Investigating the impact of integration of photovoltaic plants at a microgrid level: A case study.

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Abstract

South Africa has seen an increase in the integration of renewable resources in the distribution network for improved reliability, clean energy footprint and energy costs. The Council for Scientific and Industrial Research (CSIR)'s main campus in Pretoria has embarked on the introduction of distributed generation (DG) from solar in its electricity distribution network, and plans to add wind and biogas systems. The integration of large numbers of DG in an electrical grid poses various technical challenges for system operators and distribution utilities as they affect grid operating conditions. This paper investigates impacts of photovoltaic (PV) integration to an existing CSIR distribution network. DIgSILENT PowerFactory simulation software tool is used to model and simulate the existing network. The simulation results of the network performance before and after the integration of PV plants are compared.

Keywords: Distributed generation; renewable generation; network assessment; integration; micro-grids.

1. Introduction

South Africa depends mainly on fossil fuels for its total energy needs with 90% of the total primary energy needs being supplied by fossil fuels and coal providing about 77% of the total national energy needs [1]. The country has taken initiatives to incorporate more renewable energy (RE) generation sources in its energy mix by 2030 as stated in the Integrated Resource Plan (IRP) 2010, as well as in the draft IRP of 2018 [2]. In order to reduce the dependency on electrical energy from fossil fuels, distributed renewable energy technologies are becoming increasingly important in the energy supply systems of many countries [3]. In South Africa, the Renewable Energy Independent Power Producer Procurement Program (REIPPPP) has played an important part by facilitating private sector investment into grid-connected RE generation. Furthermore, the load shedding implemented by Eskom in 2008, 2014 and 2015 as well as the high cost of electricity and need for reliability of supply also contributed to the increased uptake of PV systems in the residential and commercial/industrial sectors [4].

The introduction of DGs in power systems offers a number of opportunities depending on the penetration levels, location and the operational characteristics of the distribution system [5]. Some of the benefits include cleaner production of power, improved reliability of power supply and also reduced losses in both the transmission and distribution systems. However, grid integration of RE generation into existing electrical networks poses technical challenges. This is because distribution systems were initially designed to operate without generation on the distribution system or at the customer load side, hence the need to investigate impacts of integration of DG on the electrical network to assist grid planning and operation. The CSIR main campus in Pretoria introduced DG generation (solar PV) in its network. The DGs are integrated into the existing 11 kV medium voltage (MV) and 400 V low voltage (LV) network. About 8 MW of solar PV is planned to be integrated in the existing grid [6] and the implementation will be done in phases. As the PV penetration level increases, integration issues may arise. It is against this background that this research study focuses on solar PV plants integration on the existing electrical network. The aim is to analyse and investigate impacts of integration of PV plants on the grid. Some of technical impacts include, voltage variation, reverse power flow, increasing of short-circuit capacity at the point of connection, protection coordination, islanding issues, harmonics etc. [4].

Grid impacts as specified in distribution and RE codes were assessed. The assessment was done in line with the requirements as set out in South African distribution and RE codes. This paper consists of the following sections: network description, methodology, results and discussion as well as the conclusion.

2. Network description

Fig 1 below shows the network single line diagram (SLD) used for the study. The network is supplied by the City of Tshwane (CoT) at 132 kV infeed. Two 15 MVA transformers step down the 132 kV high voltage (HV) to 11 kV (MV). The campus reticulation consists of five MV (11 kV) rings feeding a combination of substations and mini substations which then provide the buildings' LV supplies. The network is a ring or loop type system but is operated radially with normally open points on each ring. Power factor correction equipment is installed on the 11 kV busbar in the main substation. About 1920 kWp capacity of PV plants have been integrated in the grid, Table 1 shows a list of the PV plants on the campus. According to the grid connection code for Renewable Power Plants (RPPs) [7], all CSIR plants fall under category A, and this category includes RPPs with a power rating of less than 1 MVA.

