Tier 1/IFIXX:

Voltage Control Options on Low Voltage Busbars

Version: 2.0

Report title:

Solutions for voltage control options at LV busbars

Executive Summary

The aim of the voltage control options project is to deploy a range of voltage management methods and techniques across several distribution substations which will be assessed in terms of their ability and effectiveness to regulate line voltage in real-time in a safe and economical manner. In addition, the ability to correct poor power factor and the feeder power quality will also be assessed.

This document describes the impact of various voltage control devices on the voltage regulation and existing network capacities. The scenarios with and without the PV penetration are both considered. The result shows that the voltage control devices investigated and trialled in this project will not only help network operators to maintain the voltage level, and also significantly increase their network capacity.

This report also gives the recommendation of voltage control options in the existing distribution network, in order to improve the power quality and voltage regulation with increasing amount of distributed generation connected.

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1. Introduction

In order to reduce the level of carbon dioxide (CO_2) emission with the increasing demand of electrical energy, the UK government is targeting that 15% of energy should be generated from renewable resources in 2020 and achieve the carbon reduction of 80% by 2050 [1]. This target of carbon reduction means that there will be a significant increase of distributed generations in the low voltage network between now and year 2050, such sharp increase will introduce a challenge for network operators to maintain the voltage regulation and power quality in the distribution networks. In addition, the increasing energy demand with introduction of new forms of loads such as electric vehicles and heat pumps could impose a risk for the network to exceed the their total capacity.

When the distributed generation sources are connected directly into the LV network at periods of low demand, could cause voltage rise in the network, forcing the voltage to exceed the regulated voltage level. Hence this issue will limit the amount of distributed generation into the network.

Several voltage control options are considered in this report in terms of their ability to increase the network capacity and maintain the voltage level. Devices investigated include capacitor bank, distribution transformer with On Load Tap Changer (OLTC) and energy storage. Several case studies were carried out in order to maintain the feeder voltage within the +10% and -6% statutory limits. The simulation models of six trialled network including Dunton Green, Edge Green Lane, Greenside, Howard Street, Leicester Ave and Landgate were used. The network capacity and voltage regulation control for each network were investigated.

2. Network voltage regulation studies

2.1 Network assumptions

Several case studies are carried out by selecting six network feeders, each from the six trialled networks. The feeder selected from each network either has the most number of loads or longest cable distance, and each feeder has a large proportion of PV connected. The details of the feeders selected are shown in Table 1. The aim of this study is to analyses the effectiveness of voltage control devices under several different network conditions, hence some of the network assumption may not reflect the current network conditions, however it is very important to predict different network and load scenarios so that it might be the case suitable for future network conditions.

The six selected feeders are listed in Table 1 along with the maximum PV rating and total load demand used. The load demand of 1.5kW per customer is used to calculate the total load demand. The total PV ratings are significantly increased in order to create a scenario when there is a significant voltage rise effect in the network.

Table 1: Increased total ratings of the PV and total maximum load demand

Type	Total PV rating (kW)	Total load demand (kW)
Dunton Green 260055770	157.5	105
Howard Street 216044696	576	180
Landgate 63057172	324	150
Leicester 69051565	330	123
Greenside 527400008	456	223.5
Edge Green 66074753	396	234

2.2 Network voltage regulation studies using OLTC

As shown from Table 1, the PV ratings are at their maximum possible, this is the scenario when nearly every household on network has PV connected, as expected there will be voltage rise issues on the network, therefore it is important to deploy transformer with OLTC to step down the voltage at the substation so that the end of feeder voltage still maintain within the statutory limits.

In Figure 1(a), the voltage profile without PV generations is shown and the voltage drop is due to the maximum load demand only. The different lines show different voltages from different phases. Figure 1(b) shows the network voltage profiles with the PV connected. Comparing these two network conditions, it is clear that with the PV penetration in the network will increase the voltage per phase to as much as 10% at end of the feeder with 0% tapping.

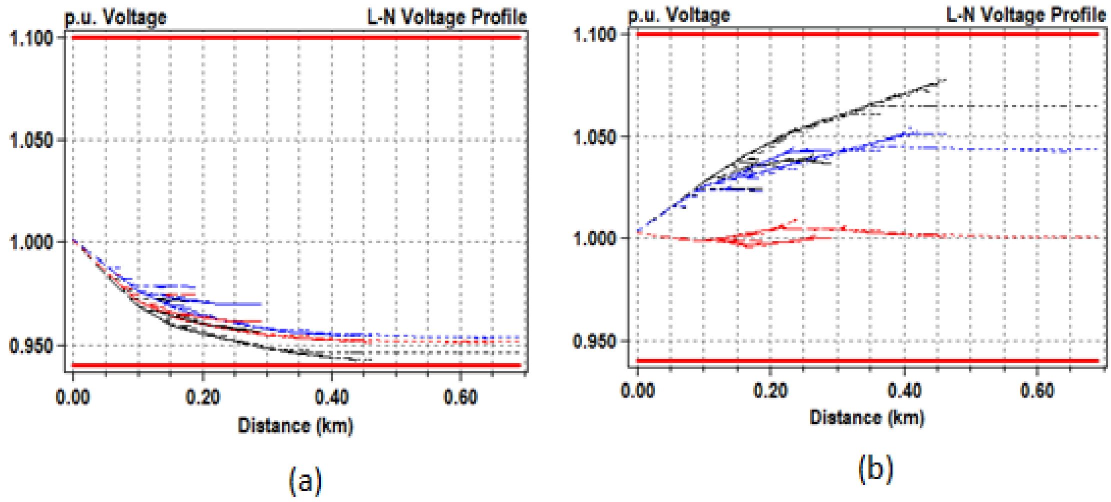


Figure 1: Dunton Green feeder voltage profile (a) without PV connection (b) with PV connection

By altering the tap position of the OLTC from 0% to -4% could effectively control the voltage rise problem as in Figure 2. The end of feeder voltage is dropped by approximately 4% according to the results.

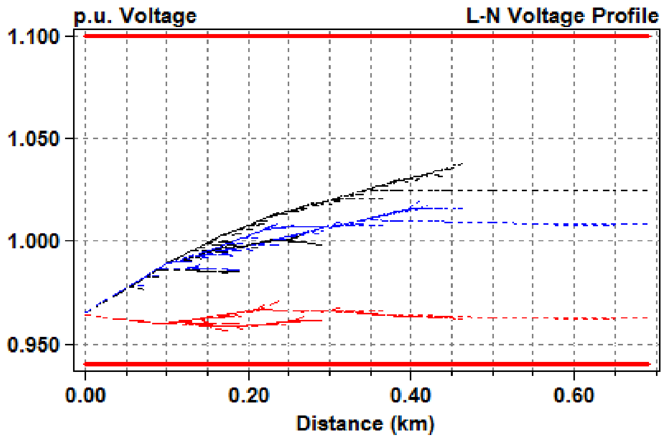
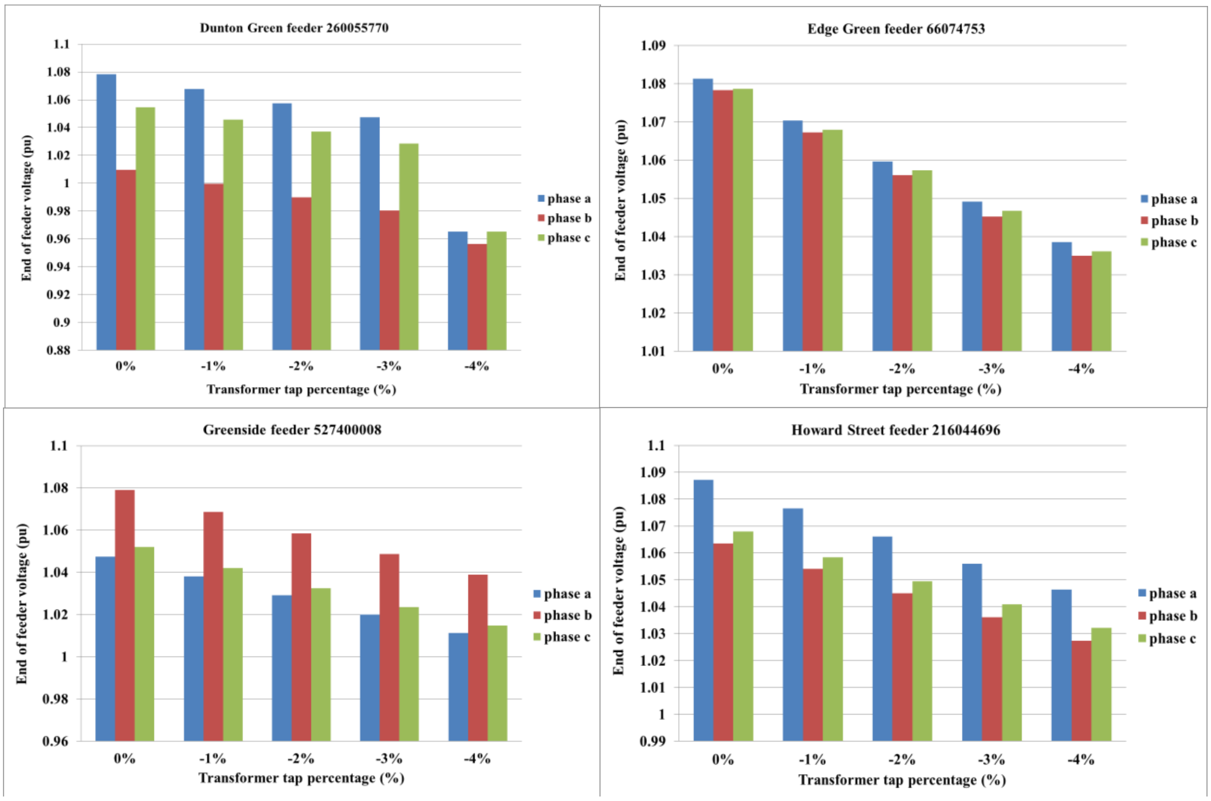


Figure 2: Dunton Green feeder voltage profile with the PV connection and -4% tapping

By altering the OLTC tap positions in increment of 1%, from 0% to -4%. Figure 3 gives the general trend of voltage drop based on various transformer tap positions. The figure shows that the OLTC can effectively control the voltage level in the network within its statutory limits to overcome the voltage rise issue throughout the feeder.



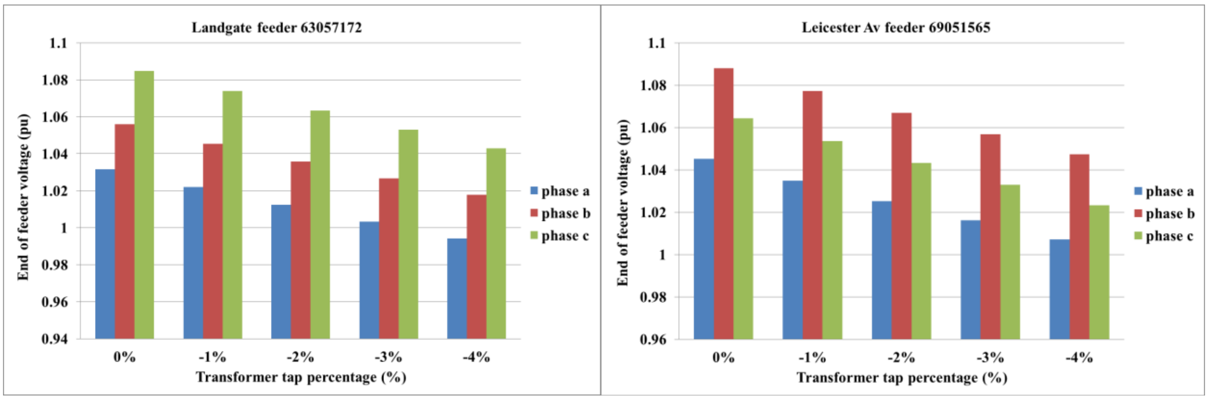


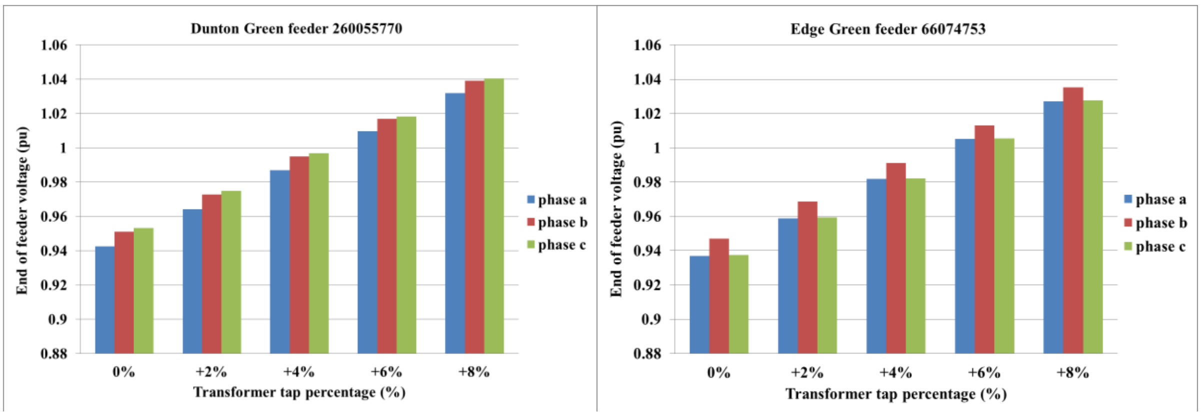
Figure 3: End of feeder voltage with various tap positions for six network feeders

In the case when the PV output are not at their maximum while the load demands are still maintains the same, as shown in Table 2. This scenario is more close to the current network conditions, whereas with a smaller amount of the PV generation could actually help to reduce the voltage drop at end of the feeder.

Table 2: Total ratings of the PV and total maximum load demand

Type	Total PV rating (kW)	Total load demand (kW)
Dunton Green 260055770	63	105
Howard Street 216044696	96	180
Landgate 63057172	18	150
Leicester 69051565	30	123
Greenside 527400008	57	223.5
Edge Green 66074753	18	234

When towards the evening period of the day with less daylight, the output from PV generators will dramatically reduce further, and house load demands will slowly increase, this could lead to further network voltage drop throughout the feeder. The OLTC could hence increase the tap position to step up the feeder voltage. Figure 4 shown that the voltage level at end of the feeder was increased by altering the tap position from 0% to +8%.



