THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Performance Evaluation of Distribution System Interconnected with Solar PV Plants Using DIgSILENT

Moilwa Stella
M.Sc. Student, Department of Electrical Engineering, University of Botswana, Botswana
Setlhaolo Ditiro
Senior Lecturer, Department of Electrical Engineering, University of Botswana, Botswana
Sakala Japhet
Retired Professor, Department of Electrical Engineering, University of Botswana, Botswana

Abstract:
Many African countries, such as Botswana, receive high insolation that can be used to generate electricity. However, they still rely on thermal power generation and imports from neighbouring countries through various African power pools. Thermal generation methods result in an increase in carbon footprint. Therefore, in pursuance of the global climate change goals, the Government of Botswana has subscribed to allow all end users with the capacity to install solar rooftops and sell extra electricity to the power utility. These interconnections of solar PV plants to the grid are bound to bring challenges to the steady state system performance. This research, therefore, evaluates the performance of the integrated system focusing on the greater Gaborone distribution system (GGDS), where five government projects are being piloted. The study has adopted two scenarios by providing a performance comparative analysis between the system baselines to a solar integrated system using DIgSILENT Power Factory software. The system studies conducted include power flow, effects on voltage and line loading. This research found out that integrating PV plants to GGDS distribution network improves voltage profiles and a decrease in overall percentage loading of the feeders and interconnectors. However, some notes could only permit a limited loading. In conclusion, the implications of the effects of solar PV on the distribution system differ from one circuit to another; therefore, it calls for utilities to conduct an intensive network assessment for each particular feeder before interconnecting with solar.

Keywords: *Distributed Generation (DG), Renewable Energy Sources (RES), performance evaluation, distribution system, Photovoltaic (PV), penetration levels, DIgSILENT*

1. Introduction

The government of Botswana (GoB), like most nations, has pledged to reduce greenhouse gas (GHG) emissions to zero by 2036 [i]. In pursuance of these climate change goals, GoB, through the only utility, Botswana Power Corporation (BPC), is driving the development of renewable energy projects with guidelines that are meant to allow self-generation of electricity to permit selling extra electricity to the grid.

The motivation behind carrying out this study relies on this initiative. In this regard, many industries, institutions, and shopping malls that have installed PV generation plants or are considering developing new ones are already connected to the grid, especially in greater Gaborone. However, the increasing integration of Distributed Generation (DG) into the grid requires an extensive analysis because it comes with a number of technical, quality, economic and research-related challenges [ii]. Most distribution system networks were originally designed on the basis that the system has a single source of voltage on each feeder. The inclusion of multiple Renewable Eenergy Sources (RES) departs from this original notion. Therefore, extensive research is currently ongoing at a global scale to ensure a robust operation of the grid in the presence of these DGs. Therefore, it is with this background that this detailed study is proposed to determine effects on voltage profile and line loading using a greater Gaborone BPC distribution system (GGDS) as a base case.

Effective and efficient interconnection of solar PV plants with the grid is critical in both steady-state and transient-state operations. While the connection of PV plants to the distribution system should improve the energy mix, de-load the system, and reduce network losses in the utility's system, the performance of the system needs to be investigated. Although there is an increasing understanding of the effects of solar penetration on performance, further investigations are needed. In particular, it is important to determine how many solar systems the network can host and the guiding principles. The findings of the research provide knowledge to address the implications of connecting solar PV systems to the distribution system.

The study has various benefits, including improving understanding of the effects of PV systems on the distribution system and establishing operational and performance margins of the solar generation plants, which provides a basis for proposing a policy framework to be recommended for planners.

2. Literature Review

According to [iii], two research methodologies used to study the performance of grid interconnected with solar PV plants are numerical and experimental investigation methods. The studies presented here are restricted to an investigation using an experimental approach, which appears to be the most significant approach used by researchers in this field. The literature indicates that interconnecting solar PV (SPV) plants to the grid affects the active and reactive power reliability because the power produced is subject to variations which subsequently affect the voltage profile, voltage stability and protection of the distribution grid [vi].

The author in [v] carefully analyzed grid interconnection of the LV distribution network and concluded that buses with a higher number of clients connected to their different phases, in addition to an uneven distribution across phases and distances to the transformer, are facing a troublesome scenario, having a greater probability of causing imbalances in the grid. Consequently, these buses and their adjacent ones will have a higher voltage fluctuation when microgeneration starts being injected into the network. In 2015, [iv] found out that solar PV integrations in the distribution grid have both positive and negative effects, with significance in increasing the voltage profile and decreasing line loading and losses. These improve the steady state stability of the grid.

According to a study conducted in [viii] to establish which level of penetration causes problems, it was noted that the maximum penetration level of a feeder was always higher than 50% except on feeders with maximum load. Certain studies were conducted to determine the effects on the distribution lines in relation to changing or increasing the penetration level, and the conclusion was that increasing penetration levels lead to an increase in losses [viii]. [iv] who used the exact sizes of the available rooftop drew the same conclusions and attributed this to reverse power flow, which can increase the loading of the line [ii].

