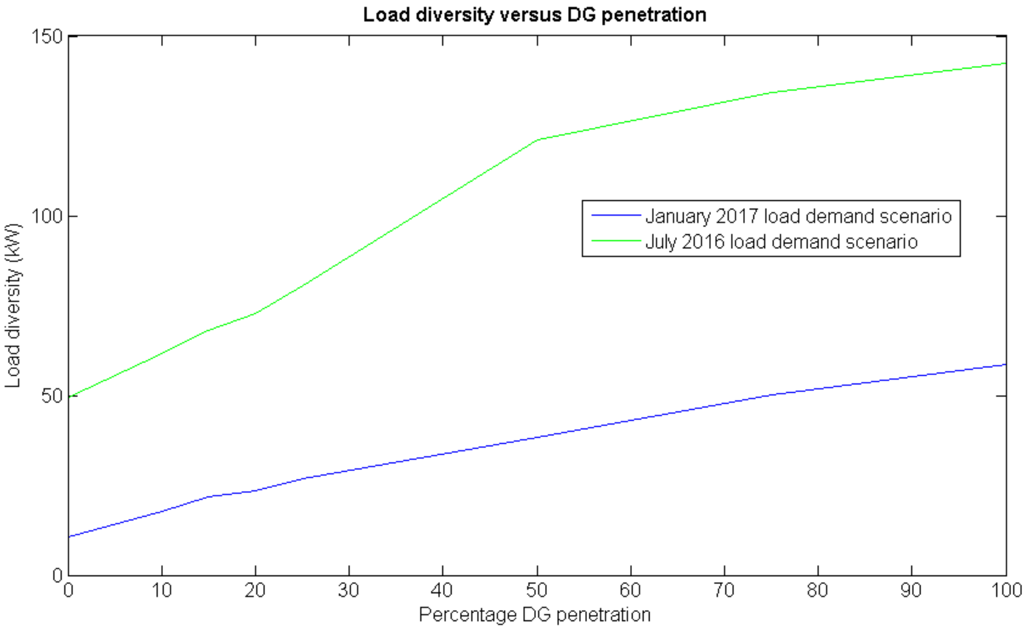

Figure 5.31. Load diversity versus DG penetration (case study, central DG)

5.3.1.6.2 De-central DG scenario

The same trend as noted for the central DG scenario, with regards to the increase in load diversity with increasing DG penetration, can be noted for the de-central DG scenario, as seen in Figure 5.32. The increase in load diversity is once again due to reduction in the coincident load demand. Load diversity increased by approximately 127% and 149% for the January 2017 and July 2016 load demand scenarios respectively.

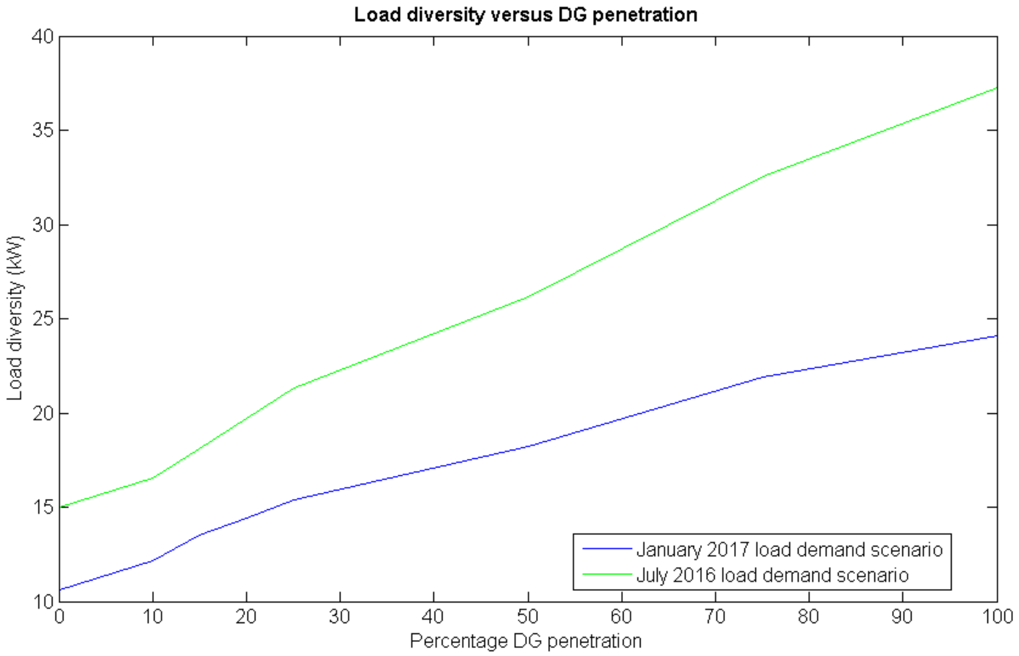

Figure 5.32. Load diversity versus DG penetration (case study, de-central DG)

