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Impact of Increasing Distributed Solar PV Systems on Distribution Networks in South Africa

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***Abstract*—**South Africa is experiencing an exponential growth of distributed solar PV installations. This is due to various factors with the predominant one being increasing electricity tariffs along with decreasing installation costs, resulting in attractive business cases to some end-users. Despite there being a variety of economic and environmental advantages associated with the installation of PV, their potential impact on distribution grids has yet to be thoroughly investigated. This is especially true since the locations of these units cannot be controlled by Network Service Providers (NSPs) and their output power is stochastic and non-dispatchable. This report details two case studies that were completed to determine the possible voltage and technical losses impact of increasing PV penetration in the Northern Cape of South Africa. Some major impacts considered for the simulations were ramping of PV generation due to intermittency caused by moving clouds, the size and overall hosting capacity and the location of the systems. The main finding is that the technical impact is different on a constrained feeder vs a non-constrained feeder. The acceptable PV penetration level is much lower for a constrained feeder than a non-constrained feeder, depending on where the systems are located.

***Keywords*—**Medium voltage networks, power system losses, power system voltage, solar photovoltaic, PV.

I. Introduction

The use of alternative energy sources for consumer energy needs is becoming more popular. At the end of 2017, it was estimated that a total capacity of 285 MW (~140 000 installations) of small to medium scale solar Photovoltaic (PV) was installed in South Africa with most of the system locations unknown to NSPs [1]. Although this was only ~0.65% of the total installed capacity in South Africa at the time, this capacity has been increasing in an exponential manner. This increasing penetration poses a risk to the stability of the distribution network as the power injections from these generators change magnitude and direction of network power flows thus causing an impact on network operation and planning practices of distribution with both technical and economic implications [2]. The South African policies and standards which have been created/ amended to govern the installation requirements and penetration levels of Small Scale Embedded Generation (SSEG) are fairly new and most customers are unaware that they even exist. This along with the customers' general disregard of governing principles can result in customers installing with systems resulting in undesirable penetration levels. The challenges that can be associated with high and undesirable SSEG penetration levels are power flow fluctuations, increased technical losses, overloading of equipment such as Medium Voltage (MV)/Low Voltage (LV) transformers and cables, grid protection malfunction and voltage variation, unbalance and overvoltage [3]-[7]. Overvoltage is seen as the predominant challenge in many LV grids with PV and is also considered one of the main limiting factors when increasing PV penetration in MV/LV grids [8].

Voltage management is considered to be an existing problem in the South African distribution environment. This is due to ageing networks and infrastructure coupled with poor to no maintenance on many of the networks; as well as long spans of varying sizes of poor current carrying conductors. PV has proven to be a technology that is very intermittent in nature meaning that the output generated can increase and decrease very quickly. This is predominantly due to PV production being affected by shading due to moving clouds, resulting in uncontrolled variability. The rate at which the output power of a generator changes is called the ramp rate and for PV systems this rate is between 10% and 20% per second [9]-[11]. This is very high even when compared to another renewable source like wind generation which has ramp rates of about 10% per minute [12]. This intermittency causes fluctuations in voltage that are not always predictable or being monitored and they could occur on time scales which are too fast for conventional voltage regulation devices that take long to react [12]. Furthermore, this occurrence takes place various times in a day and this results in the voltage regulation equipment being used in a way that it was not designed for and eventually can result in progressive failure [13]. In South Africa, generally the MV/LV transformers installed on the networks are not auto-transformers and cannot auto-react to these intermittencies. This can result in an increase of switching frequency, voltage issues and customers experiencing poor quality of supply.

The maximum generation limit per customer as well as overall maximum allowable generation that can be connected to an MV network is stipulated in the utility standard NRS 097-2-3. The overall maximum generation is limited to 15% of the maximum loading of the network. This is based on maximum change in LV voltage due from generators of 3%.