On the other hand, [ix, x] studied the voltage profile at the point of common coupling (PCC) due to the connection of the SPV plants. They reported that the effect of the nature and profile of the load connected to the weak distribution grid in the presence of PV has not been studied before. Hence, it was important since the voltage instability may depend not only on the parameters of the distribution grid but also on the nature and profile of the connected distributed generator and load [x]. The study was done using a comprehensive simulation method and simple mathematical modelling to analyze the effect of varying magnitudes of loading patterns on the voltage of the distribution system. The proposed model describes a method to estimate the permissible PV penetration ratio for the distribution feeder, which helps in the selection of overhead conductors to improve the X/R ratio, utilization of the on-load tap changing facility within the distribution transformer and connecting/disconnecting flex loads for improving PV penetration.

Authors in [x, xi] also assessed the post-grid technical impact (Demand Profile; Power Factor at the PCC and found out that the load profile was significantly distorted due to the active generation of the SPV, the power factor at the PCC bus deteriorated within the periods of active solar PV generation [xi]. One weakness noted from the study is that the paper obtained results manually; a simulation could have been performed for comparison. This study and the current research are relevant in that they both assess the impact of DGs. The current research uses the recommended practical interventions depending on the problem caused. The study has also clarified the effects to be considered, i.e. effects on load/demand profile on the power transformers, utility power factor, harmonics, reactive power demand, and utility voltage Profile at the point of common coupling. Taxonomy of typical distribution feeders with various levels of PV penetration to determine which penetration levels create voltage or current problems were studied in [xiii]. It was noted that the Maximum PV penetration generally decreases as the distance from the feeder source to the PV system increases. However, most feeders still tolerate moderate to high PV penetrations, even for PV systems near the end of the feeder. A simulation and analysis approach uses a cloud shadow model to recreate the variable output power of both distributed and large, centralized PVs at various locations on a feeder [xiii]. This is done to help distribution planners better understand and predict these likely impacts on voltage quality and avoid overly conservative decisions on the amount of PV installed on a feeder.

It can be seen that solar PV integration has attracted implementation and research in different areas such as LV distribution networks, positive correlation between peak loading and solar generation, profile at the PCC, behaviour with relation to the feeder source and many more. Even though studies indicating the effects of solar PV penetration in different voltage systems have been conducted, no implementation or active research has been carried out in Botswana since the inception of the solar rooftop programme.

3. Method

To achieve desirable results, modelling and simulation were carried out on the BPC distribution system with and without interconnection of the solar PV plant to compare the two cases. The goal was to determine the effects of interconnecting solar in a distribution system. The authors also wanted to test the effect of different PV penetrations on performance. The considered distribution grids are radial, ring and/or a combination of both types and the maximum demand is over 200MVA. Substations that fall under the area are numerous. The largest substation is equipped with 2X40MVA, 132/11kV transformers. Each substation supplies a dedicated area and its environs and also acts as an alternative source. There are existing solar grid interconnections in the area, such as the 1300kW Plant in Phakalane and the distributed small-scale residential solar rooftop installations. All these use grid power as backup. DIgSILENT Power Factory software, which is dedicated entirely to designing and analysing power systems, was used in this work.

3.1. Grid Areas Models

Modelling was done on the selected three commercial grid areas where the projects for the government initiative are currently being piloted, as shown in the Greater Gaborone in table 1. The national roof top net metering program is being piloted in five areas in Greater Gaborone: Airport Junction Mall (APJ), Bank of Botswana (BOB), Okavango Diamond Company (ODC), Botho University (BU) and Diamond Trading Company (DTCB). The program is limited to the system-wide aggregate capacity of 10MW for the first 12 months, while 2MW is reserved for domestic consumers, and the rest is rolled out for commercial use. Tlokweng residential grid area was also studied to determine the effects on residential network.

Grid Area	Load Zone	Capacity	No. of Buses
Gaborone Block 8 Industrial	Commercial and industrial	APJ-2.2MWp	15
		DTCB: 950kWp	
		ODC-Future	
Gaborone Government Enclave	Commercial and light Industrial	BOB-500kWp	13
Gaborone Kgale View	Commercial	BU-200kWp	11
Tlokweng Residential Feeder	Residential	35kWp	66