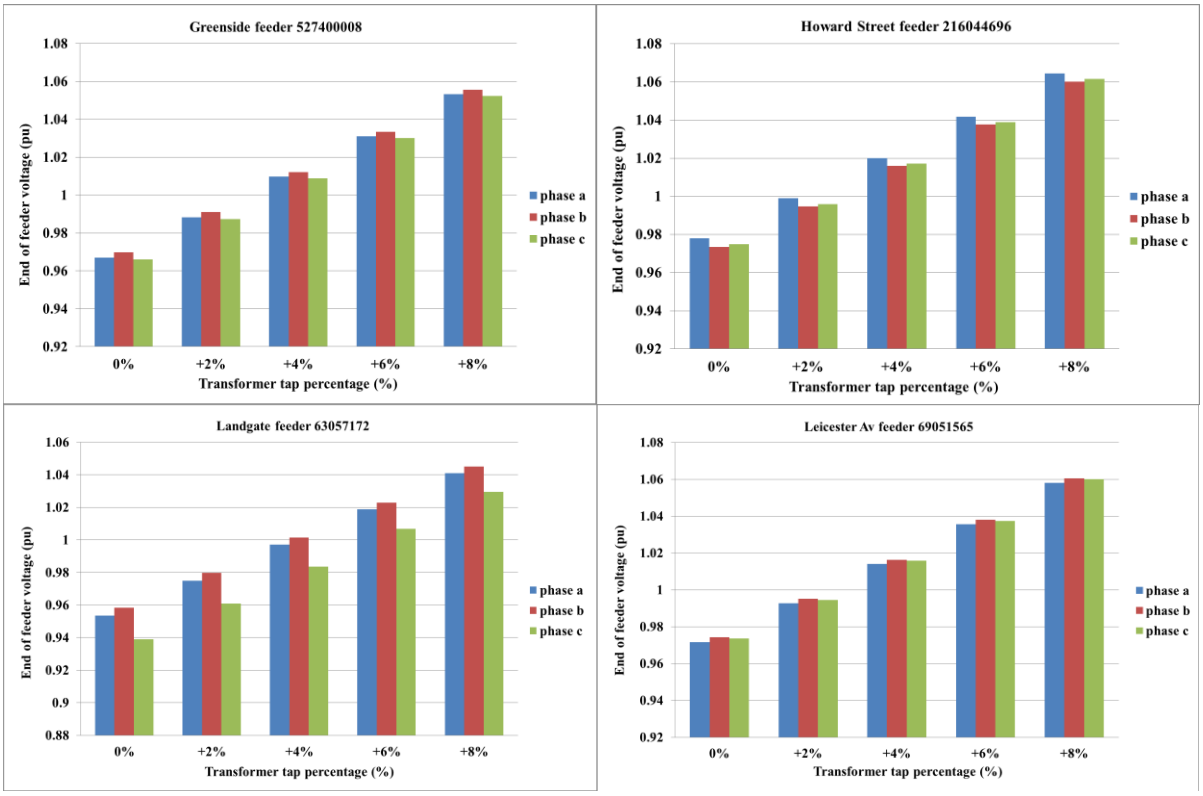


Figure 4: Feeder voltage with various tap positions for six network feeders

The network conditions with and without PV connections, is shown in Figure 5. The Figure 5(a) shows the Dunton Green feeder voltage profiles without PV connection. Figure 5(b) shows the feeder voltage when the PVs are implemented into the network. The voltage rise caused by PV pushed the end of feeder voltage from approximately 0.95pu to close to 1pu for two phases, one phase has less voltage rise due to less proportion of the PV penetration.

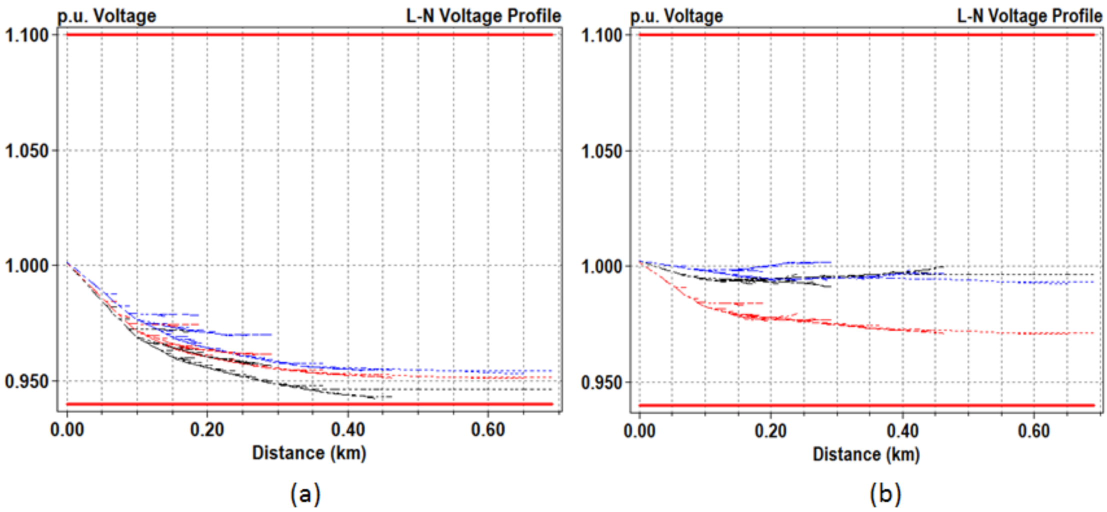


Figure 5: Dunton Green feeder voltage profile (a) without PV connection (b) with PV connection

By altering the tap position of OLTC to +6% as in Figure 6, the end of feeder voltage can be further increased by another 6%. This operation is controlled by AVC depending on different reference voltage settings on site.

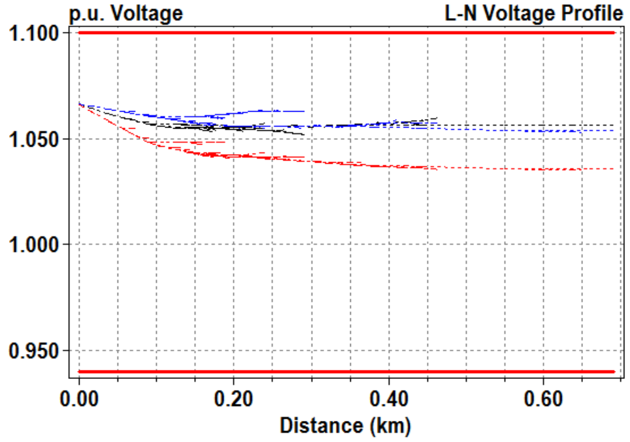


Figure 6: Dunton Green feeder voltage profile with the PV connection and +6% tapping

2.3 Network voltage regulation studies using capacitors

In the case when there are a large number of loads connected to one feeder, this could lead to significant voltage variation between substation point and end of the feeder, hence controlling the voltage through distribution transformer with OLTC could become less effective. Therefore voltage boost along the feeder is another option which needs to be considered. For the purpose of improving the network voltage at the period of maximum demand, implementing capacitor banks along the feeder could produce reactive power and further boost the network voltage level.

However the size of the capacitor bank should always be much less than the size of the transformer, to prevent reverse power flow and creating resonant current. In theory, the capacitor could be less beneficial when it is installed at substation compare to middle point along the feeder, where a higher voltage drop occurs. Considering the feeder when there are PVs connected, various sizes of the capacitor were used to study the effectiveness of voltage boost.

Considering the case when the capacitor is installed at or near substation location, when a 150kVA capacitor is connected to Dunton Green feeder as shown in Figure 7, the voltage profile becomes more close to unity (1pu) comparing the case with no capacitor bank connected. However the amount of voltage boost is not significant.

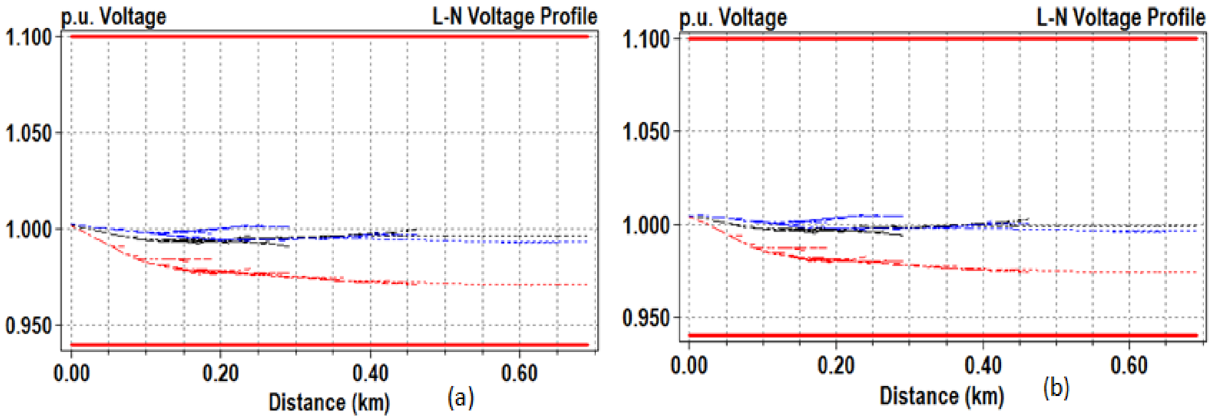


Figure 7: Dunton Green feeder voltage profile (a) without capacitor connection (b) with a 150kVar capacitor bank

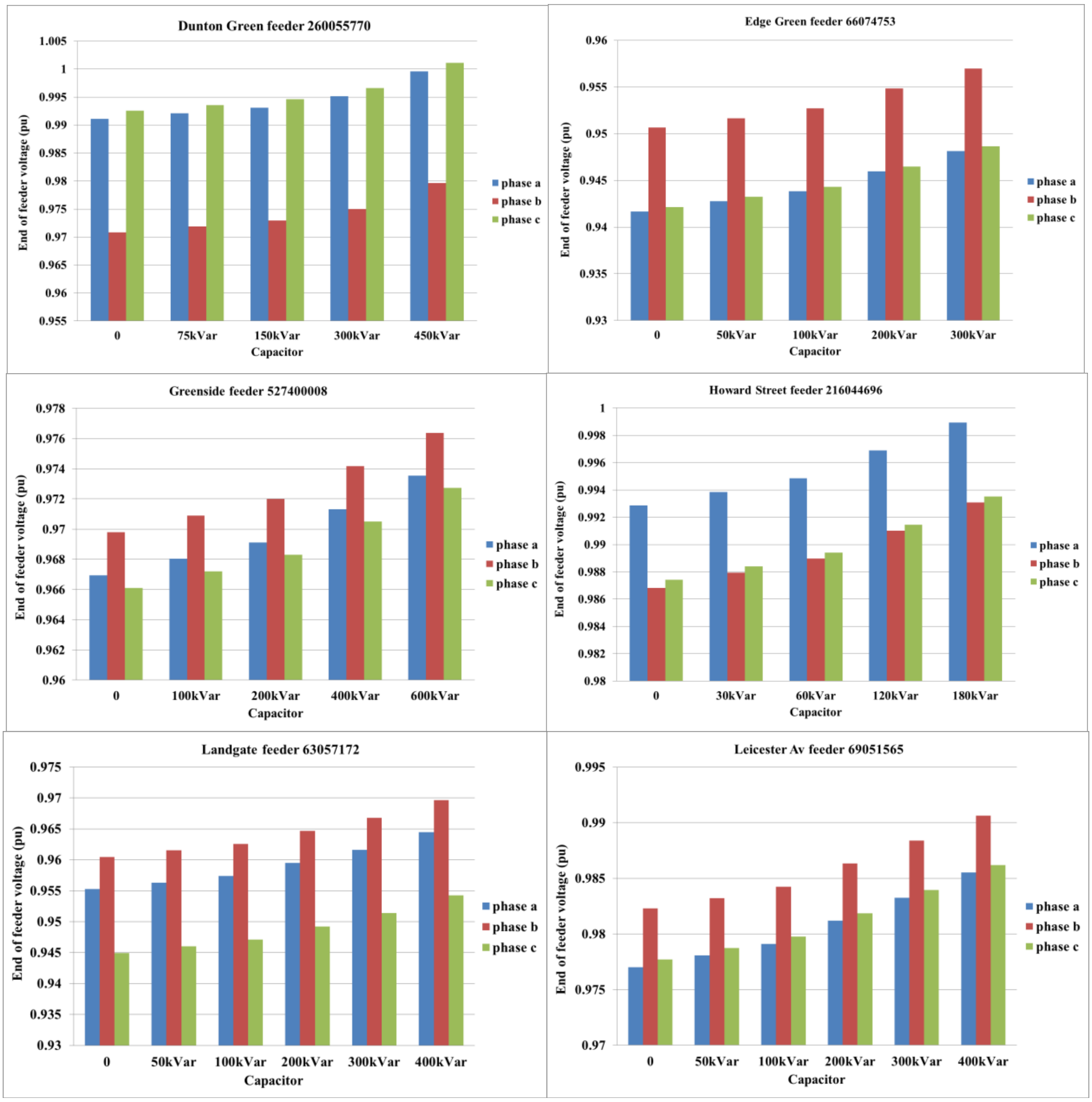


Figure 8: End of feeder voltage with various capacitors and PV connection

Figure 8 shows the boost in end of feeder voltage when implementing various sizes of capacitors. The three phase voltage gradually increases in six selected feeders. Considering the case when there is no PV connected with the loads. The resulted voltage levels are shown in Figure 9, with less voltage rise.

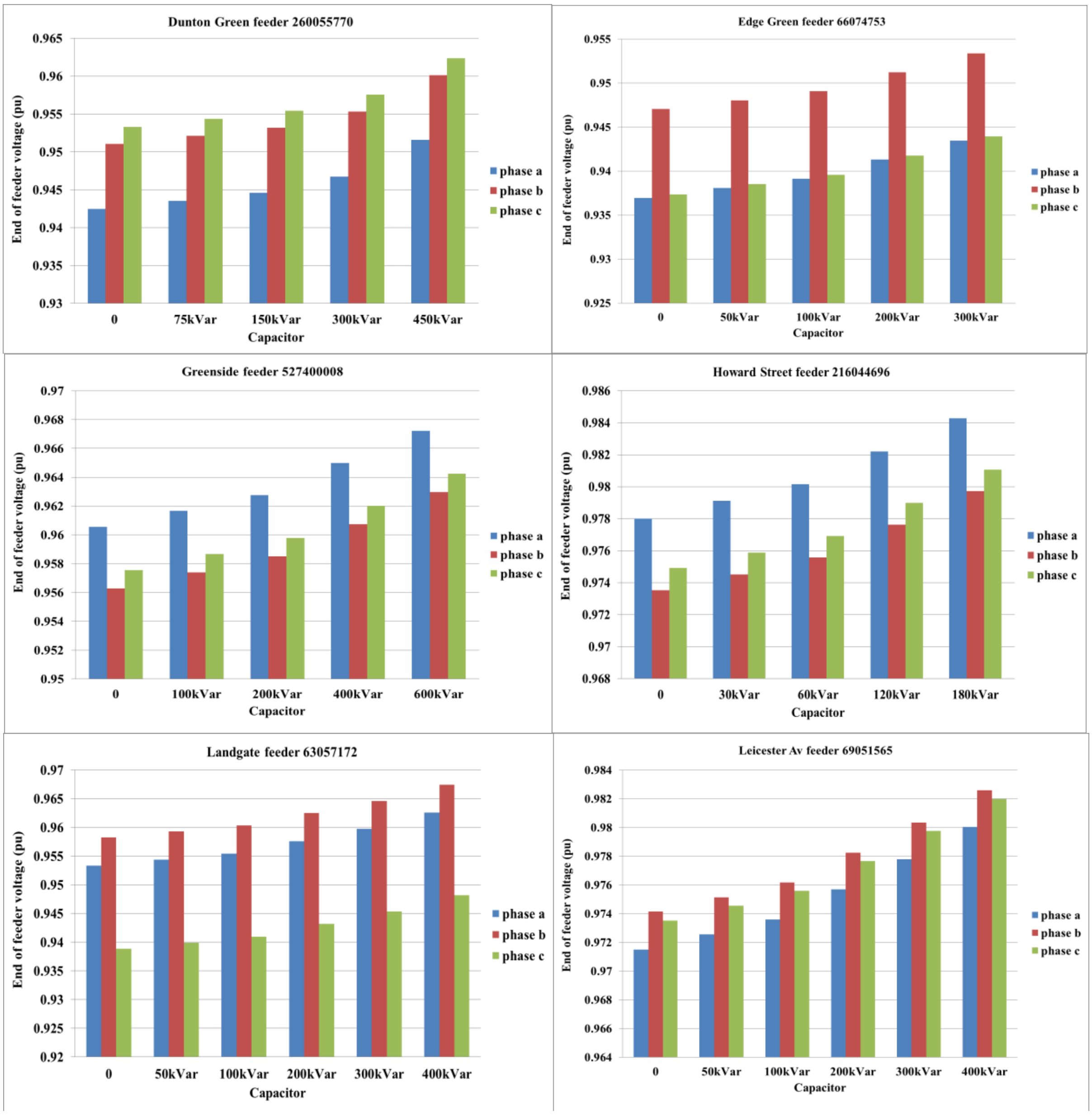


Figure 9: End of feeder voltages with various capacitors without PV connection

In the case when the capacitors are installed at around middle point of the feeder as shown in Figure 10, the voltage level at around middle point is noticeably further boosted compare to when it is connected at substation.