II. Theory

A. Impact of Generation on Voltage in a Distribution Network

In a traditional unidirectional distribution feeder, voltage magnitude at the end of the feeder is less than the source voltage [14]. The traditional way of managing voltage on an

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MV feeder as described above includes operating the transformer by changing the tap settings, wide area control, reinforcement of networks by increasing the cross-section of the conductor (this will also reduce the impedance of the network) and the installation of voltage regulators and active transformers. However, this comes at a cost and if this equipment is not fast reacting to cater for the intermittent nature of PV, other equipment may be required. Furthermore, once PV systems are installed on the grid, they can potentially interfere with voltage management techniques and can subsequently affect the voltage profile along the feeder because the power flow may not be unidirectional anymore [14].

In some cases, even when the penetration of PV installed is low and reverse power flow does not occur, the current may decrease and result in a reduced voltage drop. This can cause an overvoltage or voltage rise situation especially at low loading conditions [14]. Some studies have also concluded that high power fluctuations, especially at high PV penetration levels could result in rapid voltage changes in the network. In [8] the voltage rise experienced in an LV distribution network is derived using the illustration in Fig. 1 where a Thevenin equivalent of the rest of the grid until the Point of Common Coupling (PCC) is used.

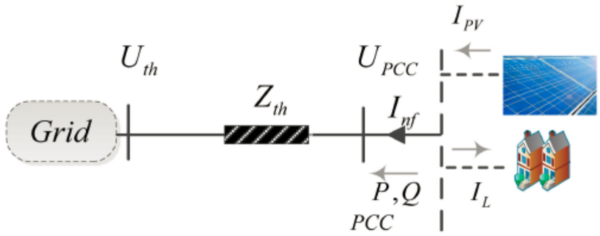

Fig. 1 Thevenin equivalent of a PV system connected on an LV network [8]

The voltage rise at the PCC when net export occurs can be calculated using (1):

$$\Delta U \times U_{th} \cong P \times R_{th} + Q \times X_{th} \quad (1)$$

where U_{th} is the Thevenin voltage; ΔU is the voltage change; P & Q is the real and reactive power exported into the grid from the PV system, respectively; and R_{th} & X_{th} forms part of the thevenin impedance of the grid.

1) Allowable Limits and Report of Voltage

The standards generally considered when assessing Quality of Supply (QoS) of a given network is NRS 048 suite of standards. Part 2 (Voltage characteristics, compatibility levels, limits and assessment methods) and Part 4 (Application guidelines for utilities) are specifically important with regards to the work in this report. These standards specify the voltage quality parameters. Furthermore, acceptable limits, compatibility levels and assessment methods for these parameters are specified.

In the NRS 048 standards voltage regulation is defined as "the ability of the steady-state Root Mean Square (RMS) voltage to remain between the upper and lower limits" [15]. The specified compatibility level for the supply voltages is as per Fig. 2. This shows that allowable levels for LV and MV voltage are ± 10% and ± 5%, respectively [15]. Furthermore, it is considered a violation of these levels if exceeded for a consecutive 10 minute period. This corresponds to the limits used by network planners in Eskom as specified in DST 34-542 (Distribution Voltage Regulation and Apportionment Limits) i.e. for MV networks is ± 5% and for LV networks is ± 10% of the nominal voltage of the network.

1	2
Voltage level V	**Compatibility level** %
< 500	± 10
≥ 500	± 5

Fig. 2 Allowable deviation from standard or declared voltages [16]

NRS 097-2-3 (Simplified utility connection criteria for low-voltage connected generators – SSEG) specifies that the maximum LV Rapid Voltage Change (RVC) is 3%. It is specifically mentioned that this is considered as best practice to account for transients induced by PV due to clouds. Furthermore a maximum voltage rise of 1% is allowable.

B. Losses and Loading

Technical losses generally consist of line, load and transformer losses. As previously discussed in [2], when DG systems are installed closer to the load then it can result in reduced systems losses. However, this is only true until reverse power flow starts to occur i.e. when generation exceeds loading requirements. This is due to the fact that line losses are proportional to the square of current magnitude flowing through the line [14]. As shown in [2] losses plotted against penetration level would resemble a U-shaped or bathtub curve.