Table 1: Modelled Grid Areas

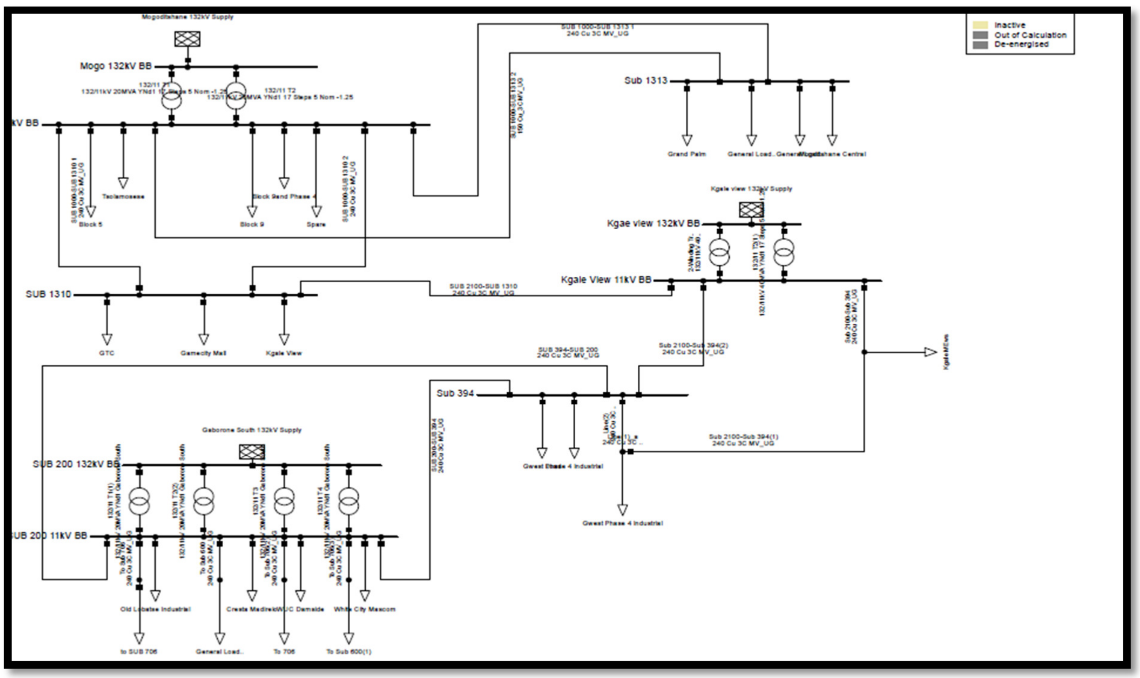


Figure 1: Grid Model Gaborone Kgale View Grid Area: Botho University

Sub-1313 is located at Gamecity Mall and is supplied through 11kV 150mm^2 XLPE interconnectors from Sub 1000, a 132/11 kV 2x 20MVA substation located in Mogoditshane. There is also an 11kV 240mm^2 XLPE cable terminating at Sub 2100, 132/11 kV 2x 40MVA substation. This Sub-2100 also interconnects with SS 394 as an interconnector cum feeder at Kgale View. SS 394 links with Sub 200, a 132/11 kV 4x 20MVA. All the 11 kV feeders emanating from therein pick up loads of Cresta, BITRI, Madirelo, Fairgrounds, Extension 14, UB-FET, Old Lobatse Road Industrial, White City, New Naledi, Main Mall, Parliament Annexure A, South African Embassy, State House, WUC Dam side, G West Phase 4 Industrial, Part of G West residential, White City, Main Mall, American Embassy, Museum, Extension 5, Old Industrial KBL, Station, Algo, Tlokweng Central, Rail Park Mall and Tlokweng Botshabelo ward.

4. Results and Discussion

Voltage profile and line loading were the Load flow Analysis (LFA) performance parameters the authors evaluated in this paper. The distribution grid data obtained from BPC were in their raw state. This data was processed by computing the positive, negative and zero phase sequence system parameters. The total energy and power consumption for the areas were given by the utility company. The following sub-sections present the findings of the performance evaluation of GGDS interconnected with SPV plants against the baseline. The effect of integrating SPV plants at different penetrations on voltage profile and line loading is presented. Under LFA limits, the steady state results for all simulations are analyzed against the criteria of allowable voltage and thermal limits. As per the Electricity Supply Regulations of 1988 of Botswana, a healthy system voltage should be maintained at ±5% for all nominal voltage levels. BPC System thermal limits for transformers and transmission lines are 80% of the nominal rating. Exceeding these limits can reduce the life expectancy of the line or cable [xv]. The effect of PV system in terms of voltage rise and reverse power flow is examined. The case study has been done with different combinations of PV and load.

4.1. Baseline Scenario

4.1.1. Voltage Profiles

In this sub-section, the base results for the four grid substation feeders and loads are presented. Sub-section 3.1.1 presents the voltage profiles while 3.1.2 presents the line loadings. In table 2, we present the grid areas, the substation name and codes, and load names as used by BPC, rated voltages, actual voltage levels (real, p.u values) and percentage voltage drops (error) are also presented. Table 2 summarizes the results of the base case for the substations and loads of considered locations. The voltage deviations are within the accepted limits, where most are less than the rated voltage by a very small margin. The positive value of +0.071% is only noticed at Gaborone Kgale view.