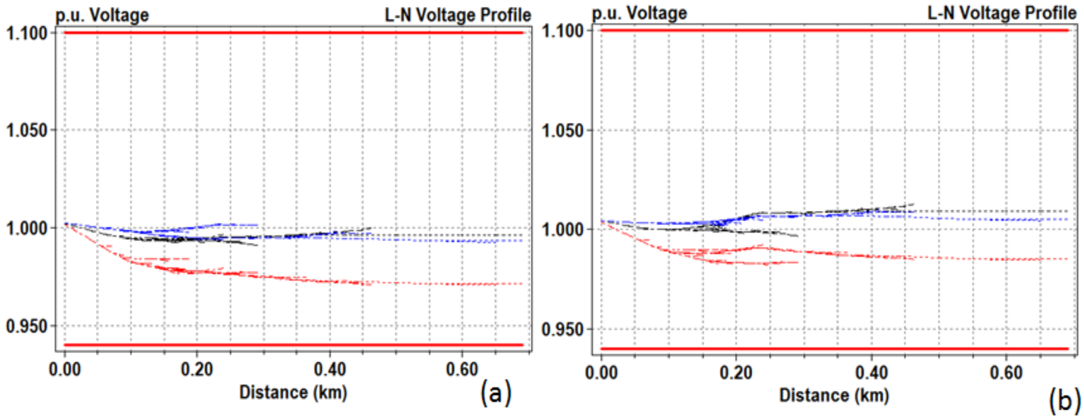
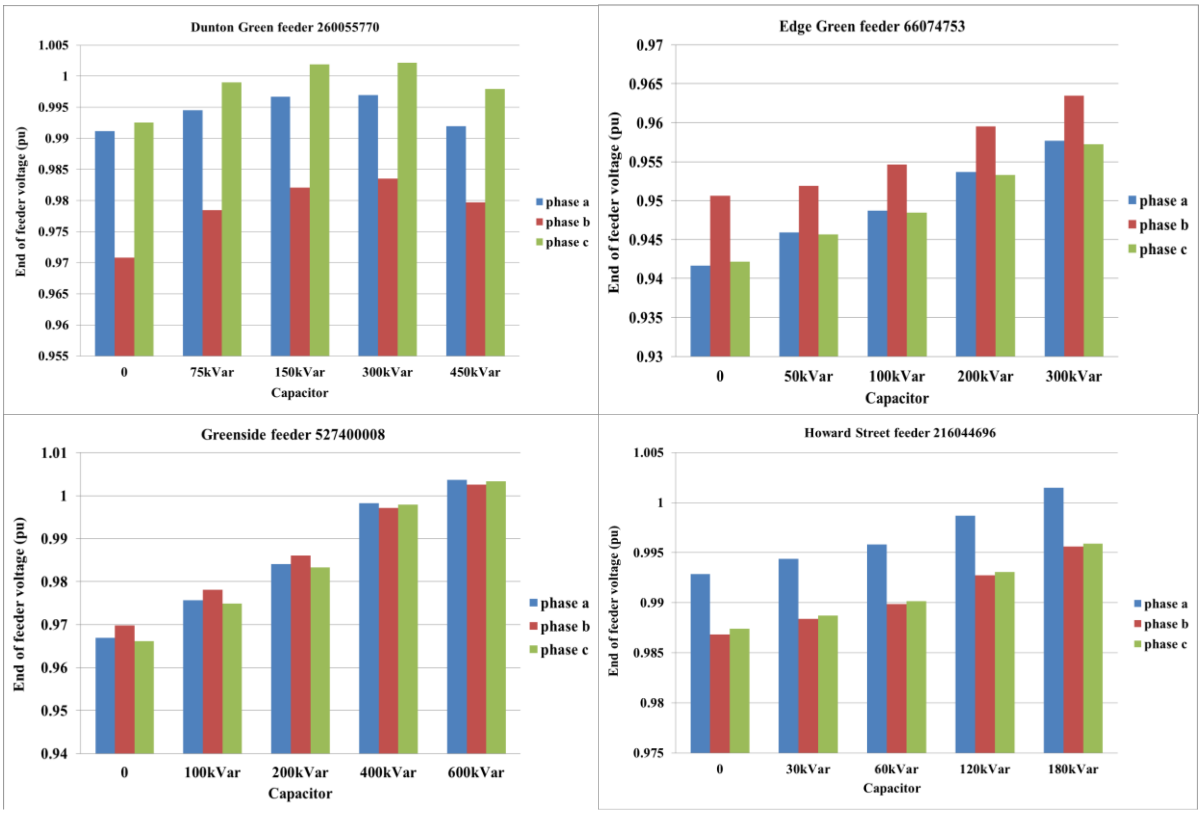


Figure 10: Dunton Green feeder voltage profile (a) without capacitor (b) with a 150kVar capacitor bank at mid-point

Implementing all capacitors at middle point of six selected feeders, the resulted voltage levels are shown in Figure 11. Comparing Figure 11 and the previous figures when the capacitor are connected near substation, it can be noted that there is more significant voltage boost, however when the size of the capacitor bank increased to 450kVar at Dunton Green feeder, the voltage dropped further instead of boosting, hence the appropriate size selection is also essential.



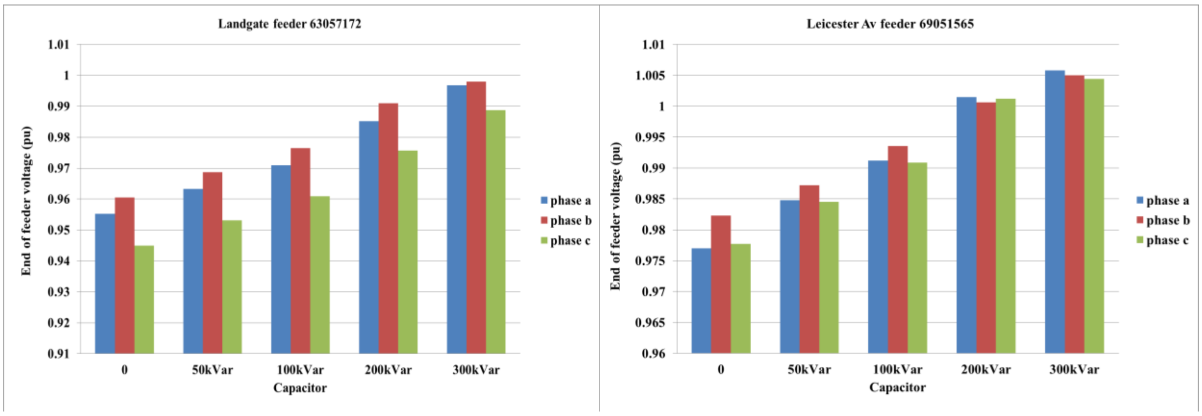
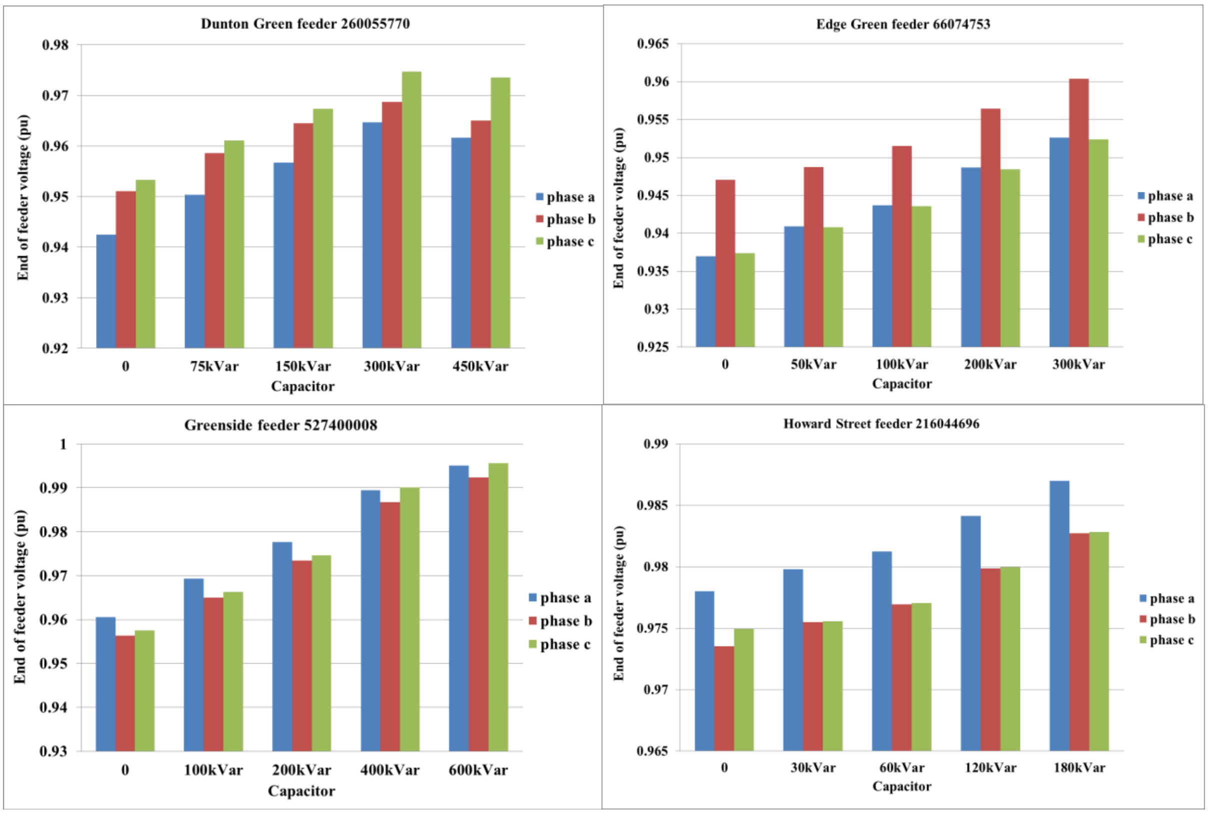


Figure 11: End of feeder voltages with capacitors at mid-point with PV connections

Considering the case without the PV connections as in Figure 12, the end of feeder voltage becomes lower due to no voltage rise resulted from PV connection. The voltage level in this case is only affected by the load and the capacitor banks connected.



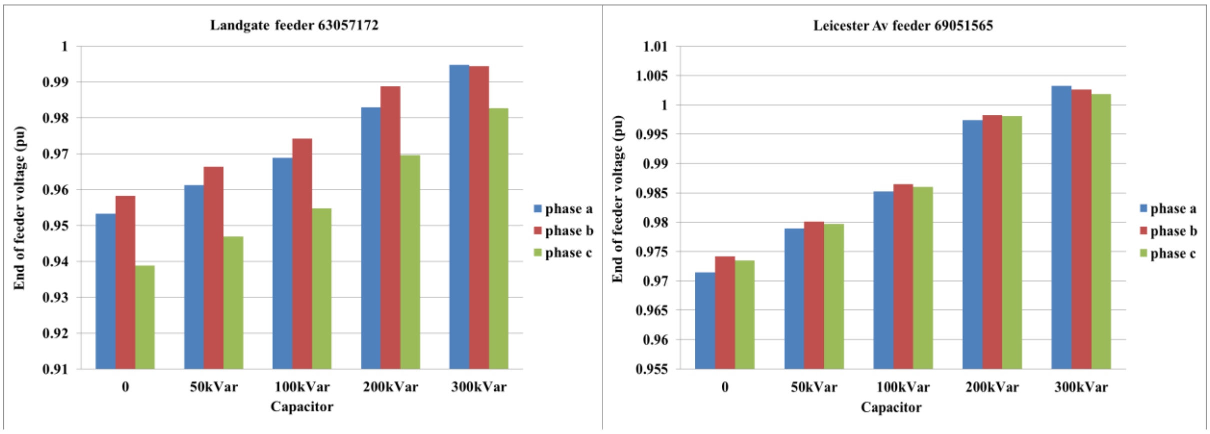


Figure 12: End of feeder voltages with various capacitors without PV connection

To further investigate the difference of installing capacitor at middle point compare to when it is installed near substation. The voltage drop for Dunton Green feeder was recorded as shown in Table 3, the voltage were recorded at end of the feeder.

Table 3: End of Dunton Green feeder voltage drop without PV connection

Installing at substation			
	Voltage drop without PV connection (pu)		
	phase a	phase b	phase c
no Capacitor	0.04868	0.01975	0.03928
75kVar	0.0486	0.01973	0.03923
150kVar	0.04852	0.0197	0.03919
300kVar	0.04837	0.01966	0.03909
450kVar	0.04804	0.01954	0.03873
Installing at mid-point			
	Voltage drop without PV connection (pu)		
no capacitor	0.04868	0.01975	0.03928
75kVar	0.04425	0.01994	0.0379
150kVar	0.04001	0.01762	0.03457
300kVar	0.03233	0.01479	0.02755
450kVar	0.03036	0.01466	0.02442

It is noticeably more effective to install the capacitor banks at mid-point location where there is more significant voltage drops.

2.4 Network voltage regulation studies using storages

One the effective method to control voltage in distribution network is through storage installation. The increasing amount of the distributed generation has allowed the energy storage to bring several benefits to the existing network. The renewable generators connected to the network such as PVs are generally considered as an intermitted source, which produce power during the daylight period and ineffective at night. These types of the source cannot alter the energy production based on the load demand.

By installing energy storages into the network, they could therefore be charged during the period of low demand and release power during the peak load demand period. The storages generally considered based on its two operation mode, charge and discharge mode.

During the charging mode, the storage being treated similar as a load that consumes active power. During the discharging mode, the storage acts similar to a generator as a backup power supply. It is known that the integration of PVs into the network will cause a certain amount of voltage rise, by using energy storage in the network, it could use the additional amount of the power generated to charge the unit therefore eliminates the voltage rise issue.

In addition, the increasing amount electric vehicles in the future could lead to more and more electric charge stations in the network, such charge station in theory could also being treated like an energy storage unit. During the period of low demand such as daytime period, the storage elements in the charge stations could draw any excessive power generated from PV and release them during peak period. Therefore helps the network to maintain the voltage level within the statutory limits.

This section investigates the effect of installing energy storages at different locations within the network, during both charge and discharge operation mode. The influence of PV connection with storages is also being investigated. The network used for this study is given in Table 1 previously, the maximum rating of the storage is generally selected to be less than the transformer rating to prevent instable current which could damage the units within the network. The PV is considered to have a maximum rating of 3kW.

2.4.1 Installing storages at or near substation

To investigate the effect of installing storages in distribution network with and without the PV connections, the storage unit is first being implemented at the substation level. The storage during charge mode is first being investigated, the different sizes of the storage reflects the amount or percentage of the unit being charged.

In this case with the maximum penetration of PV, the storage will act similarly as a load hence reduce the voltage rise caused by PVs. The storage unit being implemented is in three phases. As shown in Figure 13(a), the voltage profile clearly illustrates a voltage rise effect. When the storage is being connected close to the substations as in Figure 13(b), the storage is being charged therefore have the similar effect as having an extra load connected to the network.