In [16], it was shown that system losses are minimum at a penetration level of ~5%, however as the penetration level increases, losses increase and may supersede the losses with no PV installed.

With regards to line loading, two studies conducted in [17] had opposing results just because the cases were slightly different. Case 1 studied the increase of PV penetration resulted in a reduction in line loading for Mölndal area because systems provided power locally thus reducing the flow for power from the source. Case study 2 for Orust area grid resulted in an increase in line loading such that violations occurred on the line supplying the substation. This was when the PV penetration increased to 60% and higher and because the load demand had been met with excess power being transmitted to other substations in the area.

It is concluded that loading and losses are not necessarily always increasing or decreasing at set penetration levels but it always case specific and depends on a suite of factors.

III. Methodology

The objective of this work was to determine how increasing penetration of PV installed on the LV side of the grid affect voltage and losses with realistic loading conditions and PV data in South Africa. Two cases have been simulated using replica MV network models with lumped LV loads in Digsilent Powerfactory. One network was capacity and thermally constrained network and the other a non-constrained network. These were selected due to available hourly load data and generation data for a whole year. Network and generator names are confidential and will not be disclosed.

Various PV penetration levels of 15%, 30%, 50% and 75% of peak load of the network were modelled and in each of those penetration scenarios, the location of the PV systems were changed to represent cases for PV installed evenly throughout the network (All PV), installed only at the beginning of the network (Beg PV), installed only at the middle of the network (Mid PV) and installed only at the end of the network (End PV). The PV system sizes were calculated as a ratio of transformer capacity to overall PV installed capacity. Voltage, technical losses and thermal loading measurements for a whole year were recorded which were developed from performing detailed temporal quasi-dynamic simulations in these cases and analysed and compared to the case with no PV to make appropriate conclusions. Relevant standards were used to determine if any violations occur. Specific aspects from the standards are: i) MV voltage should not exceed 1.05 per unit(p.u.)., maximum thermal loading of equipment is 85%, maximum voltage change from generators should be less than 3% and power factor for small generators should be 1 [18]-[20]. Even though there is a standard that governs the specifications of the required inverter [21], customers are generally not prone to abiding by or even knowing about these specifications; hence it was assumed that the inverter will not have over-voltage protection and therefore, not switch off at high voltages as per the requirement.

IV. Case Study 1 Information and Results

This section provides some details about the network in case study 1 and highlights the key findings from the simulations completed for the scenarios mentioned above. This 22 kV/19 kV network is very constrained with the end of line voltage being less than 0.95p.u. during most times, which is in violation of the NRS 048 utility QoS standard. There are 38 transformers installed with total capacity of 2.1 MVA. The backbone length of the network is ~30 km with a total length of ~167 km. The bottom half of the network has 19 kV Single Wire Earth Return (SWER) conductor installed, which has a significantly lower current carrying capacity than the other parts of the network. The peak load recorded for 2019 was 2.74 MVA and with 0.96 leading power factor. A visual representation of the network is depicted in Fig. 3. Furthermore, the peak and average hourly load for the network for a year is depicted in Fig. 4.