5.3.1.7 Loss factor

5.3.1.7.1 Central DG scenario

Loss factor, being a function of load factor, varied in a similar manner as described in section 5.3.1.4. The variation of loss factor for increasing DG penetration for the January 2017 and July 2016 load demand scenarios can be seen in Figure 5.33. The magnitude of the variation in load factor for varying DG penetration levels is greater than the magnitude variation for load factor. This is due to the relationship between load factor and loss factor, as given in Table 3.6.

Loss factor decreased by approximately 52% for the January 2017 load demand scenario, whereas loss factor decreased by approximately 18% for the July 2016 load demand scenario. The difference between the decrease in loss factor for the two load demand scenarios is because of the difference in reduction of the coincident demand for each scenario. The percentage increase for loss factor was larger for the case study compared to the hypothetical study. This is as a result of the larger decrease in coincident demand which affects load factor and therefore loss factor.

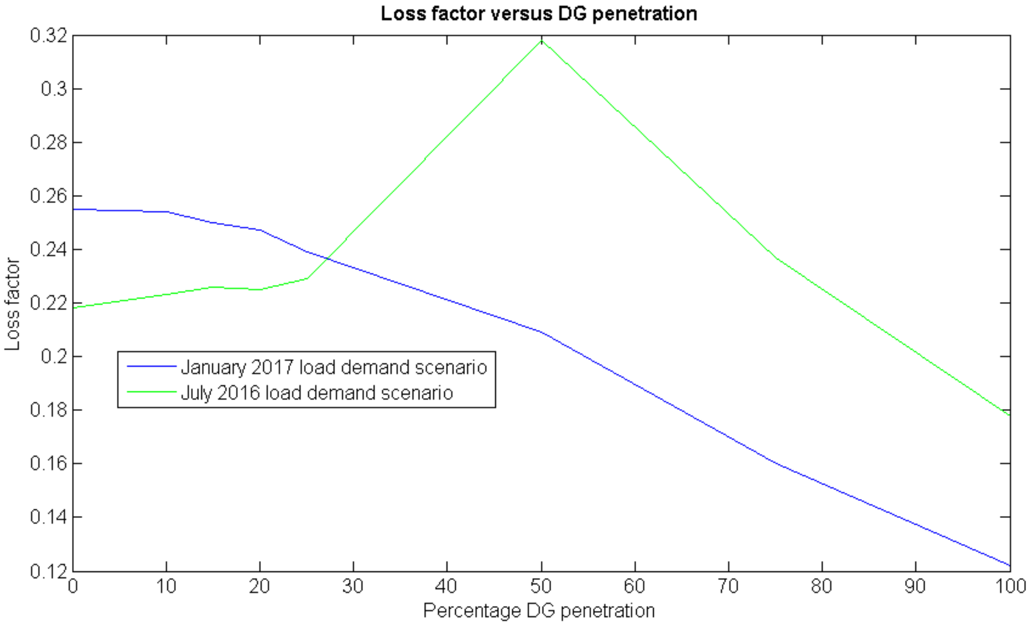

Figure 5.33. Loss factor versus DG penetration (case study, central DG)

5.3.1.7.2 De-central DG scenario

Loss factor, being a function of load factor, varied in a similar manner as described in section 5.3.1.4. The variation in loss factor for the de-central DG scenario can be seen in Figure 5.34. For the January 2017 load demand scenario, loss factor decreased by approximately 6%, which is not in line with the results obtained for the hypothetical study. This is as a result of the increase in load factor noted in section 5.3.1.4. For the July 2016 load demand scenario, loss factor increased by approximately 4% which is in line with the hypothetical study.