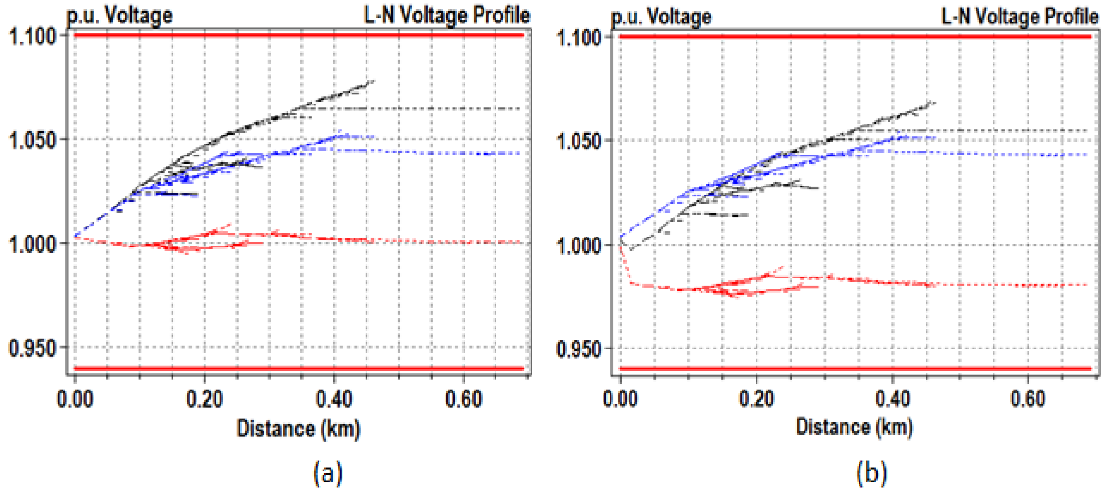
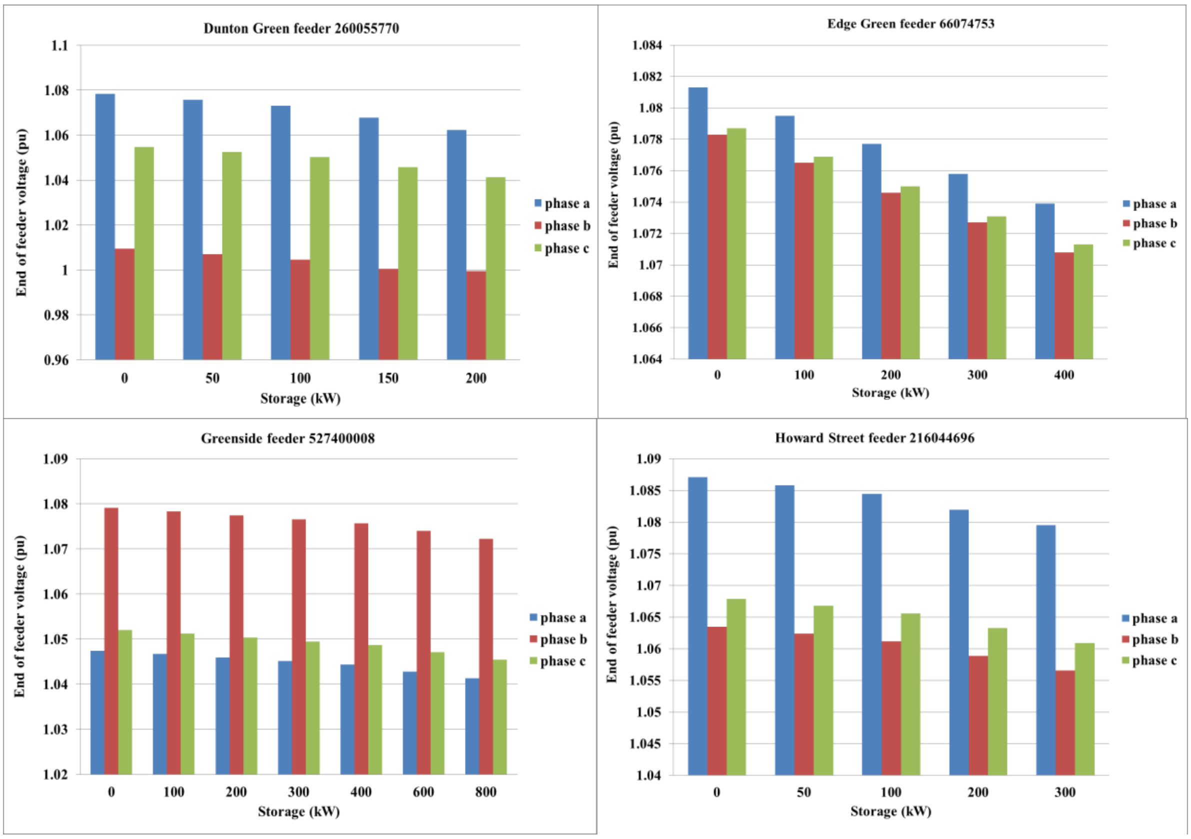


Figure 13: Dunton Green feeder voltage profile (a) with PV connection and without storage (b) with PV connection and storage during charging mode

By implementing the storage unit during charge mode in six network feeders as in Figure 14, the amount of the maximum voltage drop is depending on the amount of the storage being charged. The simulations were carried out considering maximum penetration of PV, therefore this is the scenario which likely to occur during the day at off peak period when the PVs are at their most effective.



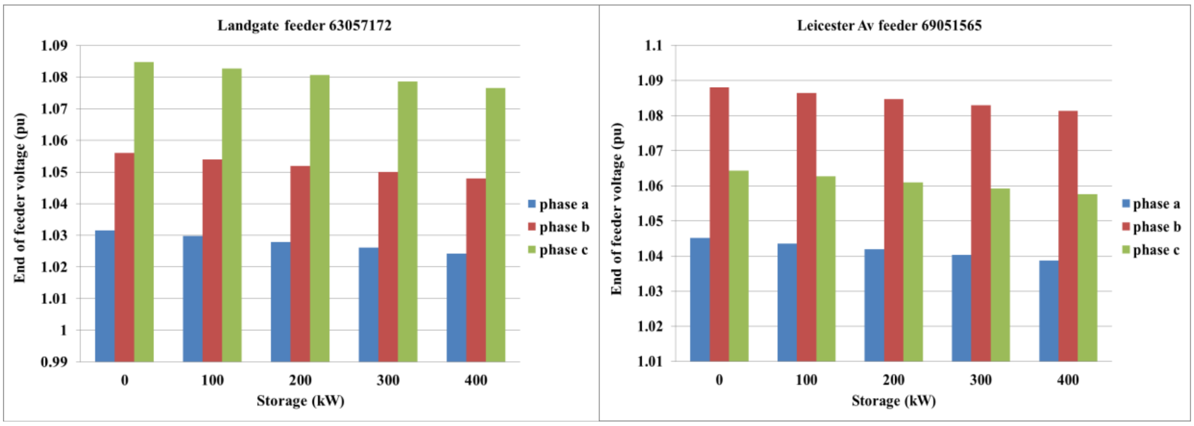
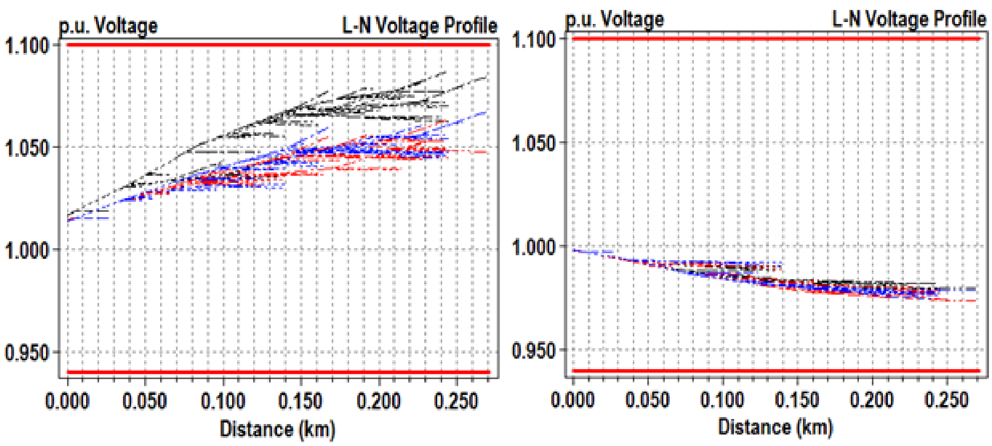


Figure 14: network voltages profiles with various storage capacity and maximum PV at substation (the three phase voltage profiles in six types of network respectively)

Six network feeder voltage levels with various storage sizes are shown in Figure 14. The amount of voltage drop caused by storage is approximately 0.01pu. Hence the storage will help eliminate a proportion of the voltage rise in the network, however the amount of voltage reduction is limited or may not as effective as transformer with OLTC in this particular scenario. If however the storage elements are all fully charged, there would be no additional effect to the network. This could happen after a certain storage charging period, while the PVs are still producing power which injects back into the network.

Figure 15 represents the difference of voltage profile with and without with PV connection at Howard Street network feeder.



(a) (b)

Figure 15: Howard Street feeder voltage profile (a) with PV connection (b) without PV connection

Figure 15(a) clearly shows that the high penetration of PV would dramatically increase the network voltage level. Thereby the previous case shown that the additional storage acts as a load during charge state and also helps to reduce the voltage rise effect. Figure 15(b) shows the voltage profile without any PV connection, during this scenario the storage element could switch to discharging mode therefore behave like a generator. The storage unit will continue to supply power to the network until it fully discharged. In reality there is typical a reversed amount of power for the storage, hence the storage would never be fully discharged or fell below of its reversed power level. Furthermore, the voltage level would be boosted by the storage element during discharging period.

Figure 16 shows the growth rate of voltage level for the six network feeders. Therefore the storage element should be considered as a buffer between the maximum PV generation during off peak and minimum PV generation during peak period.

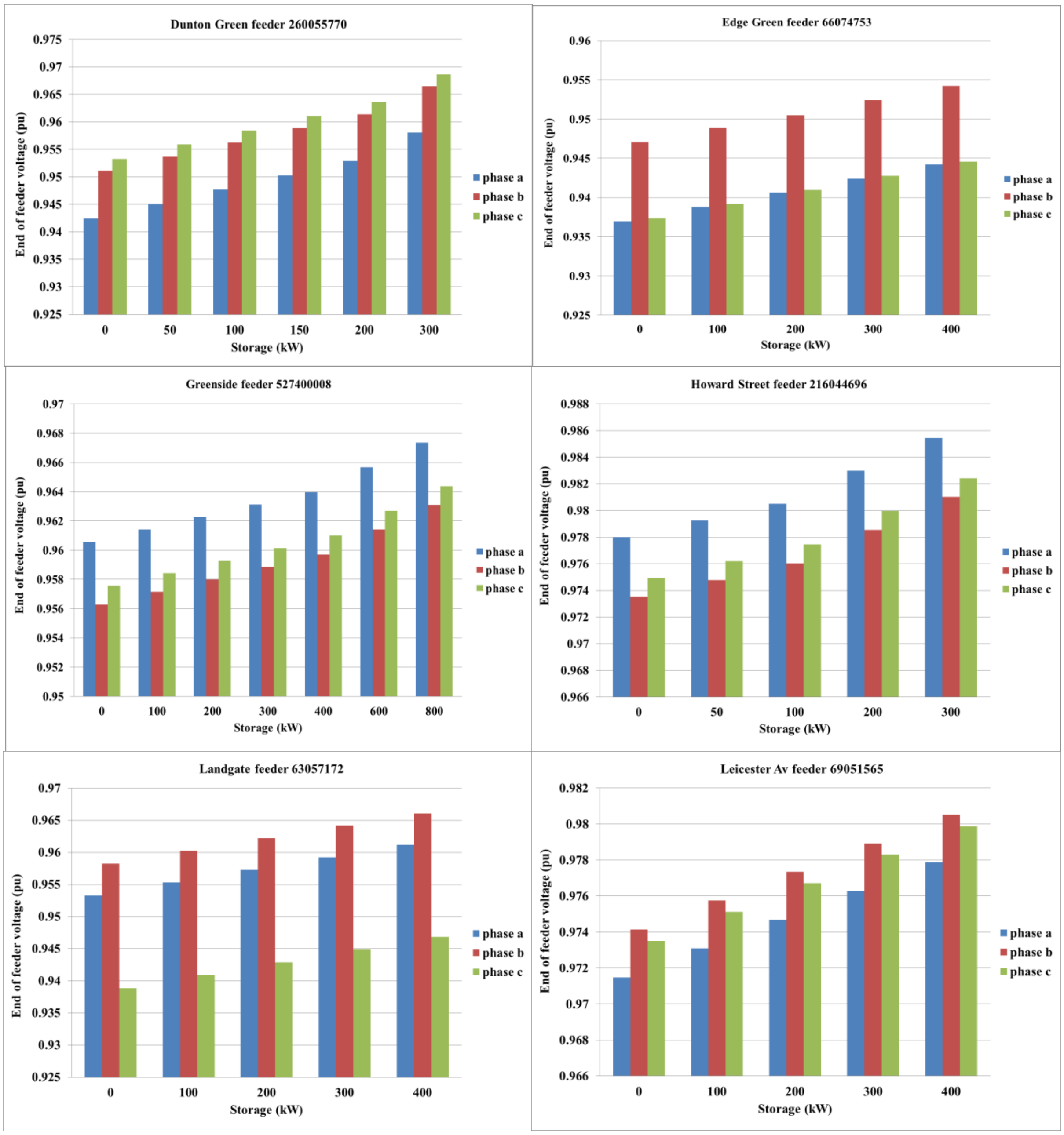


Figure 16: Six network feeder voltage profiles with various storage sizes during discharge mode near substation and without PV connections

2.4.2 Installing storages at mid-point location

The location of storage element in this section is being implemented around the mid-point location for each feeder. The Figure 17(a) shows the voltage profile with PV connections which causes the voltage rise throughout the feeder. Figure 17(b) shows the voltage profile when the storage unit is connected and working in charging mode. There is more voltage drop in this scenario compared to when it was implemented near substation.