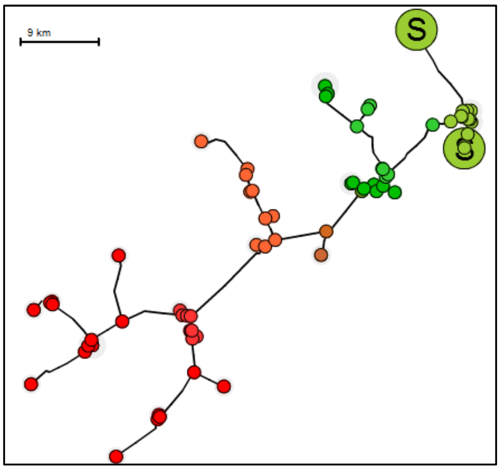

Fig. 3 Geographic diagram for case study 1 22/19 kV feeder

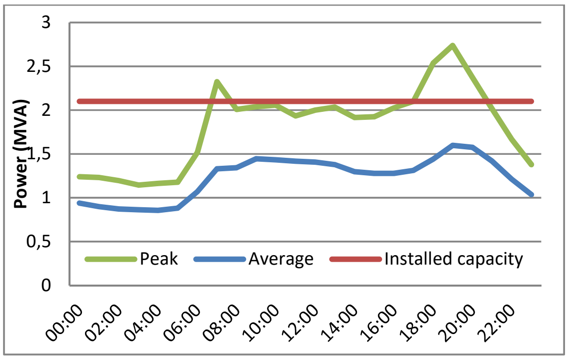

Fig. 4 Peak and average hourly demand for case study 1 22/19 kV feeder (2019)

A. Case Study 1Results

1) Impact of Ramp Rate on Voltage

The ramping of PV can significantly impact the voltage on a network and are generally caused by intermittency induced by moving clouds. The MV end of line voltage changes that occurred due to intermittency for 5 days in 2019 that had substantial ramp rates in each PV scenario for each PV penetration case is tabulated in Fig. 5. It is evident that installing PV at the end of the network results in a higher voltage change and always surpasses the allowable limits for RVC as given in network planning and NRS 048 standards (if comparable). The highest ramp was almost a 76% (of installed capacity) decrease in output power over two hours. These ramps were averaged over either an hour or two and it is therefore assumed that there will be significantly higher ramp rates that will occur in a higher temporal resolution. Furthermore, the recommended penetration of 15% of peak load actually results in a voltage change in excess of 3% in the End PV case for all 5 days selected. The beginning PV location case does not result in voltage changes over 3% in any PV penetration scenario. Moreover, the voltage changes do increase with increased PV penetration as expected.

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Date	Scenario	Highest ramp rate (% of installed capacity)	Time	MV voltage change (15% PV)	MV voltage change (30% PV)	MV voltage change (50% PV)	MV voltage change (75% PV)
01 February 2019	End PV	Decreased 75.6%	In 2 hours	6.30%	7.59%	15.11%	19.23%
	Mid PV			2.01%	2.36%	5.16%	7.13%
	All PV			1.78%	2.15%	4.81%	6.70%
	Beg PV			1.00%	1.08%	2.11%	2.87%
08 April 2019	End PV	Increased 60.6%	In 1 hour	4.71%	8.66%	12.92%	17.11%
	Mid PV			1.02%	2.21%	3.72%	5.44%
	All PV			1.68%	3.45%	5.65%	8.14%
	Beg PV			0.19%	0.59%	1.11%	1.74%
08 May 2019	End PV	Increased 66.6%	In 1 hour	6.26%	11.07%	16.71%	22.83%
	Mid PV			2.07%	3.40%	5.12%	7.13%
	All PV			2.79%	4.79%	7.34%	10.32%
	Beg PV			1.15%	1.59%	2.17%	2.88%
05 November 2019	End PV	Increased 52.3%	In 1 hour	4.14%	7.21%	10.38%	13.23%
	Mid PV			1.10%	2.10%	3.34%	4.77%
	All PV			1.66%	3.14%	4.92%	6.90%
	Beg PV			0.38%	0.72%	1.17%	1.70%
30 December 2019	End PV	Decreased 74.7%	In 2 hours	5.58%	10.14%	14.81%	19.21%
	Mid PV			1.09%	2.54%	4.34%	6.41%
	All PV			1.91%	4.06%	6.63%	9.47%
	Beg PV			0.05%	0.54%	1.19%	1.97%

Fig. 5 Voltage changes that occurred due to ramping of PV in each PVscenario and penetration case for case study 1

2) Impact of PV Penetration on Voltage

Analysis of the MV and LV p.u. voltages for each penetration case shows that the End PV case results in voltage violations as per the NRS 048 and network planning standards for all penetration cases including the 15% allowable penetration limit. Furthermore, only in the 75% PV penetration scenario results in voltage violations in all PV location cases. It must be noted that the end of line and middle of line voltages are improved in all penetration scenarios for End PV case. These voltages are also improved in the All PV and Mid PV cases for 30% - 75% PV penetration scenarios.