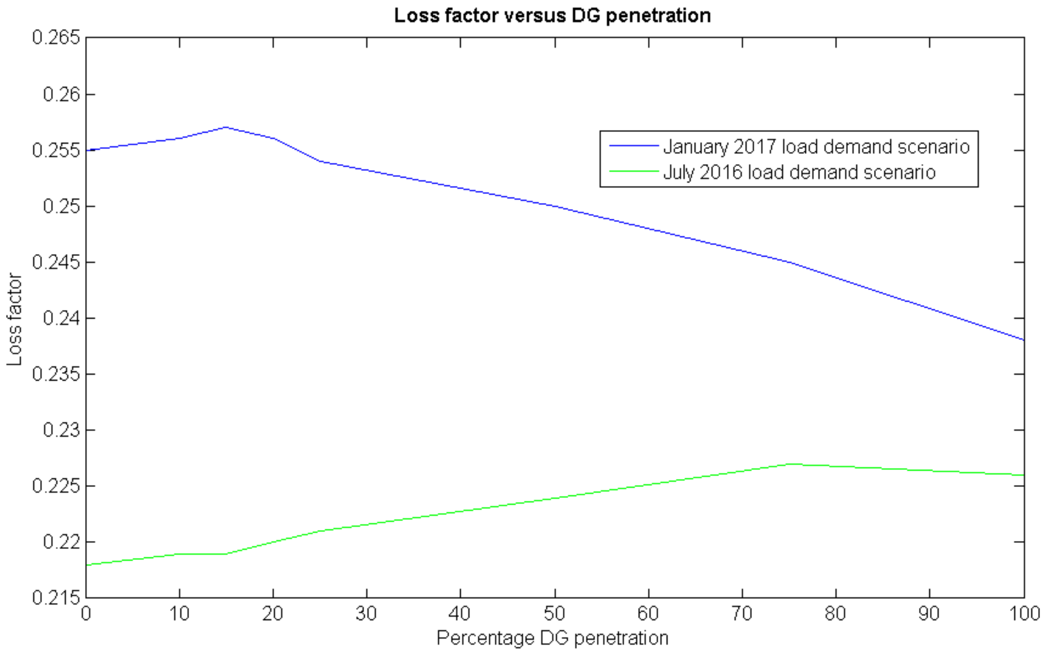

Figure 5.34. Loss factor versus DG penetration (case study, de-central DG)

5.3.2 Network parameters

5.3.2.1 Central DG scenario

With the decrease in the coincident load demand, an increase in supply voltage is expected. The minimum supply voltage occurs during peak load demand, as has been noted for the other scenarios. The impact of DG penetration on supply voltage at the low-voltage terminals of the supply transformer can be seen in Figure 5.35 for the January 2017 and July 2016 load demand scenarios. Although there is an improvement in voltage supply, the increase was not significant for this case. The largest improvement can be seen in the minimum supply voltage for the July 2016 load demand scenario.