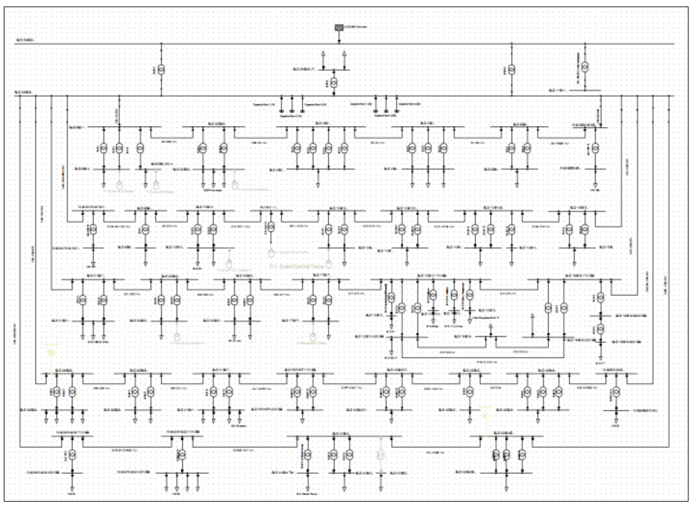

Fig. 1. Single line diagram

PV Plant	Connection Voltage	Power Output
PV1 Single Axis Tracker	11 kV	558 kWp
PV2 Dual Axis Tracker	400 V	203 kWp
PV3 Rooftop	400 V	250 kWp
PV4 Rooftop	400 V	167 kWp
PV5 Rooftop	400 V	147 kWp
PV6 Rooftop	400 V	172 kWp
PV7 Rooftop	400 V	263 kWp
PV8 Rooftop	400 V	160 kWp

Table 1. PV Plants

3. Methodology

This section presents the methodology followed to investigate the PV impacts on the existing distribution network. The process is summarised in Fig 2. The analyses and simulations were done using DIgSILENT PowerFactory software, a computer aided engineering tool for the simulation and analysis of power systems. Two scenarios were investigated.

Scenarios I - The network is assessed at Times of System Peak (TOSP) and maximum PV generation.

Scenarios II - The network is assessed at Minimum System Load (MSL) and maximum PV generation.

The campus TOSP recorded was in summer February 2016 at 14:30 pm while lowest minimum load was observed in December 2016 at 11:30 am during Christmas holidays.

The CoT infeed represents the external grid for the purposes of this study. The solar PV generation was modelled using the in-built DIgSILENT PV system, operated in power factor control mode and maintaining a unity power factor at the point of common coupling (PCC). Maximum solar PV plants generation of 80% was assumed.

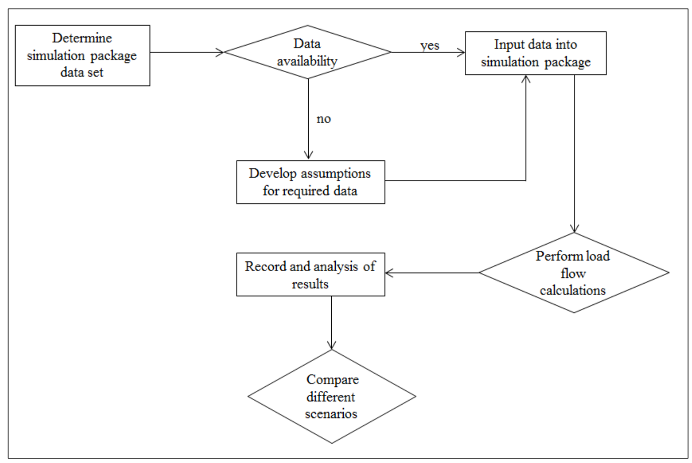

Fig. 2. Process flow of methodology

The load flow study was performed on the developed network model to assess the impacts of existing PV plants, i.e. assess the voltage profiles, short circuit levels and network power losses for scenarios with and without PV plants.