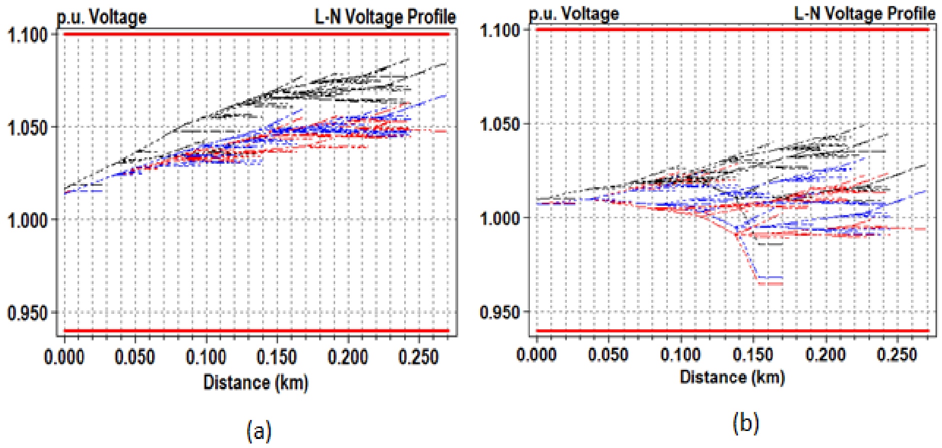
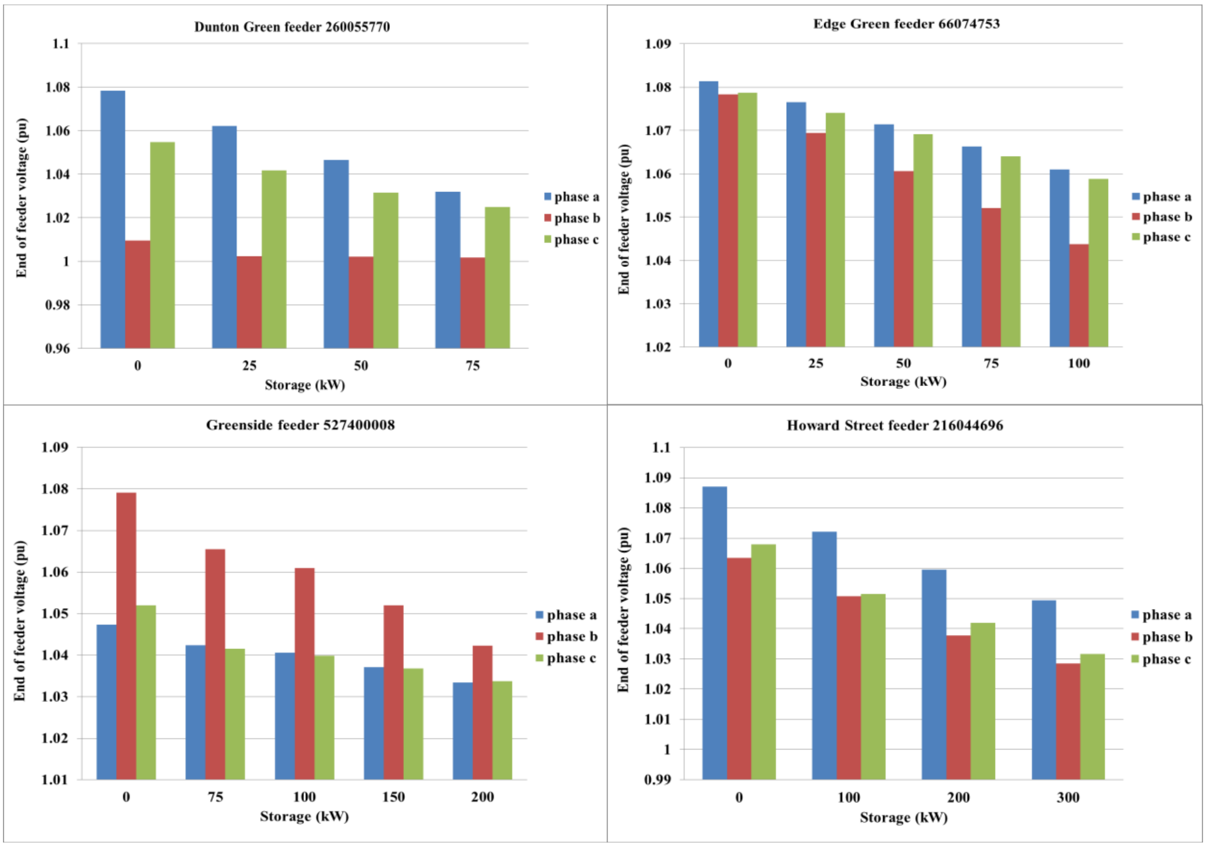


Figure 17: Howard Street feeder voltage profile (a) with PV connection (b) with PV connection and storage at mid-point location



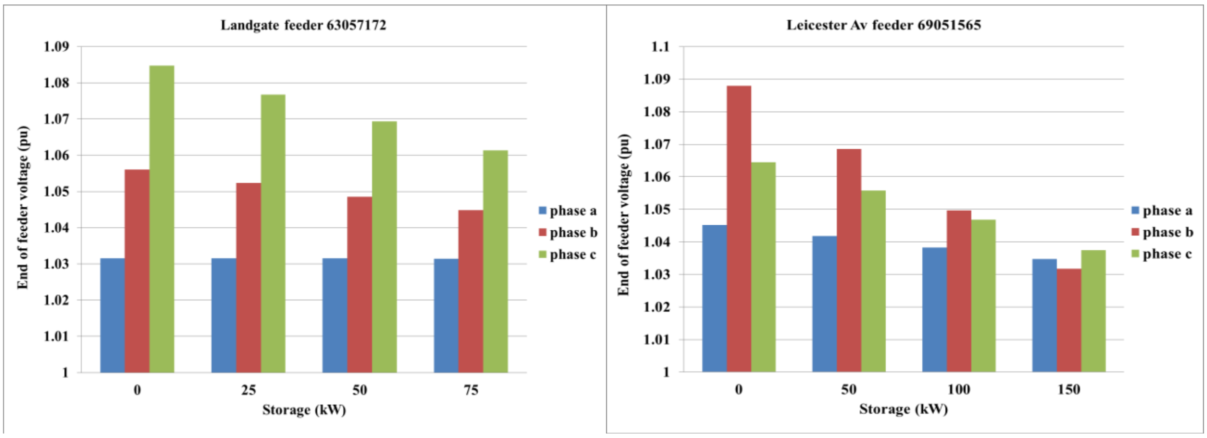
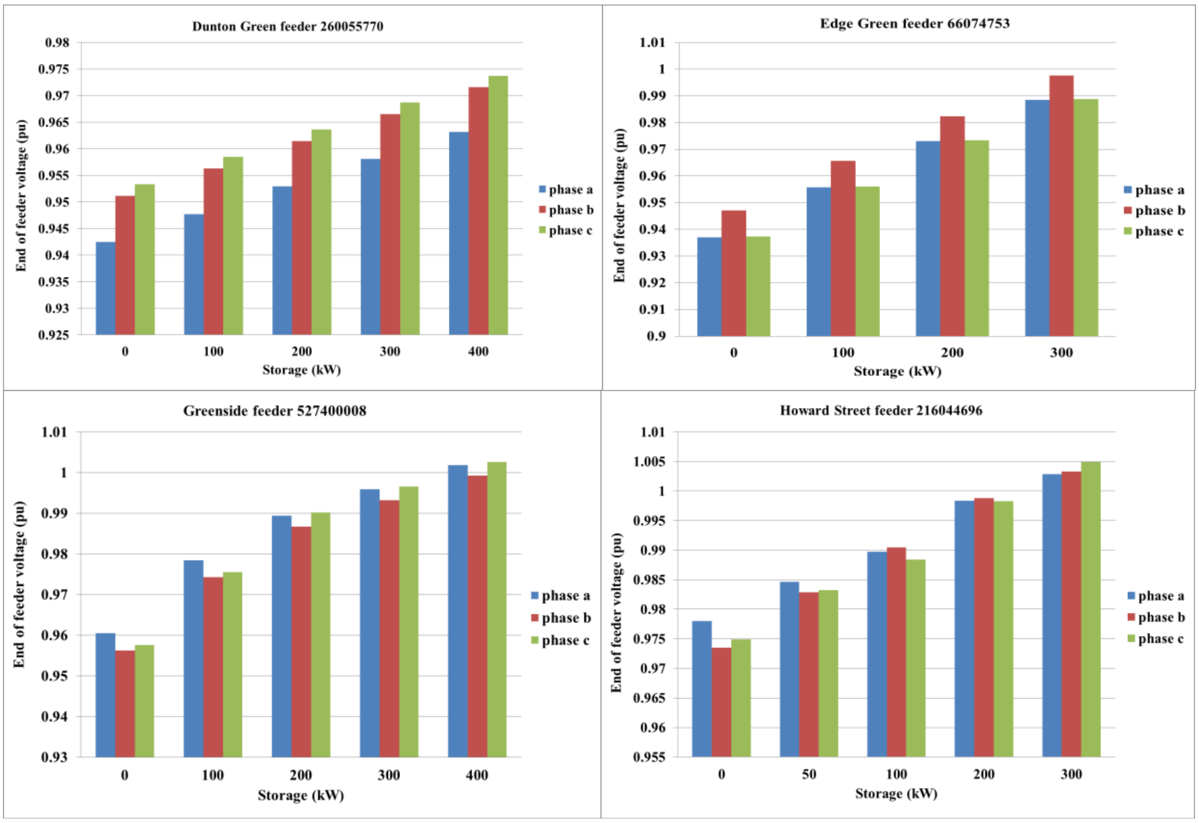


Figure 18: Six network feeder voltage levels with PV connection and various storage sizes during charge mode at mid-point location

Figure 18 shows the voltage level of six network feeders when the storage is connected near mid-point location and operating during charge mode, it can be seen that the unit is able to significantly reduce the voltage level compares to when it was implemented at substation, therefore the storage offers an effective option to address the voltage rise issue caused by PV, when the storage unit is located near mid-point.

During the period of maximum load demand with no PV generation, the storage is then switched to its discharging operation mode, the voltage level of the six network feeders are shown in Figure 19.



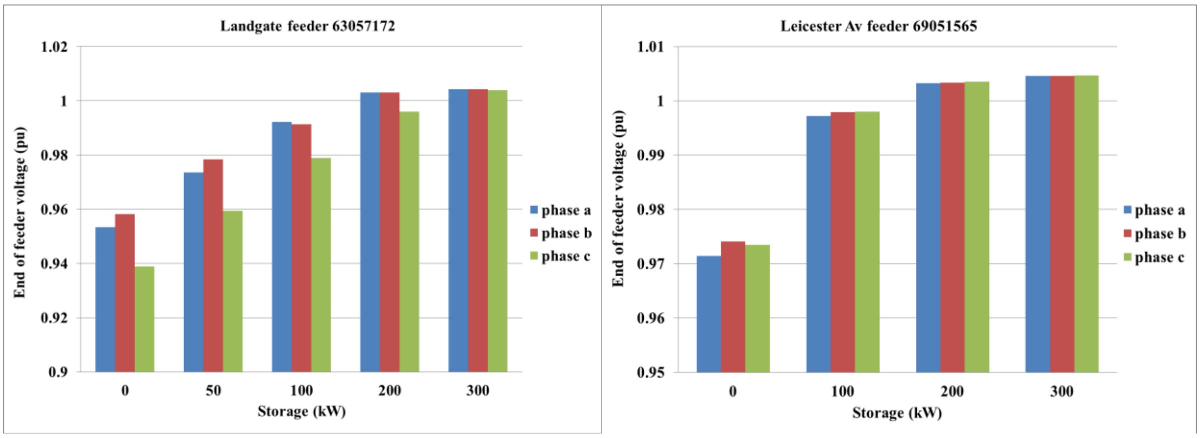


Figure 19: Six network feeder voltage levels with various storage sizes at mid-point location without PV generation

Figure 19 shows the storage could provide the additional power to the network during the period of high load demand. Under fully discharged condition, it is able to boost the voltage level further compared to when it was at substation. Hence the most effective location to install the storages is at locations further down the feeder.

3. Network capacity

This document describes the study on network capacity of six distribution networks by installing different voltage control equipment. The first aim of this report is to use various voltage control options to regulate the voltage on the network, furthermore to investigate which option increases more network capacity while maintaining the voltage level within the statutory limits.

This report will help network operators to make decisions on which are the more suitable devices to use in order to prepare for the future change in load demand. Voltage control options such as energy storage, capacitor banks and distribution transformer with OLTC were considered. The load conditions with and without the PV were simulated for each options.

The result shown that the voltage control devices investigated will help network operators to maintain the voltage regulation and also significantly increase the network capacity.

3.1 Network introduction and assumption

In order to reduce the level of carbon dioxide (CO_2) emission with the increasing demand of electrical energy, the UK government is targeting that 15% of energy should be generated from renewable resources in 2020 and achieve the carbon reduction of 80% by 2050 [1]. This target of carbon reduction means that there will be a significant increase of distributed generations in the low voltage network between now and year 2050, such sharp increase will introduce a challenge for network operators to maintain the voltage regulation and power quality in the distribution networks. In addition, the increasing energy demand with introduction of new forms of loads such as electric vehicles and heat pumps could impose a risk for the network to exceed the their total capacity.

When the distributed generation sources are connected directly into the LV network at period of low demand, it could cause voltage rise in the network, forcing the voltage to exceed the regulated voltage level. Hence this issue will limit the amount of distributed generation into the network. Therefore it is important while maintaining the voltage regulation, the voltage control options being considered should also give a significant increase in distribution network capacity.

Several voltage control options are considered in this report in terms of their ability to increase the network capacity and maintaining the voltage level. Devices investigated include capacitor bank, distribution transformer with On Load Tap Changer (OLTC) and energy storage. Several case studies were carried out in order to maintain the feeder voltage within the +10% and -6% statutory limits. The simulation models of six trialled network including Dunton Green, Edge Green Lane, Greenside, Howard Street, Leicester Ave and Landgate were used. The network capacity for each network using these devices were plotted and compared.

The network simulation models used for this study are based on the actual network data, the number of PV implemented in the network model are according to the existing network record. The study shown in this report is to implement the PV at its existing location and increase the output by an increment of 1kW for each case study. Therefore the results reflect the impact of distributed generation increase on the network capacity. Such study could also apply to other distributed generations such as wind, or a combination of distributed generators such as PV and wind generators.

The process of finding the network capacity is by running the voltage profile for each substations under different load conditions and installing voltage controls, such that the maximum capacity is at scenario which the end of feeder voltage is just above the -6% statutory limits, and the voltage at every nodes should also below the maximum statutory limit (+10%). For the studies described in this report, a maximum of +5% tap position is used. The transformer ratings at the substation level are at 800kVA. The rating of the capacitor banks considered was 100kVar, 250kVar and 400kVar. The energy storage selected is at 100kW. Figure 20 shows the PV penetrations of the six networks simulated in this study. The study with PV generation will not be carried out at Greenside network, due to only a single PV connection at this network according to the data.

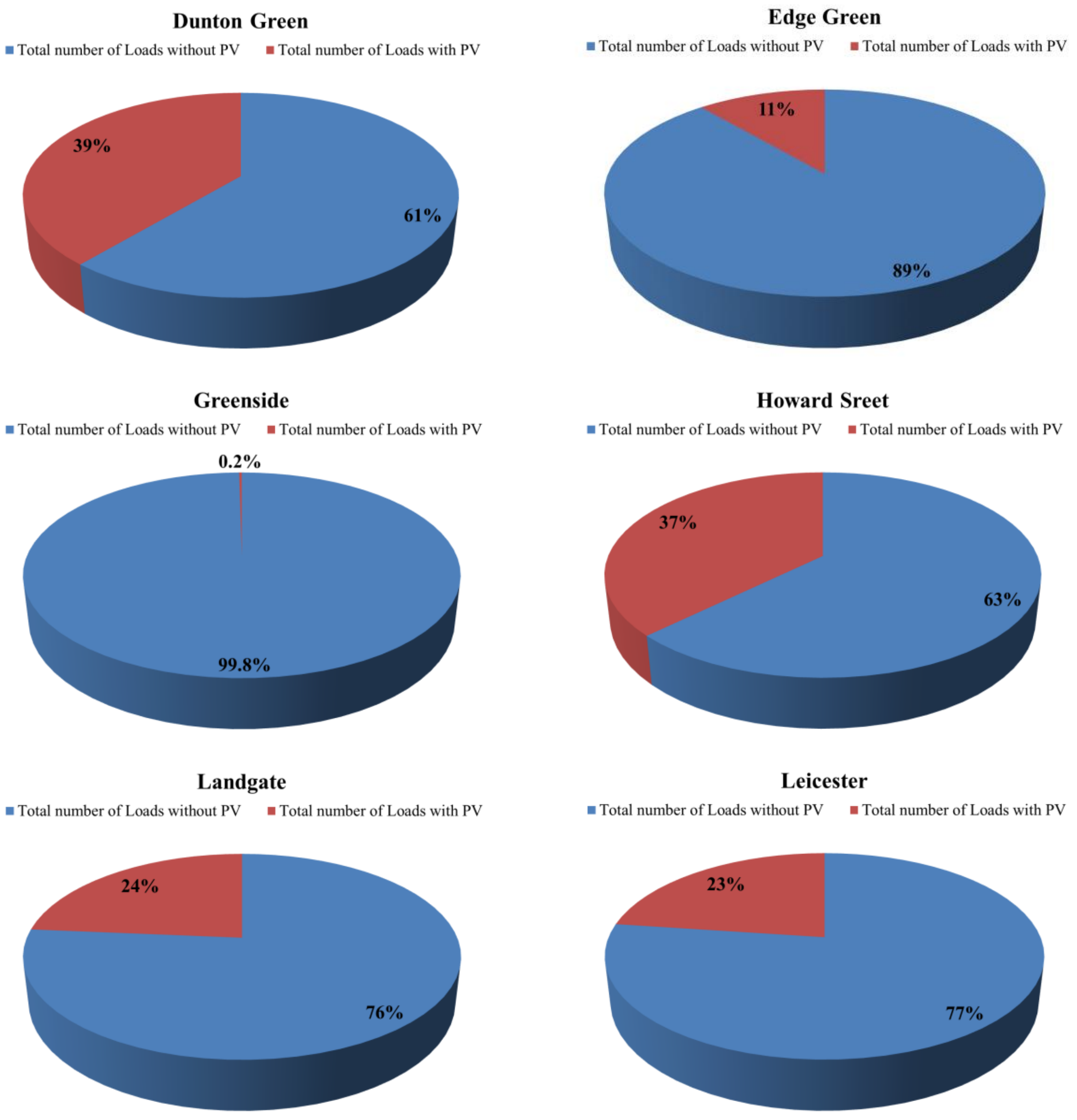


Figure 20: PV penetration of six distribution networks

3.2 Network with OLTC installed at the substation

The substation voltage can be regulated by installing an OLTC for the distribution transformer. If the network demand is high, the OLTC will increase the substation voltage so that the downstream feeder voltages could be maintained within the limits. Figure 21 shows the network capacities with and without the OLTC installation for six distribution networks. Since PVs are connected at the feeders, the network has also been simulated with different amount of PV generations.