3) Impact of PV Penetration on Technical Losses

The results from the study show that losses are decreased until a 30% penetration level is reached only for the End PV scenario but for all other scenarios total losses decreased when compared to the No PV scenario. It seems that losses improved the most in the All PV scenario, followed by Mid PV and Beg PV.

Fig. 6 illustrates the total losses for each PV case and scenario for Case study 1. The maximum loading of the network is also improved in all PV location cases and PV penetration cases except for when PV penetration is at 75% and the PV is installed at the beginning of the network.

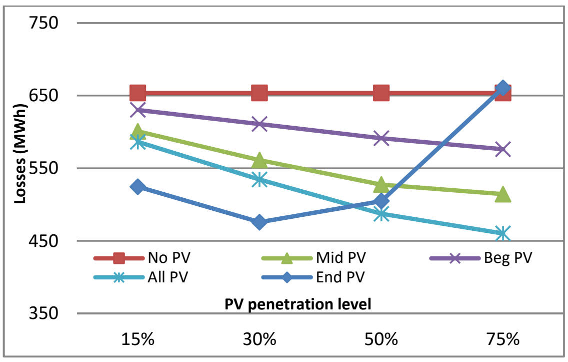

Fig. 6 Total losses in each PV penetration case for all scenarios in Case study 1

4) Impact of PV Location on Technical Losses

Fig. 6 shows the impact of location of PV systems on overall total losses for the network. PV installed at all load points on the network seems to be the best case for improving losses followed by PV being installed only at middle or only at the beginning of the network. The scenario where PV is installed at the end of the network seems to negatively impact losses after 30% PV penetration level; however, only in the 75% PV penetration scenario does the overall losses worsen to the point at which it is more than that of the No PV case. Furthermore, for the 15% PV penetration scenario the losses for the End PV case are the least. This is evident in Fig. 7 where the technical losses relative to PV generation profile for one day is depicted for each PV location case.

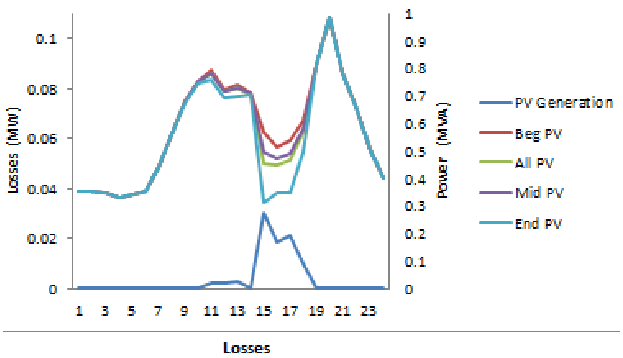

Fig. 7 Losses for one day for Case study 1 in all PV location scenarios for 15% PV penetration case

5) Impact of PV Location on Voltage

The voltage at all points is higher for End PV scenario compared to all the other scenarios as evident in Fig. 8. This figure depicts the MV voltage at the beginning, middle and end of the network in all PV scenarios for the 15% PV penetration case on 8 May 2019. This voltage “rise” effect for each scenario is consistent in all PV penetration cases where the End PV scenario results in the highest voltage change followed by All PV, Mid PV and Beg PV scenarios.

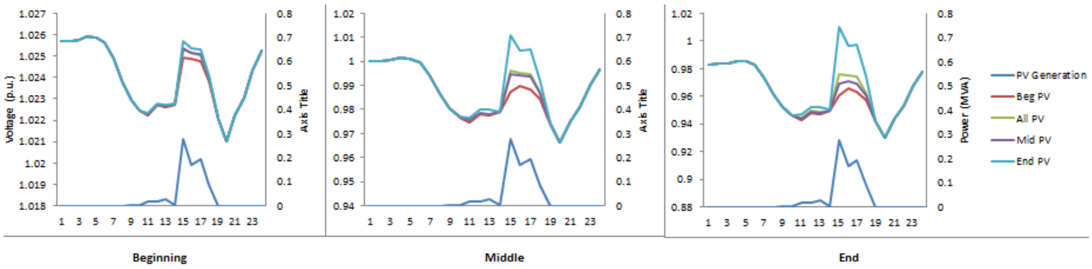

Fig. 8 MV p.u. voltage at beginning, middle and end for Case study 1 in all PV scenarios for 15% PV penetration case