Grid Area	Substation	Load	Rated Voltage (kV)	Voltage Level (kV)	Voltage (pu)	Error (%)
Gaborone Block8 Industrial	Sub-2200	APJ	11	10.9	0.99	-0.01
	Diamond Park SS	DTCB & ODC	11	10.7	0.98	-0.02
Government Enclave	Sub 800	BOB	11	10.6	0.97	-0.03
Gaborone Kgale view	Sub-1310	BU	11	10.22	0.929	0.071
Tlokweng Sub 1300 CB 9L5 Feeder	Tx 172 LV BB	Residential	0.4	0.38	0.943	-0.057
	Tx 2632 LV BB	Residential	0.4	0.39	0.966	-0.034
	Tx 87 LV BB	Residential	0.4	0.38	0.950	-0.050
	Tx 228 LV BB	Residential	0.4	0.38	0.945	-0.055
	Tx 204 LV BB	Residential	0.4	0.37	0.916	-0.084

Table 2: Bus Voltage Levels and Drops for Base Case

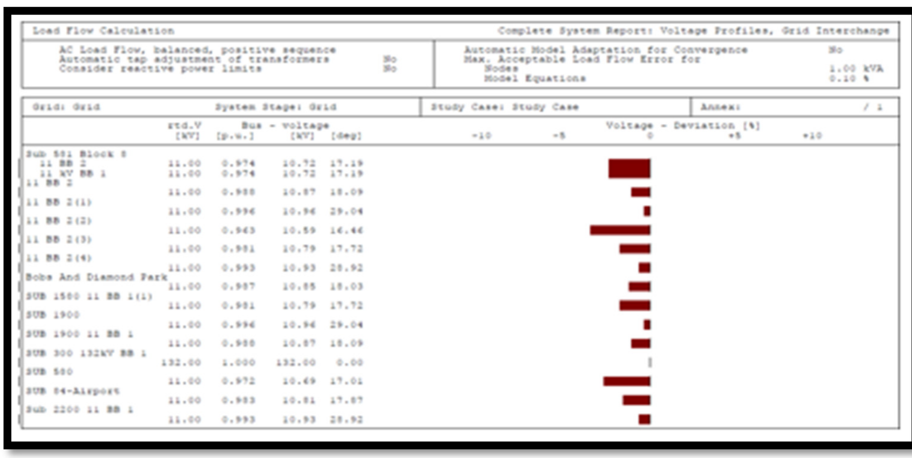


Figure 2: Bus Voltages for Base Case of Gaborone Block 8 Industrial Grid Area

The typical voltage profiles of Gaborone Block 8 grid area in figure 2 show a decrease in voltage. The voltage deviations are due to the line losses and it varies depending on the length of the line or the cable.

4.1.2. Line Loading

The baseline line loading for all the grid areas was obtained, and these are presented in table 3. The results show that the selected feeders are loaded below 80% except '*Toff feeder to DOL 21'*, which is loaded at 88.19%. A typical line loading diagram for Gaborone Government Enclave area is shown in figure 3.

Area	Feeder/Interconnector	Percentage Loading (%)
Gaborone Block 8 Industrial Area	Sub-1900-Sub-2200 Incomer 2	21.62
	Sub Diamond Park SS	18.23
Government Enclave Area	Sub 800-Government Enclave Feeder	32.58
Gaborone Kgale view Area	Sub-1000-Sub-1310 Interconnector 1	26.46
	Sub-1000-Sub-1310 Interconnector 2	17.17
Tlokweng Sub 1300 CB 9L5 Feeder	To Tx 166	38.12
	To Tx 148	16.58
	To Tx 84	37.63
	To Toff DOL 21	88.19
	To Toff M151	73.71

Table 3: Normal Bus Feeder/Interconnector Loading

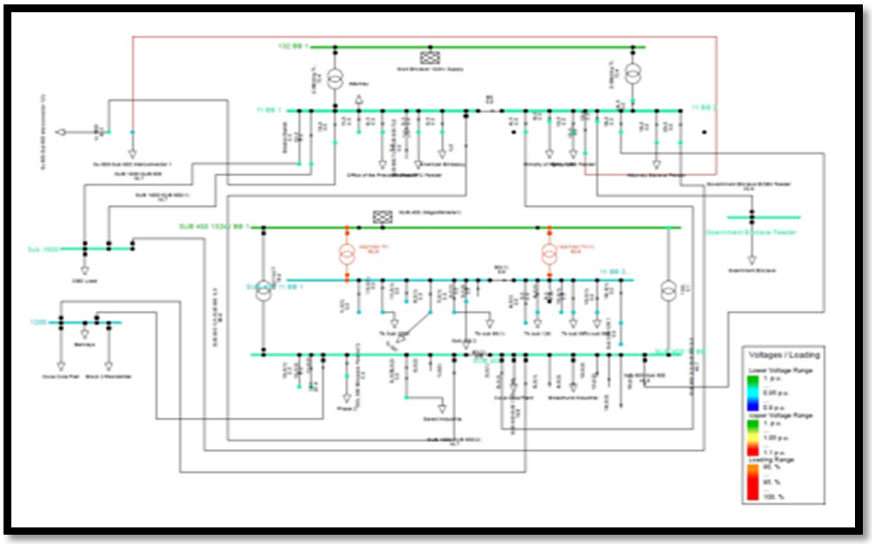
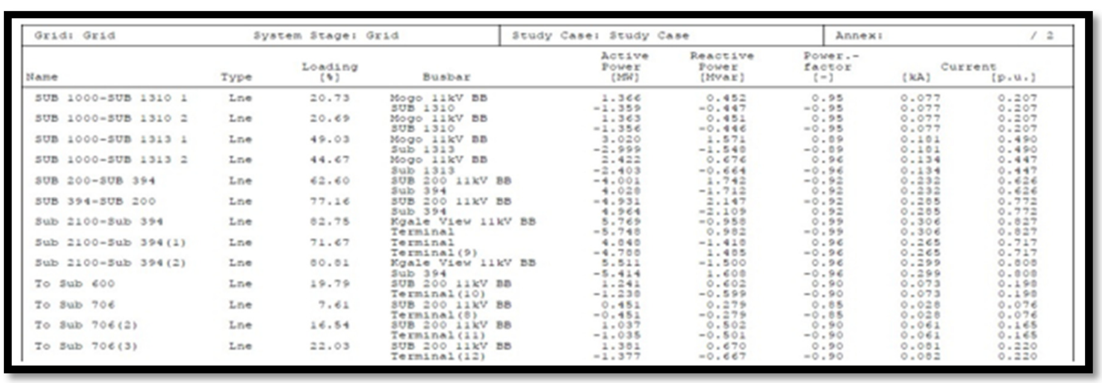