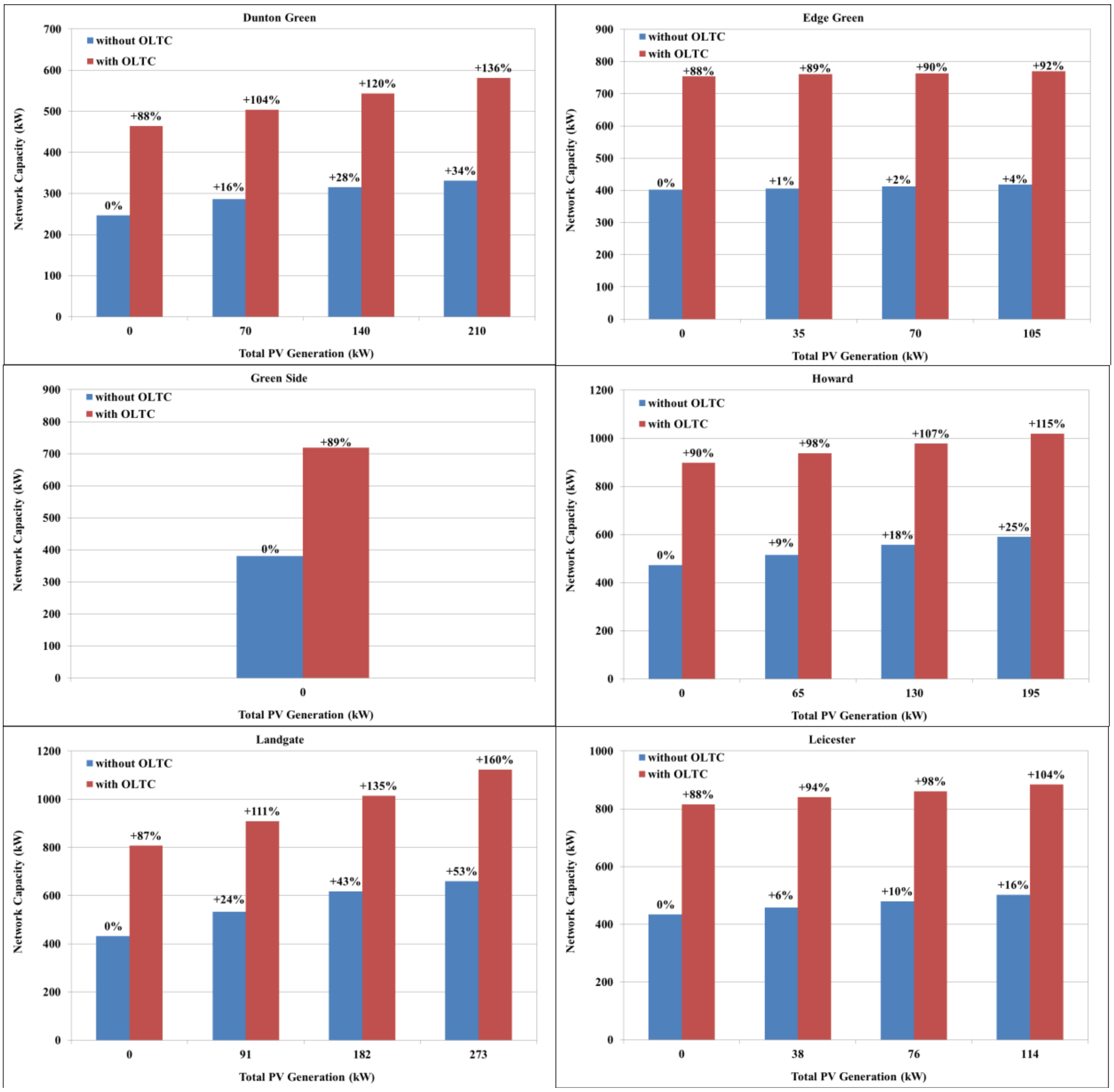


Figure 21: Network capacities with and without the installation of OLTC

According to Figure 21, the employment of transformer with OLTC is able to increase the network capacity by as much as 90% when PV outputs are at zero. The network capacity increases slightly as the total PV generation increases. The network capacity increases by as much as 53% even without the installation of transformer with OLTC. However, the capacities increased by installing the OLTC are much larger than the capacities increased due to PVs. Also shown in Figure 21, the amount of capacity increases are different depending on different network conditions. For instance, the Landgate network has the highest amount of increase by +160%, this is also partly due to the network has highest amount of PV generations. During period of low demand and amount of PV generation is high, the voltage level will be raised to just below the regulation level at substation hence the voltage at most nodes in the feeder are higher, causing voltage rise even at end of the feeder, therefore allowing more loads to be connected. Installing transformer with OLTC proves to be a very effective way to increase capacity as it controls the substation busbar voltage thereby allowing all feeders to be affected.

3.3 Network with capacitor installed on the feeder

Since voltage can be controlled by the reactive power compensation, the network model has been tested by employing a capacitor to regulate the reactive power flow. The capacitor can be installed at the substation or on the feeder. Study shows that it is more effective to install the capacitor at feeder mid-point instead of the substation where more voltage drop occurs. Figure 22 illustrates the network capacity increase when a capacitor of 100kVar, 250kVAr and 400kVar is installed at mid-point of each substation feeder that has the highest amount of voltage drops or has longest main cable length.

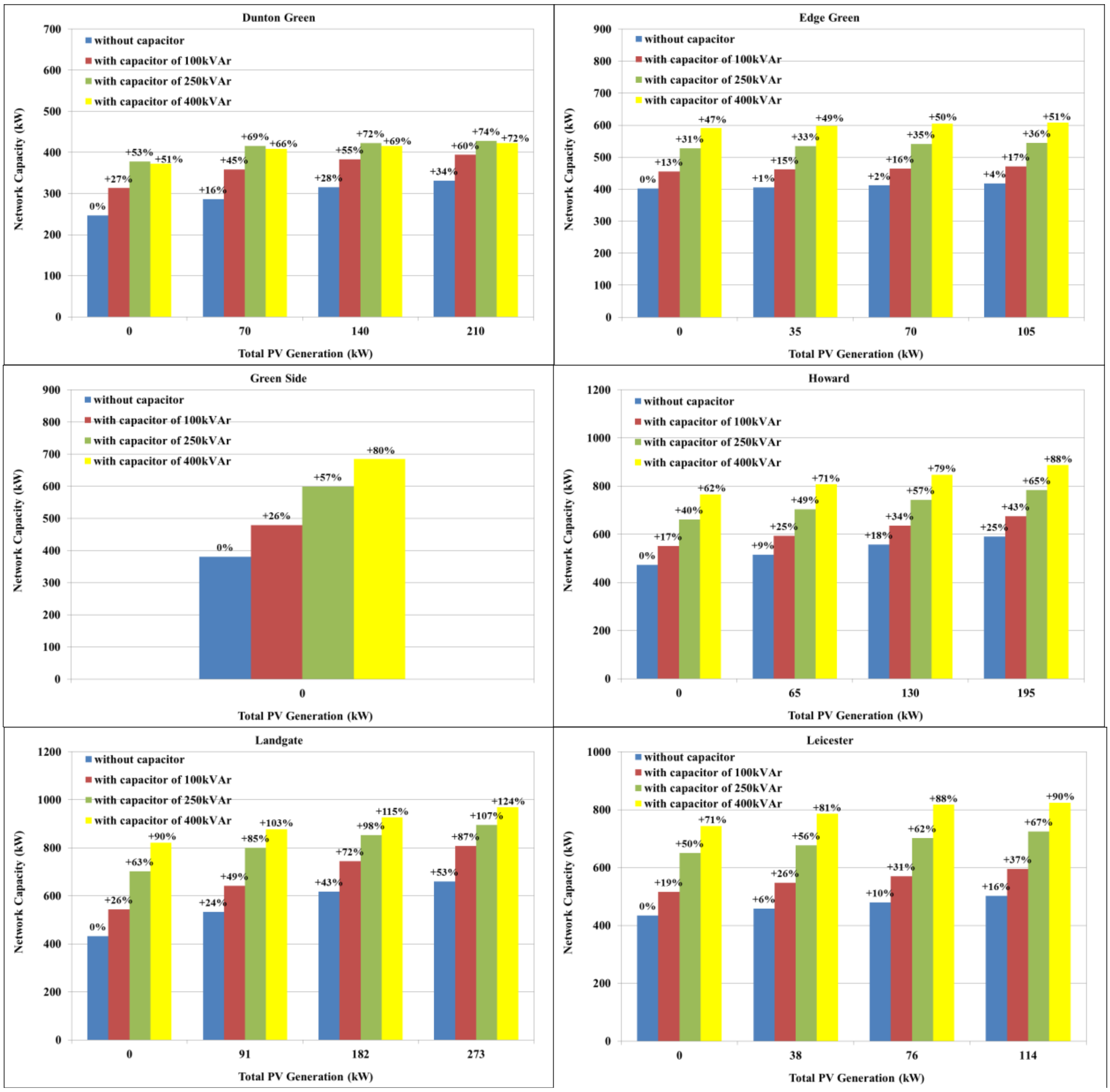


Figure 22: Network capacities with different capacitors installed on the feeder

By changing the total PV generation, Figure 22 indicates the network capacity with different capacitor rating. When there is no PV generation, the employment of a capacitor with 100kVAr is able to increase the network capacity by as much as 27%. Note that the network capacity does not always increase with the higher rated capacitor banks. The network capacity has decreased slightly when the capacitor rating increases from 250kVAr to 400kVAr. This is due to the reversed power flow caused by the large reactive power injection. As a consequence, the line voltage drops increases again, reducing the network capacity instead. However when the appropriate size of the capacitor is installed, the network capacity generally increases with higher rated capacitor banks. Figure 22 shows the capacity at Landgate network increased by additional 124% when a 400kVar capacitor is used. The study also shows the amount of capacity increases are not as significant with higher rated capacitor used for some networks. This is due to some network lines are more resistive than others, therefore installing capacitor is possibly not the most effective option to increase network capacities for some networks.

3.4 Network with storage installed on the feeder

During periods of high demand, the energy storage device can be configured to the discharging mode and export power to the grid. This can help the network to maintain the voltages when load demand is high. Therefore, the network has also been tested by connecting storage of 100kW at the mid-point of the longest feeder for six networks. As the results shown in Figure 4, the employment of the energy storage device is able to increase the network capacity by as much as 77% when PV outputs are at zero. Compared with the capacitor, the installation of storage is more effective on improving the network capacity. However, the storage device is only able to provide the constant power within its energy capacity. Therefore, it cannot support the network voltages for a long period.

As shown in Figure 23, the amount of capacity increase is significantly higher at Dunton Green network than others. This is due to difference in amount of loads connected for each feeder at Dunton Green. As a result, the voltage drop on one feeder at Dunton Green is much higher than other feeders connected. Therefore by installing energy storages in this particular feeder will dramatically increase the total network capacity, as other feeder does not have low voltage issues.

In addition, it is also worth noting that for 6% increase in PV generation at Leicester network, does not lead to an addition 6% increase when the storage was installed. Similarly for Dunton Green when the storage is used, the amount of capacity increase is the same between 140kW and 210kW of total PV generation. Therefore the amount of capacity increase is also depended on the location at where the storages and PVs are mounted, in some cases the mid-point is not necessarily the most optimum location to install the storage. In some cases it may need to be installed more close to the end-point due to more voltage drop. However installing storage at mid-point will in theory affect more customers than it is installed at end-point, due to more wide spread voltage boost effect along the main cable line.

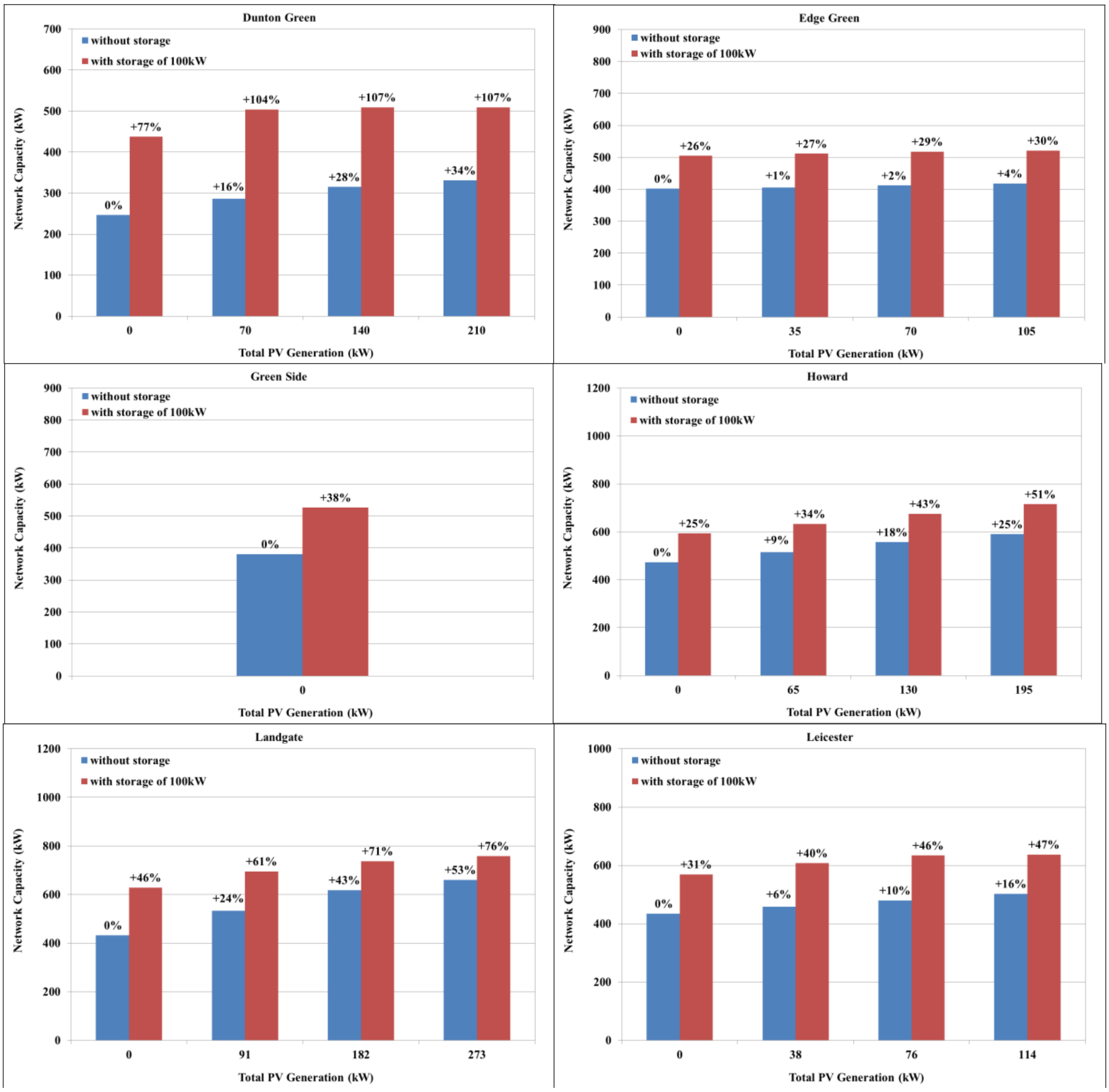


Figure 23: Network capacities with and without the installation of a storage

3.5 Network with powerPerfector installed on the feeder

Voltage regulator such as powerPerfector (pP) has also been studied for their ability to allow further network capacity increase, the network capacity with different PV penetration has been considered. As shown in Figure 24, by connecting pP unit at beginning of the feeder enabled higher capacity increase than connecting it near middle point of the feeder. This is due to the pP unit will only affect the customers that connected downstream, therefore when it was connected in the middle point of the feeder, the customer connected upper stream may still have low voltage.