V. Case Study 2 Information and Results

This section provides some details about the network in case study 2 and highlights the key findings from the simulations completed for the scenarios mentioned above. This 22 kV network is not constrained. There are 36 transformers installed with total capacity of 1.6 MVA. The backbone length of the network is ~52 km with a total length of ~114 km. there are also varying conductor sizes installed with the conductor towards the end of the network being the weakest. The peak load recorded for 2019 was 1.35 MVA with 0.9 leading power factor. A visual representation of the network is depicted in Fig. 9, along with the peak and average hourly load for the year in Fig. 10.

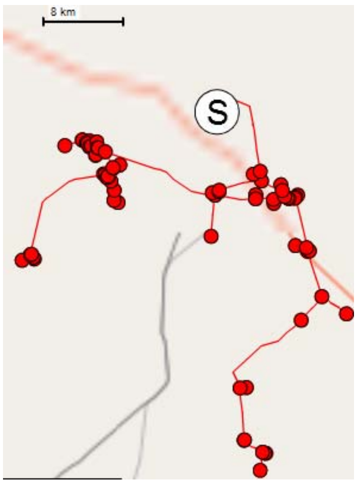

Fig. 9 Geographic diagram for case study 2 22 kV feeder

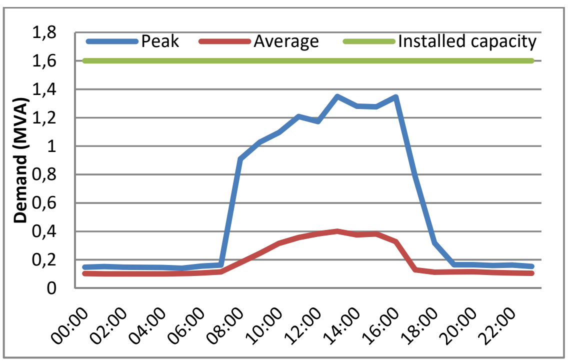

Fig. 10 Peak and average hourly demand for case study 2 22 kV feeder (2019)

1) Impact of Ramp Rate on Voltage

As previously discussed ramps caused by intermittency can impact the voltage on a network significantly. Fig. 11 shows the MV voltage changes that occurred due to intermittency in each PV scenario for each PV penetration case. It is evident that installing PV at the end of the network results in a higher voltage change and starts to surpass the allowable limits for RVC as given in network planning and NRS 048 standards, if comparable, at 50% PV penetration limit.

2) Impact of PV Penetration on Voltage

Analysis of the MV and LV p.u. voltages for each penetration case shows that the no voltage violations occur as per the NRS 048 and network planning standards for all location cases in the 15% PV penetration scenario. However, for the 30% PV penetration scenarios, voltage violations occur for the End PV and All PV cases and for the 50-75% penetration scenarios voltage violations occur for the End, All and Mid PV cases. Only the Beg PV case results in no violations for all PV penetration scenarios. It must be noted that the end of line and middle of line voltages are improved in all penetration scenarios for End, All and Mid PV cases in all penetration scenarios in that order for improvement.

3) Impact of PV Penetration on Technical Losses

The results from the study show that PV decreases total losses to below that of the No PV scenario until a certain penetration level is reached. This penetration level is ~37% for the End and Mid PV scenarios, whereas it is between 53% and 55% for the All and Beg PV scenarios. The scenario that improves losses the most is the Beg PV one and the scenario that improves it the least is the Mid PV case with End PV not so far behind. Fig. 12 illustrates the total losses recorded for each PV case and scenario for case study 2. It is interesting to note that the total losses are relatively stable for 15% to 30% PV penetration, after which the losses increase linearly for all cases.