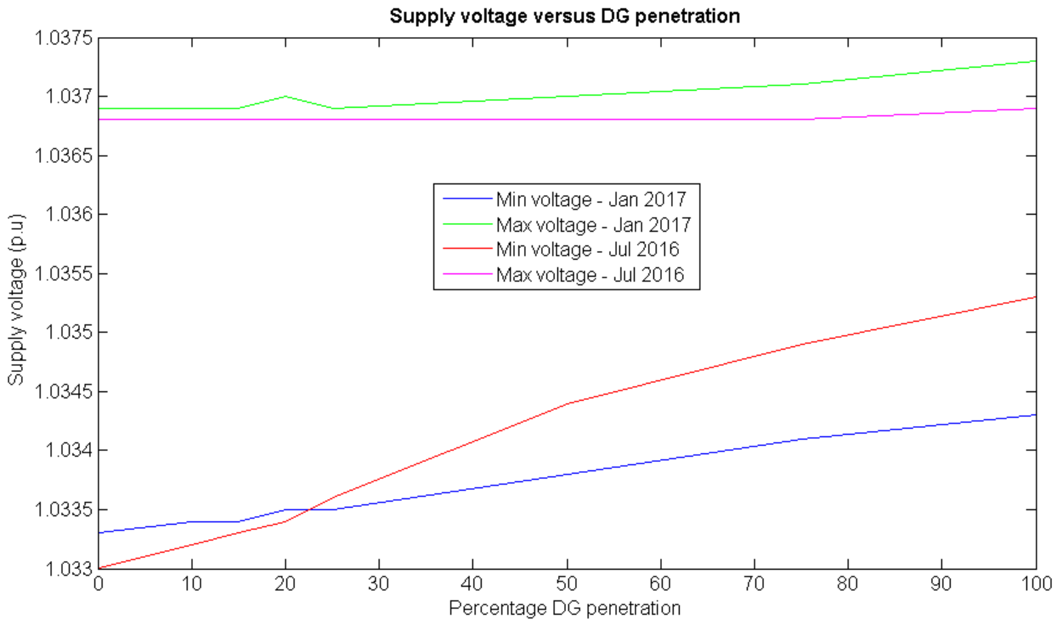

Figure 5.35. Minimum and maximum supply voltage versus DG penetration (case study, central DG)

5.3.2.2 De-central DG scenario

For the de-central DG scenario, the variation in supply voltage at DB-M3 for the January 2017 and July 2016 load demand scenarios can be seen in Figure 5.36. As noted for the previous results, the improvement in the minimum voltage is not significant, although the largest improvement can be noted for the July 2016 load demand scenario. This is due to this scenario having higher load demands and therefore low voltages at DB-M3. This can be noted by comparing the minimum voltages in Figure 5.36.

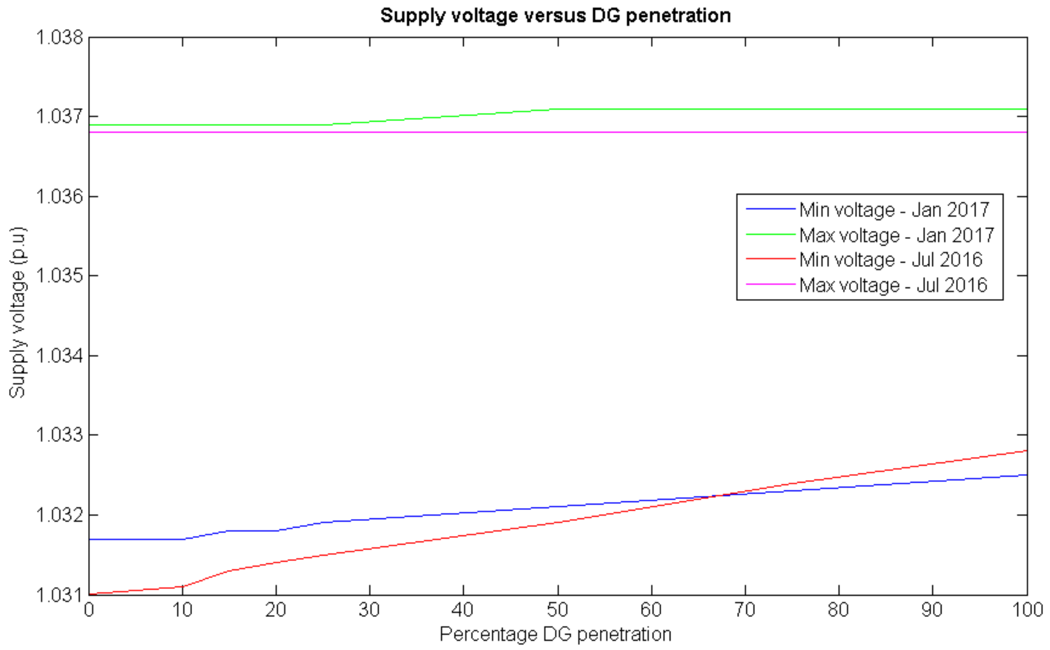

Figure 5.36. Minimum and maximum feeder voltage versus DG penetration (case study, de-central DG)

5.4 SUMMARY

From the results obtained for the case study, the impact of varying levels of DG penetration on the various load parameters, mostly aligns with the results obtained for the hypothetical study. There was slight misalignment between the results obtained for load and loss factor. This can be attributed to the difference in the load demand profiles used for the two studies (assumed versus actual) as well as different load demand scenarios. Similar trends for increase in DG penetration were present for these factors (load and loss factor) in some of the load demand scenarios, such as the initial increase and then decrease after a certain DG penetration percentage.

The impact of low levels of DG penetration on load parameters was not significant; however, an effect on load parameters could be noted. The load parameters that were the most effected at low-levels of DG penetration were coincident demand, demand factor, utilisation factor, diversity factor, coincident factor and load diversity.