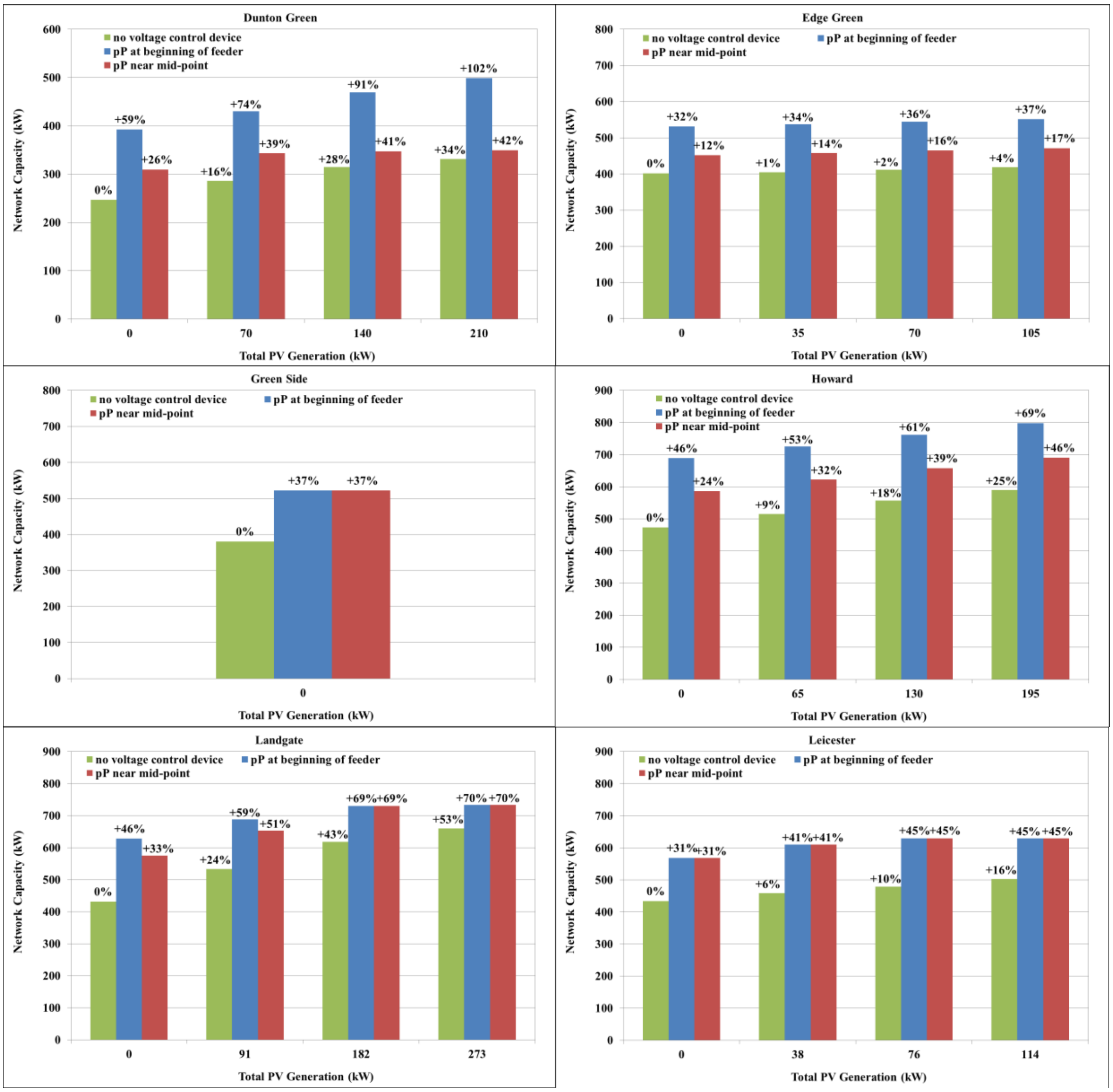


Figure 24: Network capacities with powerPerfector unit

Figure 24 shows by connecting pP unit to the network, it was able to provide between 31% to 59% additional capacity without any PV penetration. The amount of the capacity increase is directly proportional to the number and percentage of the tap positions.

3.6 Comparisons between different voltage control options: existing network

Figure 25-Figure 30 compares several different options of the voltage control equipment for six distribution networks, it can be noted that by assuming the maximum load demand is at 1kW which is close to the realistic scenario, and the network capacity of Dunton Green substation can be further increased by additional 27%. This means if total load demand is increased by more than 27%, the network will need to install either voltage control devices or undergoing major reinforcement to be able to cope with the increased demand. When considering the scenario with PV connected, it shows that the network capability can be further increased by 16%, assuming there are no power quality issues caused by the PV. By

comparing a transformer with OLTC of a maximum +5% tap, 250kVar capacitor and 100kW storage, it can be noted that the OLTC is the most effective method to increase network capability. Due to the sizes of the capacitor available are limited to prevent over compensation on the network. The energy storage is also an effective option to increase capacity, however it needs to operate in a charge and discharge mode, which means the constant supply of power over a long period is not guaranteed.

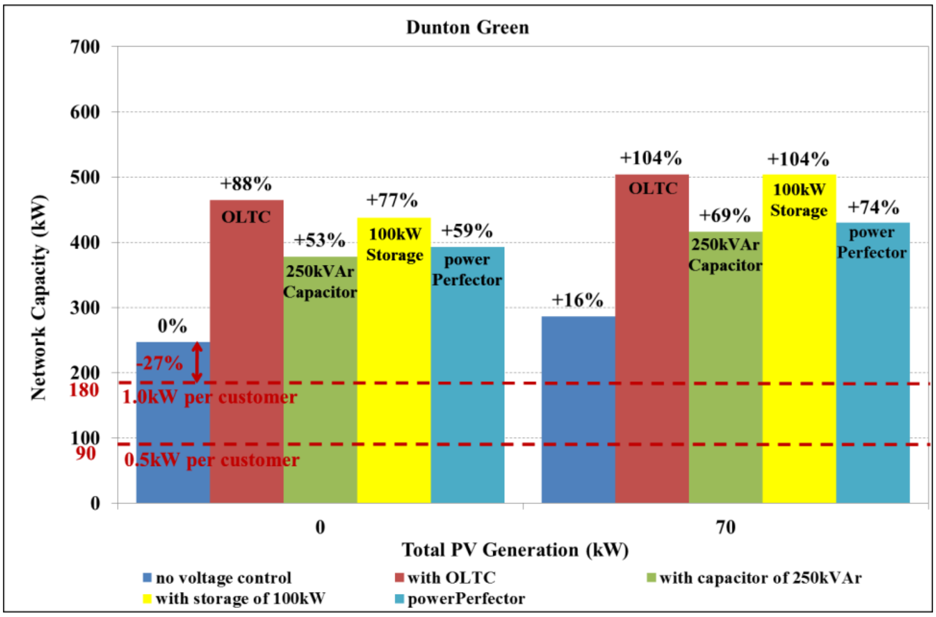


Figure 25: Dunton Green network capacities with various voltage control devices

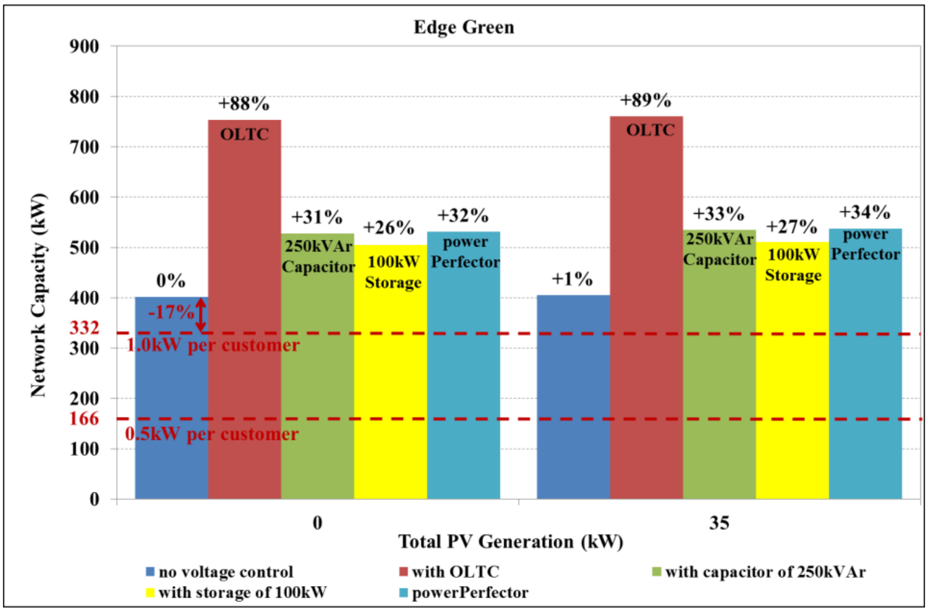


Figure 26: Edge Green network capacities with various voltage control devices

When comparing Figure 25 and Figure 26, it shows that installing capacitor and storage at Edge Green is generally not as effective as when it is at Dunton Green. This is due to different network conditions and line impedances. For example, Dunton Green has a particular feeder that has significant amount of voltage drop, and by installing voltage control equipment in this feeder will significantly increase the overall network capacity. Whereas for Edge Green, there are several heavy loaded feeders and the existing network capacity can only be increased by extra 17% compares to 27% at Dunton Green. Therefore Dunton Green has two very effective options in transformer with OLTC and storage, and Edge Green only has transformer with OLTC installation as a most effective option. Hence the existing network conditions are very important when choosing the appropriate voltage control devices.

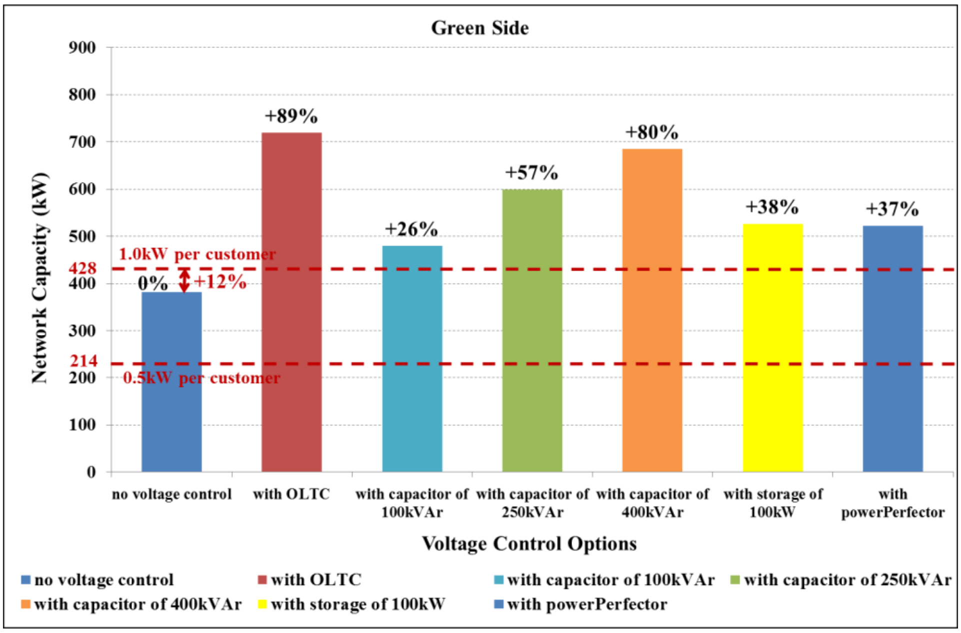


Figure 27: Greenside network capacities with various voltage control devices

Due to Greenside network has only a single PV connected according to record, therefore the study only concentrated on voltage options without PV connections. As shown in Figure 27, the distribution transformer with OLTC and 400kVAr capacitor provides the most effective options to increase the network capacity. In addition, Greenside network needs more urgent action compared to other networks as the total load demand is very close to the existing maximum capacity. Figure 27 shows the total capacity is less than the total demand assuming 1kW for each house.

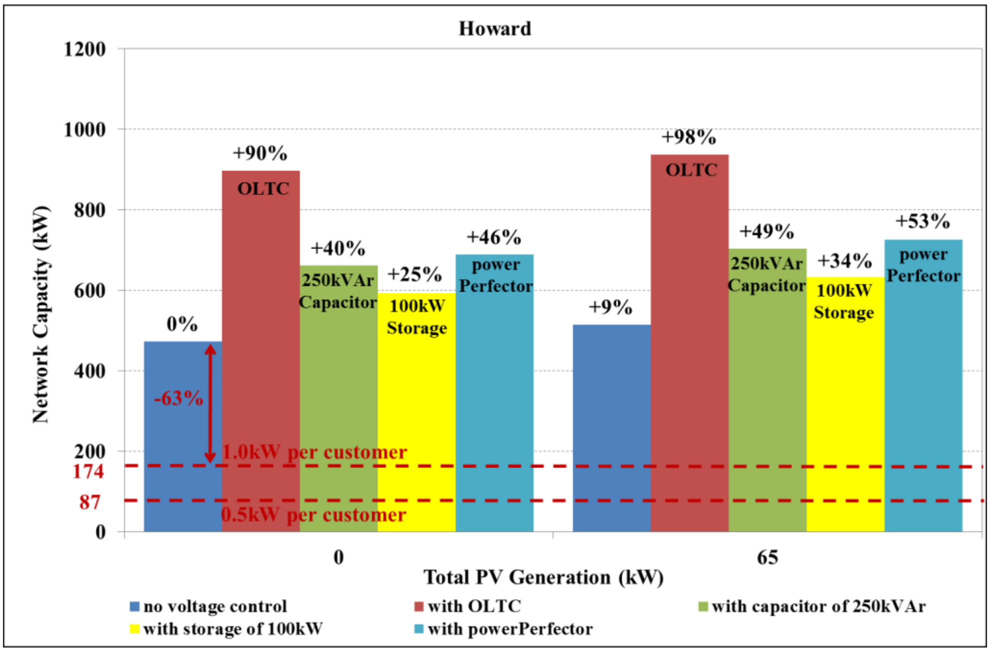


Figure 28: Howard Street network capacities with various voltage control devices

Figure 28 shows the voltage control comparisons at Howard street network, although the transformer with OLTC provides the most increase in capacity, it is also worth noting that this substation has only two feeders connected, therefore by installing capacitor or storage at both feeders could results in similar amount of capacity increase, and it is also easier and quicker to implement. Figure 29 and Figure 30 shows the comparison at Landgate and Leicester network, both substation has several feeders connected.