4) Impact of PV Location on Technical Losses

Fig. 12 shows the impact of location of PV systems on overall total losses for case study 2. PV installed at the beginning of the network seems to be the best case for improving losses, followed by PV being throughout the network. The scenario where PV is installed only at the middle of the network seems to negatively impact losses after 30% PV penetration level.

Date	Scenario	Highest ramp rate (% of installed capacity)	Time	MV voltage change (15% PV)	MV voltage change (30% PV)	MV voltage change (50% PV)	MV voltage change (75% PV)
01 February 2019	End PV	Decreased 77.4%	In 2 hours	0.88%	1.79%	2.98%	4.42%
	Mid PV			0.65%	1.34%	2.24%	3.33%
	All PV			0.81%	1.65%	2.76%	4.10%
	Beg PV			0.21%	0.47%	0.81%	1.23%
02 February 2019	End PV	Decreased 93.4%	In 1 hour	1.08%	2.14%	3.49%	5.08%
	Mid PV			0.81%	1.62%	2.66%	3.89%
	All PV			1.00%	1.98%	3.24%	4.73%
	Beg PV			0.28%	0.59%	1.00%	1.49%
08 May 2019	End PV	Increased 66.7%	In 1 hour	0.84%	1.63%	2.67%	3.94%
	Mid PV			0.65%	1.25%	2.04%	2.99%
	All PV			0.78%	1.52%	2.48%	3.66%
	Beg PV			0.26%	0.49%	0.79%	1.15%
30 December 2019	End PV	Decreased 79.4%	In 2 hours	0.90%	1.81%	2.97%	4.36%
	Mid PV			0.67%	1.36%	2.26%	3.33%
	All PV			0.83%	1.67%	2.76%	4.06%
	Beg PV			0.22%	0.48%	0.83%	1.26%

Fig. 11 Voltage changes that occurred due to ramping of PV in each PV scenario and penetration case for case study 2

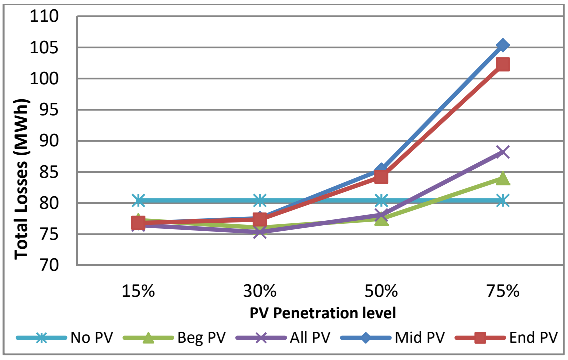

Fig. 12 Total losses in each PV penetration case for all scenarios for Case study 2

The maximum loading for each PV penetration case is worsened when compared to the no PV case; however these values still remain well within limits. The Mid PV case results in the worst maximum loading especially in the 75% PV penetration scenario.

5) Impact of PV Location on Voltage

The impact on voltage in this case study was considered to be quite minor. Fig. 13 depicts the MV voltage at the beginning, middle and end of the network in all PV scenarios for the 15% PV penetration case on 27 April 2019. The End PV scenario results in the highest end of line voltage change as a result of PV, followed by the All PV, Mid PV and lastly the Beg PV scenario.