Figure 3: Feeder/Interconnector Loading Government Enclave Grid Area

In figure 3, the Government Enclave grid area is presented, and the feeders loaded more than 80% are shown in color red. The interconnector from Sub 800 to Sub 600 is through a 240mm[2] XLPE with a design rating of 30A loaded at 99.8%. Another overloading is at Sub 400 132/11kv transformers loaded at 92.3%



Grid: Grid | System Stage: Grid | Study Case: Study Case | Annex: / 2

Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power.-factor [-]	Current [kA]	Current [p.u.]
SUB 1000-SUB 1310 1	Lne	20.73	Mogo 11kV BB	1.366	0.452	0.95	0.077	0.207
			SUB 1310	-1.359	-0.447	-0.95	0.077	0.207
SUB 1000-SUB 1310 2	Lne	20.69	Mogo 11kV BB	1.363	0.451	0.95	0.077	0.207
			SUB 1310	-1.356	-0.446	-0.95	0.077	0.207
SUB 1000-SUB 1313 1	Lne	49.03	Mogo 11kV BB	3.020	1.571	0.89	0.181	0.490
			Sub 1313	-2.999	-1.548	-0.89	0.181	0.490
SUB 1000-SUB 1313 2	Lne	44.67	Mogo 11kV BB	2.422	0.676	0.96	0.134	0.447
			Sub 1313	-2.403	-0.664	-0.96	0.134	0.447
SUB 200-SUB 394	Lne	62.60	SUB 200 11kV BB	-4.001	1.742	-0.92	0.232	0.626
			Sub 394	4.028	-1.712	0.92	0.232	0.626
SUB 394-SUB 200	Lne	77.16	SUB 200 11kV BB	-4.931	2.147	-0.92	0.285	0.772
			Sub 394	4.964	-2.109	0.92	0.285	0.772
Sub 2100-Sub 394	Lne	82.75	Kgale View 11kV BB	5.769	-0.958	0.99	0.306	0.827
			Terminal	-5.748	0.982	-0.99	0.306	0.827
Sub 2100-Sub 394(1)	Lne	71.67	Terminal	4.848	-1.418	0.96	0.265	0.717
			Terminal(9)	-4.788	1.485	-0.96	0.265	0.717
Sub 2100-Sub 394(2)	Lne	80.81	Kgale View 11kV BB	5.511	-1.500	0.96	0.299	0.808
			Sub 394	-5.414	1.608	-0.96	0.299	0.808
To Sub 600	Lne	19.79	SUB 200 11kV BB	1.241	0.602	0.90	0.073	0.198
			Terminal(10)	-1.238	-0.599	-0.90	0.073	0.198
To Sub 706	Lne	7.61	SUB 200 11kV BB	0.451	0.279	0.85	0.028	0.076
			Terminal(8)	-0.451	-0.279	-0.85	0.028	0.076
To Sub 706(2)	Lne	16.54	SUB 200 11kV BB	1.037	0.502	0.90	0.061	0.165
			Terminal(11)	-1.035	-0.501	-0.90	0.061	0.165
To Sub 706(3)	Lne	22.03	SUB 200 11kV BB	1.381	0.670	0.90	0.081	0.220
			Terminal(12)	-1.377	-0.667	-0.90	0.082	0.220

Figure 4: Percentage Loading for Gaborone Kgale View Grid Area

Typically, the line loading results for the Gaborone Kgale View grid area are presented in figure 4. In this area, all the selected feeders are loaded below 80% except the interconnector between Sub-2100–Sub-394, which is loaded at 82.75%, and Sub 2100-sub 394(2) loaded at 80.81%. Also provided in the figures are the busbar type, Active (P) and Reactive Power (Q), Power factor and current. The line loading for the other three areas considered is presented in table 3.