These are all parameters that are related to coincident demand. Factors such as load factor and loss factor were only marginally affected at low DG penetration levels. Load and loss factor were most significantly affected at high DG penetration levels. All load parameters were, however, significantly impacted at high DG penetration levels.

The most noticeable impact on load parameters was seen in the central DG scenario. This is due to the large DG system capacity integrated, which affects coincident demand more significantly when compared to the de-central DG scenario. The load demand profile is therefore impacted significantly (for the central DG scenario) and results in the greatest variation in load parameters. A variation in load parameters was noted for the de-central DG scenario; however, due to the smaller installed system capacities the effect was not as large as for the central DG scenario.

Network parameters such as supply voltage were only slightly improved at high DG penetration levels. Although only slightly impacted, the effect of increasing DG penetration to improve supply voltage could be noted and is beneficial to networks that experience voltage problems, such as under-voltage. This effect could not be accurately modelled as information or data pertaining to supply voltage within the network or upstream network information was unavailable for the study.

CHAPTER 6 CONCLUSION

With the worldwide focus on becoming more sustainable and environmentally conscious, the uptake of renewable energy DG sources is increasing. The studies conducted in this research topic have proven that introducing DG in low-voltage networks, such as commercial retail reticulation networks, does affect the load parameters. It is therefore imperative to understand what the effects of integrating DG is on load parameters, to ensure that future network planning and design is done successfully, safely and effectively. As one of the key input parameters into network planning and network design is the load parameters, for which the network should service.

Commercial retail reticulation networks typically form part of a larger power system. Understanding how load parameters are altered from the introduction of DG aids in successful and efficient network planning and design that is done at a distribution, sub-transmission or even transmission power system level. The knowledge gained by understanding how the load parameters are affected by the introduction of DG can ensure that future load forecasting is done accurately.

Determining the effect of DG on load parameters such as coincident demand, utilisation factor, load factor, diversity factor, load diversity and loss factor is important and was determined by the study. Understanding how these load parameters are altered from the integration of DG provides insight to assist in planning and design of reticulation networks, to service commercial retail customers that contain varying levels of DG penetration.

When integrating DG into reticulation networks there are many technical issues that need to be considered. Two such examples are ensuring that the thermal rating of equipment is not exceeded and voltage rise is limited to within specific tolerances. These issues did not occur in this study.

The variation between the base case load parameters (no DG present) and altered load parameters for varying levels of DG penetration were analysed, and based on solar PV DG source. It can be seen from the results that the introduction of DG into a commercial retail network can significantly alter load parameters of the composite load, as seen by the external network, at high penetration levels. Load parameters were found to be altered from the introduction of DG and varied as a function of DG penetration.

The load parameters which decreased with an increase in DG penetration were coincident demand, demand factor, utilisation factor and coincidence factor, for both the central DG scenario and de-central DG scenario. Load parameters which were noted to increase with the increase in DG penetration were diversity factor and load diversity. Load and loss factor (loss factor being a function of load factor) was not monotonic, as was noted for the other load parameters.

In both DG scenarios (central and de-central) load and loss factor were noted to initially increase with DG penetration until a certain percentage penetration, thereafter a decrease was noted. The load and loss factor parameters for the January 2017 load demand scenario, for the case study, did not exhibit such behaviour. These parameters were noted to continually decrease with the increase in DG penetration. This is as result of a greater decrease in average load compared to the coincident demand. For this demand scenario, a solar PV DG system does not have the ability to reduce the maximum coincident demand that occurs later in the day due to reduced generation output in the late afternoon or evening.

The results obtained are also in agreement with the hypothesised results and confirmed by both the hypothetical study and the case study, based on actual load demand data and reticulation network information.

The overlap between the load demand profile and DG source generation profile plays an important role in determining how the different load parameters are effected. The greater the overlap, the great the impact will be. A typical commercial load demand profile coincides with a solar PV DG source. At high penetration levels, load parameters are therefore significantly affected. As the load demand profile and generation profile of the DG source play an important role in the analysis, any changes to one of the two would result in different effects on load parameters. To accurately determine the effect of varying levels of DG penetration on load parameters would require a case by case analysis.

Coincident demand, diversity factor and load factor play an important role in the design of reticulation networks suitable to supply the relevant load demand requirements. The results obtained indicate that there is a need to re-assess the suitability of existing planning and design procedures or standards for reticulation networks due to the altering of load and network parameters from the introduction of DG sources to commercial retail reticulation networks.

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