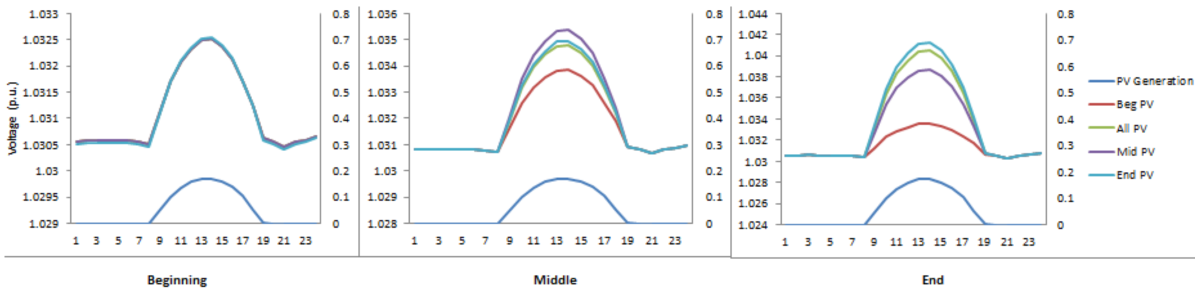

Fig. 13 MV p.u. voltage at beginning, middle and end for Case study 2 in all PV scenarios for 15% PV penetration case (27 April 2019)

VI. Conclusion

Two case studies were conducted to determine the impact of increasing PV penetration on voltage and technical losses on distribution networks in South Africa. The networks were different in that one was a thermally and capacity constrained network and the other was a lightly loaded network. It was noted that the major impacts that are to be considered when installing PV on a network are:

1. Ramping of PV generation due to intermittency caused by moving clouds,
2. Size and overall penetration level of all systems and
3. Location of the systems.

The predominant similarity in the results of the study is that as PV penetration increases so does the impact on losses and voltage on the network. Total losses can surpass the No PV case after a PV penetration level of ~40% for Case study 2 and do not surpass the No PV case for Case study 1. This is due to the fact that Case study 1 network is constrained with max loading over 100% almost at all times and Case study 2 is not a constrained feeder with significantly low loading (average 8.3%). It can be argued that the 15% penetration level (as per acceptable limit in NRS 097-2-3) for Case study 1 can result in network planning violations with respect to voltage change due to intermittency and overall voltage rise. However, this does significantly depend on the location of the PV systems and the End PV case is not suitable for this network. Furthermore, when comparing voltage variation results of both studies, it is noticeable that the voltage change % is significantly lower for Case study 2 than for Case study 1. For e.g. at a ramp rate of ~67%, the voltage change ranges for 15% penetration was 1.15% - 6.26% for Case study 1 and 0.26%-0.84% for Case study 2. This concludes that the voltage changes for the constrained feeder are significantly higher than for a non-constrained feeder. Therefore, the acceptable PV penetration level may differ due to status of the network.

The results showed that PV generators can experience extremely high ramp rates due to intermittency, as high as 93.4% of installed capacity in one hour. This results in an equally significant voltage change which the South African networks, being old and poorly designed (conductor length, sizes and number of customers) are not well-equipped to handle these changes. While it may seem that the addition of PV results in improved losses and voltage for the constrained feeder case (Case 1), it must be noted that the maximum loading on the network is increased and voltage variations result in network planning limits being violated.

It must be highlighted that temporal resolution of data will have a more significant impact on the results. Future work includes detailed studies into voltage management techniques that can be adopted for networks in South Africa that are beginning to experience higher penetration of non-compliant embedded generators.

VII. Recommendations

As seen from the results, location of PV and overall capacity to transformer ratio can have a significant impact on voltage and losses. It is recommended that these impacts be determined prior to accepting installations for connection to the grid in developing countries.

It is further recommended that the wear and tear due to voltage variations caused by intermittency be investigated to determine the financial impact to NSPs. The impact on losses (decreasing/increasing) must also be considered when analyzing the economic impact of installing PV on the grid.

Many methods to overcome voltage variation impacts have been mentioned in research including active reactive power compensation from inverters, demand response, MV/LV transformers, active power curtailment and energy storage systems, however; there is a lack of comprehensive analysis of advantages and disadvantages of them [8]. It is recommended that these be investigated if increased PV penetration levels are considered in future. It must further be noted that even though the limits for PV on MV/LV networks are specified in the NRS standards, customers may not necessarily take cognizance of these or even know they exist. Therefore, voltage impacts as seen in the results above for higher PV penetration levels may be a reality for some networks in South Africa and the previously mentioned methods of overcoming these impacts may very well become a requirement soon.

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