- **Voltage profiles**

The integration of DGs into the distribution network can result in power flow changes from unidirectional to bi-directional in a radial structure [8], and in general, the voltage level is expected to rise due to DG reverse power. The reverse power flow results in the overloading of the distribution feeders and excessive power losses. Fig. 3 below shows SLD of power system to explain the occurence of power flow reversal in a power system with DG. The system is operating at unity power factor.

The net load of the system, P_{net}, is given by equation (1)

$$P_{net} = P_{load} - P_{gen} \qquad (1)$$

Where

P_{load} = active power consumed by the load,

P_{gen} = active power supplied by the DG.

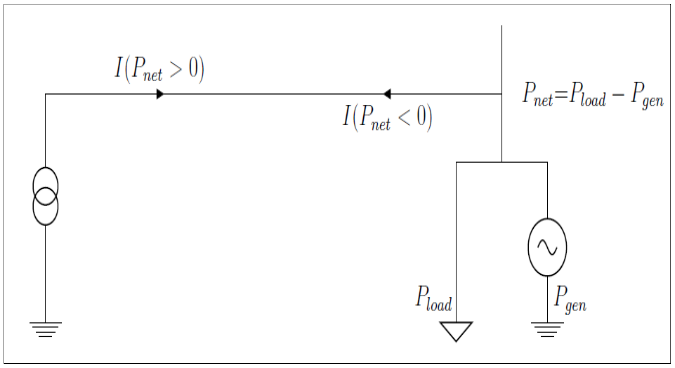

Fig. 3. Power System with DG

In a centralized power system, P_{gen} = 0 and P_{net} = P_{load} a positive quantity which corresponds with unidirectional power flow from source to load. When P_{gen} exceeds P_{load}, the resultant net load becomes negative, corresponding with reverse power flow. The load node becomes the generator node in the power system, as result power flows in the opposite direction of conventional design [9].

Load flow analyses were performed for different system conditions with and without the PV plants, to check for both voltage violations and loading of equipment (i.e. lines/cables and transformers). The South African distribution network code [10] was used for the technical assessment of the network. The voltage levels for normal steady-state conditions were maintained within 90-110% range for LV side (400 V three-phase, 230 V single-phase), as per NRS 034-1 standards [11]. The limits are also specified in NRS 048 [12]. The thermal loading ratings of network equipment must not be exceeded under normal operating conditions, i.e. 100% of normal continuous thermal rating of both transformers and all lines/cables. Fig 5 compares voltage profiles before and after PV connection.

- **Short circuit levels**

The analyses conducted show that the presence of PV systems affect the short circuit levels of the network. The installation of new generators in the distribution networks potentially increases the level of short circuit capacity [13]. They create an increase in the fault currents compared to normal conditions at with no PV systems installed in the network.

Short circuit studies were performed with and without PV to determine the magnitude of short circuit current. They were conducted using the IEC 60909 fault calculation standard. The fault levels at the point of supply were provided by CoT shown in Table 2.

External Grid Parameter	Value
Max 132 kV Short Circuit Current I"k max	19.14 kA
Min 132 kV Short Circuit Current I"k min	9.57 kA
132 kV External Grid X/R	Ratio 10

Table 2. External grid parameters

- **Network power losses**

According to [9] system losses are a direct consequence of reverse power flow. The active power loss, P_{loss}, in a conductor is given by equation (2).

$$P_{loss} = I^2 \cdot R \qquad (2)$$

Network losses analysis were performed to determine the effect on the network losses with and without integration of PV plants and the simulation results for both cases are shown in Table 3 and 5 respectively.

4. Results and Discussion

This section provides the results obtained from two investigated scenarios.

4.1 Scenarios I - Times of System Peak loads.

4.1.1 Voltage Profile Analysis

Table 3 shows the campus simulation results obtained from load flow analyses for selected buildings with PV plants connected on the 400 V bus.