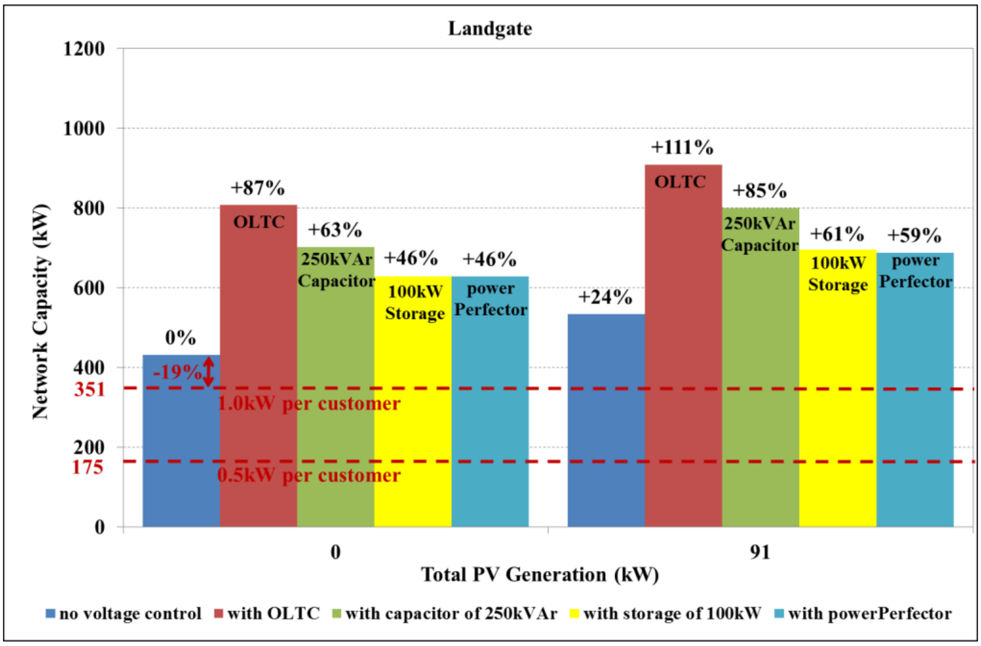


Figure 29: Landgate network capacities with various voltage control devices

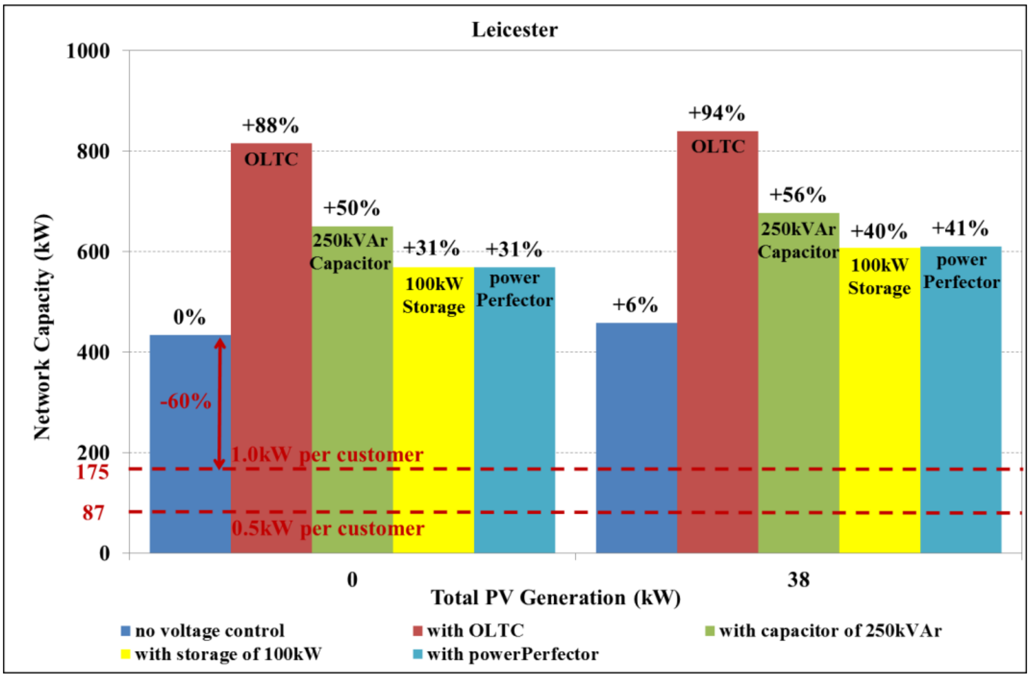


Figure 30: Leicester network capacities with various voltage control devices

As shown in Figure 29 and Figure 30, due to higher number of PVs connected at Landgate compared to Leicester, hence Landgate network will be more likely to encounter the voltage rise issues. While capacitor and storage options are also effective for Landgate network, the transformer with OLTC options seems to be more appropriate. This is also confirmed by the results shown in figures with OLTC installed, the Landgate gives +111% increase and Leicester has +94%.

3.7 **Conclusion**

The importance of voltage control in low voltage network has grown dramatically with increased new types of load and distributed generations in the network. The effects of having distributed generation such as PV and wind are relatively unknown for distribution network operators. Furthermore, the maximum amount of distributed generation and loads can be connected to each substation is also unclear.

This report investigates the amount of the additional loads can be connected to each substations with various voltage control devices installed, the boundary condition is that the voltage levels are still within the statutory limits for every nodes in the network by adding extra loads.

The devices studied in this report include capacitor banks, energy storage and distribution transformer with OLTC. A 250kVar capacitor, 100kW storage and distribution transformer with OLTC with +5% maximum tap percentage are also compared. There is a limit for maximum rating of the capacitor banks that can be installed at each substation without over-compensating the network. Similarly when selecting the size of the energy storage, it should never surplus the maximum load demand to cause reversed power flow in the network.

This study is carried out without taking consideration of the power quality issues. It was learned that by adding more distributed generations in the network would in theory increase the total capacity allowing more loads to be connected. However, this could also worsen power quality in the network by introducing additional harmonics current, causing damages to equipment that connected. Therefore distributed generation is not the ideal option to increase network capacity if they are uncontrolled. If there is embedded storage for each generator and output parameters such as power factor are properly controlled, such scenario would benefit the voltage control in the distribution network.

In general, when the voltage control is to be carried out at substation point, the transformer with OLTC provides the best solution due to the ability to boost the busbar voltage level to affect all feeders connected to it, and also lower the voltage when there is voltage rise in the network. Hence gives the largest amount of the network capacity increase. Whereas the effectiveness of other voltage control options are more dependent on network conditions.

When the voltage control is to be carried out at feeder downstream such as mid-point, energy storage provides the best solution due to its ability to absorb the excessive power at period of load demand and release it during peak demand period. This solution is generally for the substations that have one or two particular heavy loaded feeders, and other feeders have significantly less loads connected.

4. Recommendation on voltage control options

This report investigates the voltage control in LV network under several different network scenarios. The voltage control options for existing and future distribution network are given in this section. Various control techniques has been assessed throughout the project by network simulation and site trials.

4.1 On Load Tap Changer option

The distribution transformer with OLTC option is generally used to regulate and maintain the transformer secondary voltage within a permitted dead-band, the automatic voltage control relay will control the appropriate tap position used to regulate the voltage within the voltage regulation limits. The number of tap positions and steps will limit the range of the voltages it could regulate.

From the results shown in this project, the transformer with OLTC remains one of the most effective voltage control options for LV network. This is due to it is able to alter the network voltage within a wide range depending on the range of taps and amount for each tap positions.

However it is not a simple answer to say the transformer with OLTC is the most effective method compared to others, as the effectiveness of voltage control is also largely depending on the network conditions. For example when there are several feeders connected to a single substation, one of the feeders has significant higher amount of loads connected compare to other feeders, or if the cable distance is significantly longer than other feeders, therefore this feeder is likely to experience much higher amount of voltage drop at end of the feeder. In order to maintain the voltage regulation for all feeders associated with this substation, the OLTC transformer will need to use a higher tap positions to boost the voltage level at substation point, so that the voltage at end of the feeder is not below the regulation threshold. However this operation would also boost the voltage level for all other feeders, which could over boost the voltage to a level that might be too high. Therefore the voltage control unit such as voltage regulators, storage and capacitors could be more effective to use for this particular substation, due to it normally installed per feeder and at mid or end point where the maximum voltage drop occurs. It all feeders are heavily loaded and one feeder has significant more number of loads that others, then the most effective way would be to install the OLTC unit at substation and a unit such as storages further down the feeder.

The increasing number of distributed generation in the network will also limit the effectiveness of OLTC, the distributed generators such as PV panels will cause voltage rise hence changes the power flow in the network. However if each distributed generation is appropriately controlled, such as fixed power factor and operation under a voltage cap, or even controlled energy storage, then the distributed generation could be a very effective option for voltage control in LV network.

In terms of the network capacity, the OLTC could offer a significant increase for each substation over other equipment, therefore with increased load demand such as the amount of heat pump being connected, the substations with OLTC could still maintain the voltage level within the statutory limits in the future.

4.2 powerPerfector (Voltage regulator) option

Voltage regulator such as powerPerfector (pP) and MicroPlanet has the advantage of being able to connect further down the feeder to address the voltage regulation issues for any heavy loaded feeder. When the feeder has many customers and every customer has distributed generation installed, this could lead to high voltage level during the daytime with low demand, and low voltage level at period of maximum demand. The voltage regulator would be able to step down the voltage level at maximum distributed generation and boost the voltage during peak period.

However unlike other control options such as energy storage, it does not generate additional energy. For pP units that trialled for this project, the percentage per tap positions is in increment of around 4%, which could be excessive for existing distribution networks whereas the transformer with OLTC is in increment of around 1%. Each unit has 5 tap positions compared to 9 tap positions by the OLTC. This means when the voltage is over the limit set by the pP unit, it will automatically steps down 4%; when the voltage is below the set level, the unit boosts 4% in voltage level. Each unit has a single boost tap position and 3 tap positions for stepping down the voltage. The fundamental difference between the two units is the pP is operated based on a set minimum voltage.

When the unit is installed at substations, it could regulate the voltage for any particular feeder without replacing the existing transformer, therefore when the loads among each feeder is very different, the unit could be very beneficial, particularly if at a location that is difficult to install any equipment along the feeder cable.

4.3 Active filter option

It was understood that the main focus for network operators is to maintain the network reliability, and future network will also need to take consideration of the growth of new technologies effect on power quality on the network. As customer will have more access of the LV network, such as connecting PV panels into the network. Hence more control is needed for those distributed generation source, such as operating voltage cap and fixed power factor control, therefore the impact on power quality of the network could be minimised. In addition, the introduction of smart meter into customer houses could allow customer to see the network data in real time, hence some might react when there is issues such as voltage unbalance and excessive harmonics.

The harmonics is normally considered as low and high orders of harmonics, generally defined as below and above 20th order. The increasing implementation of PV and household electronics equipment will increase the harmonics level in the network. Such harmonic issues will cause several problems such as ageing effect of the transformer and cables.

Over the past years, the demand of sustainable generation has grown dramatically and there is increasing demand from local councils to allow more access to the LV network for PV connection. As the existing LV networks are designed for power flow in one direction only, the increasing amount of the PV connection will cause the power flow to be reversed and introduce more harmonics into the network. In addition this will also cause uncertainties over the protection systems, as they were designed without taking consideration of the distributed generation.

In addition, increasing proportion of the customer nowadays uses power electronics devices, which might be more sensitive to supply voltage and quality of the power supplied. With the carbon reduction target set by the UK government, there will be more and more distributed generators such as PVs connected into the network. As the loads and PV generators are all connected in single phase, therefore the voltage unbalance issue will also be worsening in the future.

This project has trialled two active filter units, in order to assess its ability to address the power quality issues and voltage unbalance in the LV network. From the results obtained during the trial, the filter units could effectively reduce the harmonics current in each phase, which would effectively allow more new types of loads and PVs to be connected in the network.

4.4 LV capacitor option

For any loads in the network will need active and reactive power, and the length of the cable will cause voltage drop. The load demand of reactive power can either be supplied from substation or by implementing the capacitor banks along the feeder cable. This project has trialled several capacitor banks manufactured by ABB, the units all being installed around mid-point of the feeder to offset the load reactive power and reduce the amount that needs to be supplied from the substation therefore less voltage drops.

The capacitor bank can be set as always switched on or switch off when it is needed, it is ideally to have a controlled capacitor bank, to match the load demand and the reactive power supplied, so that it will never over compensate the network. It is impossible to match the supply and demand in reality due to the load is constantly changing, however the unit can be controlled based on several parameters such as time of the day, voltage level, reactive power flow or current.

In addition, the voltage control using capacitor bank is less effective in the LV network compared to MV network, due to the line are more resistive. Hence for some more resistive feeders, the study shown that it gives less amount of voltage boost compares to feeders that are less resistive. The size of the capacitor can be installed are limited depending the different network conditions. Installing capacitor banks still remains an effective voltage control option for LV network, however from the economic perspective, if a large amount of voltage boost is required, it might not be cost effective compared to other equipment such as energy storage.

As for energy storage options, it was well predicted that the number of electric cars would be significant in future networks. The charge cycle for each car could last several hours, and most of customer would likely to charge them in the evening, this will cause the voltage drop during peak time to be even more significant. Hence the network may need to be further optimised and more energy storage support is needed, which might be provided by the charging stations and remote energy storages along the feeders.

While there is no significant to modernise the LV network by introducing voltage control equipment at every existing feeder at present, however this needs of introducing more technology is directly proportional to the development of distributed generation and house load changes such as electric vehicle increasing rate. The solution is not only limited to network operators but also each individual house load to limit or control the amount and quality of the power injected back into the distribution network.

Reference:

[1] "*Planning our electric future: a White Paper for secure, affordable and low-carbon electricity*", Department of Energy & Climate Change, July 2011.

Appendix: Capacity increase for six distribution networks

Dunton Green		**OLTC**	**100kVar Capacitor**	**250kVar Capacitor**	**400kVar Capacitor**	**100kW Storage**
NO PV	0%	88%	27%	53%	51%	77%
1kW PV per customer	16%	104%	45%	69%	66%	104%
2kW PV per customer	28%	120%	55%	72%	69%	107%
3kW PV per customer	34%	136%	60%	74%	72%	107%

Edge Green		**OLTC**	**100kVar Capacitor**	**250kVar Capacitor**	**400kVar Capacitor**	**100kW Storage**
NO PV	0%	88%	13%	31%	47%	26%
1kW PV per customer	1%	89%	15%	33%	49%	27%
2kW PV per customer	2%	90%	16%	35%	50%	29%
3kW PV per customer	4%	92%	17%	36%	51%	30%

Green Side		**OLTC**	**100kVar Capacitor**	**250kVar Capacitor**	**400kVar Capacitor**	**100kW Storage**
NO PV	0%	89%	26%	57%	80%	38%

Howard Street		**OLTC**	**100kVar Capacitor**	**250kVar Capacitor**	**400kVar Capacitor**	**100kW Storage**
NO PV	0%	90%	17%	40%	62%	25%
1kW PV per customer	9%	98%	25%	49%	71%	34%
2kW PV per customer	18%	107%	34%	57%	79%	43%
3kW PV per customer	25%	115%	43%	65%	88%	51%

Landgate		**OLTC**	**100kVar Capacitor**	**250kVar Capacitor**	**400kVar Capacitor**	**100kW Storage**
NO PV	0%	87%	26%	63%	90%	46%
1kW PV per customer	24%	111%	49%	85%	103%	61%
2kW PV per customer	43%	135%	72%	98%	115%	71%
3kW PV per customer	53%	160%	87%	107%	124%	76%

Leicester Avenue		**OLTC**	**100kVar Capacitor**	**250kVar Capacitor**	**400kVar Capacitor**	**100kW Storage**
NO PV	0%	88%	19%	50%	71%	31%
1kW PV per customer	6%	94%	26%	56%	81%	40%
2kW PV per customer	10%	98%	31%	62%	88%	46%
3kW PV per customer	16%	104%	37%	67%	90%	47%