5. Effects of Solar PV Plants Integration on the Existing Grid

The performance of the GGDS integrated with SPV plants is determined under this section using different penetration levels for the four grid areas, namely Gaborone Block 8 industrial area, Gaborone Government Enclave, Gaborone Kgale View Grid area and Tlokweng Residential feeder. The maximum demand for the grid areas is 43.825MW, 50.051MW, 20.058 MW and 0.75MW, respectively. The SPV plants are physically located at the selected three commercial grid areas, except for the Tlokweng Residential Feeder, where the PV plants are installed randomly. Each of these installed SPV plants has its own rated capacity. However, for purposes of this study, PV penetrations are estimated as a percentage of the maximum demand, assuming that BPC cannot allow solar PV plants to exceed the maximum permissible feeder loading. Moreover, [17] guides that the Rooftop system (RTS) should be sized such that it generates no more than 110% of the previous 12 months' consumption. Table 4 indicates the calculated percentages of the active power that will be integrated into the grid at different penetration levels of the full load. The distributed PV scenarios are shown in table 4.

PV Penetration Level	Block 8 Industrial	Government Enclave	Kgale View Area	Tlokweng Residential Feeder
30%	13.148 MW	15.150 MW	6.017 MW	0.226 MW
60%	26.295 MW	30.301 MW	12.035 MW	0.452 MW
90%	39.443 MW	45.451 MW	18.052 MW	0.678 MW

Table 4: Solar PV Power Penetration Levels for Different Grid Areas

Although it does not hold true for all equipment, for all the integrations, a power factor of 1 was considered, meaning that there is active power production only and no reactive power capability because most PV inverters are only set up to inject active power.

Figure 5 presents a load flow diagram of Tlokweng Residential Feeder solar PV integration. The results of the load-flow are tabulated in table 5.

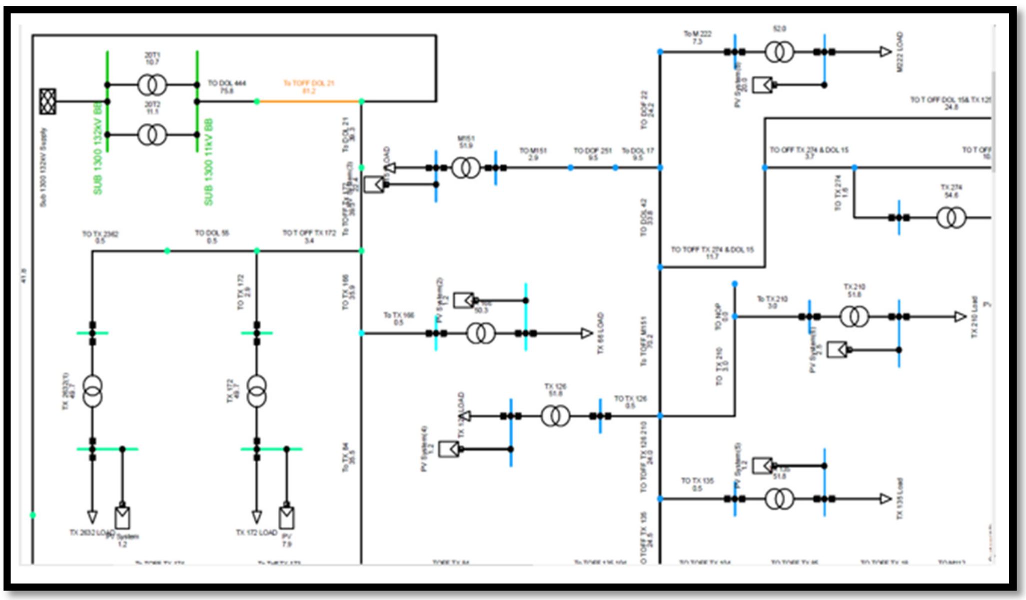


Figure 5: Part of Load Flow Diagram of Tlokweng Residential Feederrea with Rooftop Solar PV Integrations

5.1.1. Effects on Voltage Profile

The effect of connecting PV system to the existing distribution network on voltage at different penetration levels is presented in table 5. The active power input model was used to specify the active power values of the system due to the unavailability of meteorological data to undertake a solar calculation. A sample for Gaborone Government Enclave is shown in figure 6. Compared to the base case, integration of photovoltaics causes an improvement in voltage profile for selected buses such as Sub 2200 11kV BB of Gaborone Block 8 Grid area, which improved from -0.01 to +0.01 and 0.0pu for the 0%, 30%, 60% and 90% penetrations, respectively. Most show an increase except the Government Enclave sub 800 BOB feeder, which shows +0.03% to -0.02% in the 60% and 90% penetration levels. For all the Tlokweng buses, from 60% to 90% penetration levels, there is a decrease from +ve to negative values. This could indicate that the buses can only accommodate up to 60% penetration levels. The 90% will cause reverse flow. The impact of solar PV on the entire grid was investigated further for other penetration levels of 60% and 90%. Figure 6 presents the grids' voltage levels at 90% penetration levels for Gaborone Government Enclave grid area.