Busbar (400 V)	Voltage Before PV (P.U.)	Voltage After PV (P.U.)	ΔV%
Building A	0.981	0.984	0.3
Building B	0.976	0.982	0.6
Building C	0.983	0.986	0.3
Building D	0.971	0.978	0.7
Building E	0.983	0.987	0.4
Building F	0.951	0.955	0.4
Building G	0.986	0.991	0.5

Table 3. Busbar voltages

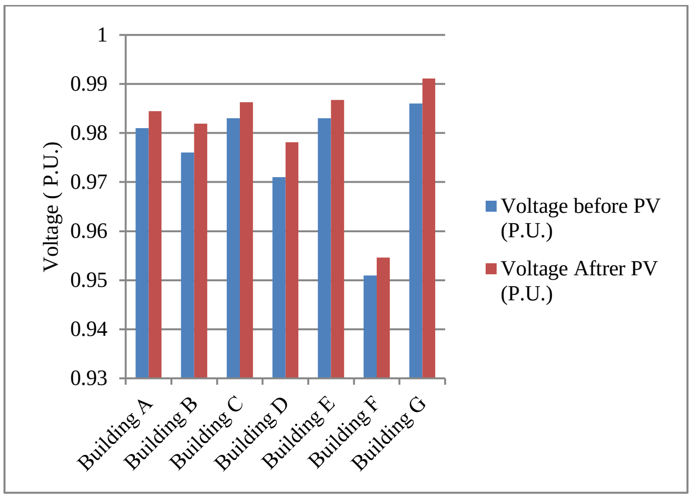

Fig. 4. Voltage profiles with and without PV connection

The simulation results revealed no thermal overload of equipment and bus voltage violation before or after the integration of PV plants, but voltages at various buses around the campus slightly increased with PV connected on the grid compared to the scenario without PV plants, see Table 3 and Fig 4. All the load bus voltages were found to be within the required regulatory requirement of ±10%.

4.1.2 Short-circuit Analysis

Three phase short circuit current were calculated for all busbars across the campus. Fig. 5 shows the short circuit currents for the selected system buses before and after PV integration on the 11 kV busbar.

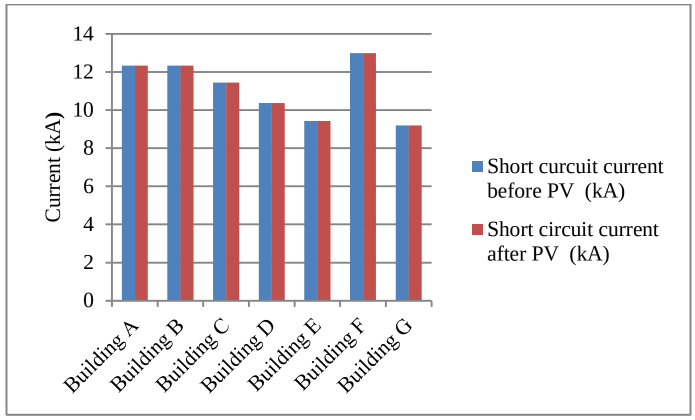

Fig. 5. Short circuit currents

Campus simulated short circuit current results before and after PV connection showed negligible change. Literature on the impacts of PV system integration mentioned that the fault contribution from a single small PV unit is not large and it will have little effect on the increase of the level of short circuit currents, as PV systems are considered as one of the least contributors to fault currents, since they employ inverters for their connection to the grid.

4.1.3 Network power losses analysis

The results of this work showed that the integration of PV systems within the CSIR network at TOSP resulted in a decrease in the grid power losses, both active and reactive power as shown in Table 4. It is evident that adding a number of small capacities of PV systems can have an effect on the losses and have a great benefit to the system.

System grid losses	**Losses before PV integration**		**Losses after PV integration**	
	Active power (kW)	Reactive power (kvar)	Active power (kW)	Reactive power (kvar)
	290.21	542.54	286.68	472.56

Table 4. Network losses at TOSP

4.2 Scenarios II - Minimum System Load

4.2.1 Voltage Profile Analysis

Table 5 shows the campus simulation results obtained from load flow analyses for selected buildings with PV plants connected on the 400 V.