Area	Bus	Penetration Levels (%)			
		0	30	60	90
Gaborone Block 8 Grid Area	Sub-2200 11kV BB	-0.01	0.01	0.01	0.00
	Diamond Park Switching Station	-0.02	0.00	0.01	+0.02
Government Enclave	Sub 800 BOB Feeder	-0.03	0.03	0.03	-0.02
Kgale View	Sub 1310 11 kV BB	0.071	0.97	1.00	1.03
Tlokweng	Tx 172 LV BB	-0.057	0.032	0.03	-0.028
	Tx 2632 LV BB	-0.034	0.032	0.03	-0.028
	Tx 87 LV BB	-0.050	0.047	0.044	-0.041
	Tx 228 LV BB	-0.055	0.053	0.059	-0.045
	Tx 204 LV BB	-0.084	0.079	0.075	-0.070

Table 5: Voltage Drops in Pu for Selected Buses

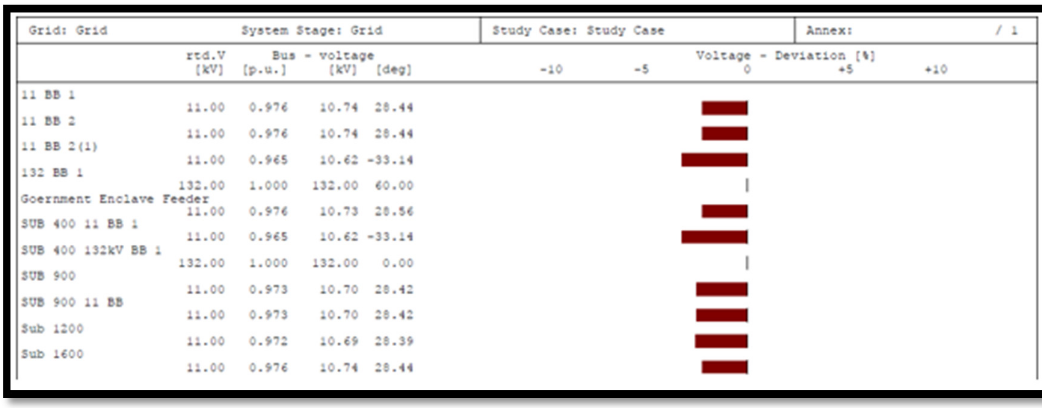


Figure 6: Bus Voltage Level/Percentage Loading for Gaborone Government Enclave Area at 90% PV Penetration

As evidenced by the voltage profile in figure 6 and table 6, an increase in penetration caused an increase in grids' voltage levels, such as the Diamond Park switching station, where the voltage drop decreased from -0.02 % at the base case to 0.01 % at the 60% penetration level. The results obtained for impacts on voltage levels, as summarized in table 6, portray that overall, the voltage drops decreased, which means that solar PV integrations improve the voltage profile of a power system.

In addition, solutions are recommended where there are system violations. The results obtained from solar plant integrations with Tlokweng CB 9L5 residential, a radial distribution feeder with a transformation of 11/0.4, reveal an increase in voltage level. This was further proven by simulating at different penetration levels. Moreover, in all the simulations, the increase in voltage level did not result in any system violation (i.e above ± 5%). The voltage level for the radial grid Tlokweng correlated with the expected theoretical impact discussed in the literature review.

The effects on voltage profiles obtained for the rest of the grid areas, namely Gaborone Block 8 Industrial area, Government Enclave and Kgale View area where there is already solar or where there is a plan for solar PV integrations, are similar to that of the radial grid even though all these grid areas are meshed networks. The only difference is that the voltage levels for the bus bars are almost the same, unlike in the Tlokweng Residential Feeder, where bus voltage levels are dependent on the distance from the Sub 1300-the source substation. For all the different penetration levels, there were no voltage violations.

5.1.2. Impacts on Line Loading

Table 6 presents the impacts of solar PV plants on line loading for the four grid areas.

Area	Bus	Penetration Levels (%)			
		0	30	60	90
Gaborone Block 8	Sub-2200 11kV BB	21.62	15.29	9.26	4.75
	Diamond Park Switching Station	18.23	12.52	7.30	1.75
Government Enclave	Sub 800 BOB Feeder	32.58	21.19	5.3	11.3
Kgale View	Sub-1000-Sub 1310 Interconnector 1	26.46	26.65	45.86	13.39
	Sub-1000-Sub 1310 Interconnector 2	17.17	17.29	29.70	8.76
Tlokweng	Tx 172 LV BB	39.91	38.12	34.47	32.05
	Tx 2632 LV BB	16.58	16.58	5.74	5.39
	Tx 87 LV BB	40.43	37.63	34.03	31.64
	Tx 228 LV BB	88.19	85.11	76.39	71.65
	Tx 204 LV BB	82.37	73.71	65.87	61.78

Table 6: Percentage Selected Feeder/Interconnector Loading- Four Grid Areas

According to the results in table 6, the integration of Solar PV in most areas caused a reduction in line and feeder loadings. These exclude Sub 800 BOB Feeder, which presents a rather increase from 60% to 90% penetration level. Both KgaleView Sub-1000-Sub-1310 and interconnectors 1 and 2 have increased from 30% to 60% penetration levels of 26.6% to 45.86% and 17.29 to 29.70%, respectively. This increase in line loading can be attributed to the fact that whenever the substation load demand is met, power needs to be transmitted to other substations in the area. Overall, increasing penetration level causes a decrease in line loading percentage.