Busbar (400 V)	Voltage Before PV (P.U.)	Voltage After PV (P.U.)	ΔV%
Building A	0.985	0.988	0.3
Building B	0.982	0.987	0.5
Building C	0.987	0.99	0.3
Building D	0.978	0.984	0.6
Building E	0.985	0.989	0.4
Building F	0.956	0.959	0.3
Building G	0.990	0.995	0.5

Table 5. Busbar voltages

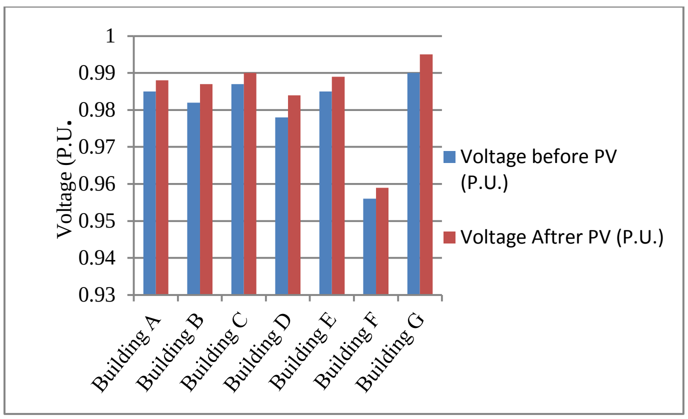

Fig. 6. Voltage profiles with and without PV connection

The bus voltages at minimum loading have increased compared to TOSP voltages but were still within the required regulatory requirement of ±10%.

4.2.2 Short-circuit Analysis

Fig 7 shows the short circuit currents for the selected system buses before and after PV integration on the 11 kV busbar.

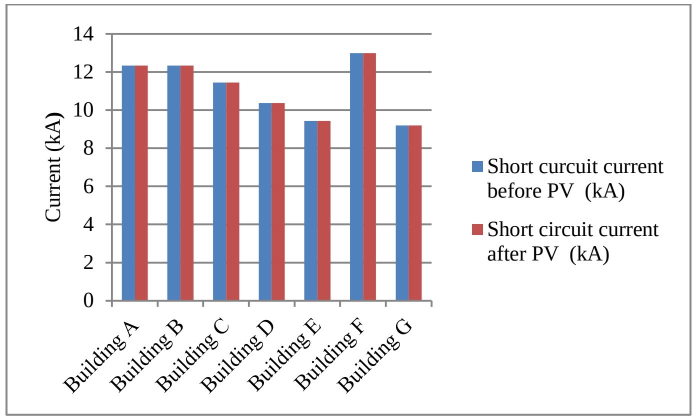

Fig. 7. Short circuit currents

4.2.3 Network power losses analysis

Table 6 system losses at minimum loading, there is slight increase in losses.

System grid losses	Losses before PV integration		Losses after PV integration	
	Active power (kW)	Reactive power (kvar)	Active power (kW)	Reactive power (kvar)
	259.34	309.82	265.55	320.92

Table 6. Network losses at MSL

5. Conclusion

Impacts of PV integration into the distribution network have been investigated for different scenarios. Simulation results showed that increasing PV capacity influences power flow, voltage variation and, losses. The following conclusions were drawn from this study.

- The integration of solar PV plants on the CSIR distribution grid has caused an increase in voltage level, but no voltage violations were recorded on all busbars and equipment were within their thermal operating limits and this is good for power quality improvement for both scenarios.
- There is not much difference in three phase short circuit current results for both with and without PV plants.
- The grid losses for the campus resulted in decrease with the PV plants integrated on the grid both active and reactive power at TOSP and this is a very positive contribution both in terms of energy savings and grid efficiency whereas at minimum loading there is slight increase in losses.

Future Work

Future work will need to include more scenarios. The locations and penetration levels of DGs in the network should be included in order to determine how the network will react under different levels of PV penetration.

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