Theoretically, it is expected that an increase in solar PV power penetration results in a reduction in line loading. This is the case with the integration of PV in all the selected four grid areas except for the Gaborone Government Enclave. This holds true because the integration of solar power provided power locally and reduced the flow of power from the source, where instead, the line loading for the cables increased with an increase in penetration levels.

However, for Gaborone Government Enclave grid area, the integration of PV resulted in an increase in line loading with increase in PV penetration to the line supplying the substation where PV was coupled. This increase in line loading can be attributed to the fact that whenever the substation load demand is met, power needs to be transmitted to other substations in the area. At a penetration level of 60% and higher, the interconnector from Sub 800 to Sub 600 led to a line loading violation to about 99.5% as shown by the red coloured line in figure 7. This, therefore, means that no more solar Power Plants can be integrated beyond 60%.

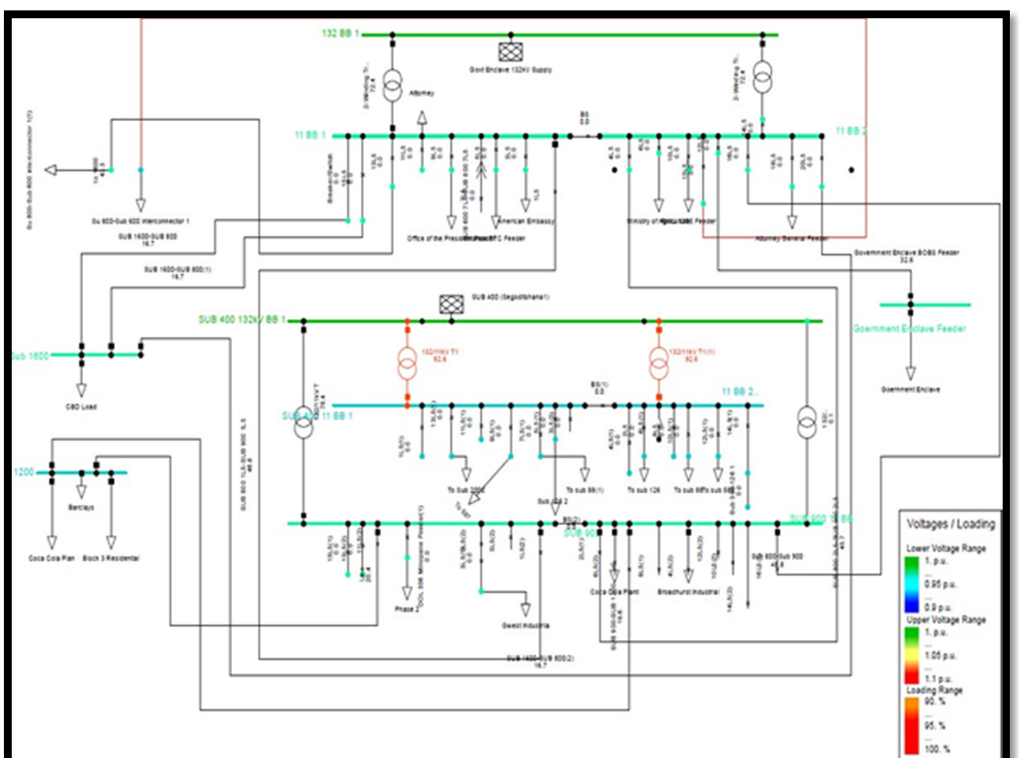


Figure 7: Feeder/Interconnector Loading Government Enclave Grid Area

6. Conclusion

The study was conducted to evaluate the performance of the greater Gaborone Distribution system with selected grid areas interconnected with solar PV plants. The study shows that the types and characteristics of primary and secondary distribution systems used in the greater Gaborone area for BPC power systems are a combination of radial and meshed network distribution systems. The objectives of the research were met and the following are the main conclusions formulated for the selected grid areas where the pilot projects are being implemented using the grid data received from BPC.

- Integrating solar PV plants into the greater Gaborone distribution network causes an increase in voltage levels and hence improves the voltage profiles. The voltage levels and voltage profile increase with an increase in penetrations in all the selected grid areas.
- Integrating rooftop solar PV power plants into the grid decreases the overall percentage loading of the feeders and interconnectors of the grid substations. The decrease applies to all grid areas integrated with PV at different penetration levels (30%, 60% and 90%).
- It is highly unlikely that the connection of the PV plants will result in significant reverse power flows as most of the installations are rated lower than the substation loads.

7. Acknowledgements

The authors would like to express their heartfelt gratitude to Botswana Power Corporation for allowing them to conduct research on their network and providing all the relevant data.

8. References

i. State of Nation Address, by His Excellency the President of Botswana, Dr Mokgweetsi Eric Keabetswe Masisi, 9th Nov 2020.
ii. Khyani, H. K., & Vajpai, J. (2014). Integration of solar PV systems to the grid: issues and challenges. International Journal of Engineering Research & Technology (IJERT), ETRASCT, 2(3), 393–397.
iii. P. Kenneth and K Folly, "Voltage Rise Issue with High Penetration of Grid Connected PV", 2014.
iv. E. Mulenga, "Impacts of integrating solar PV to an existing grid Case Studies of Molndad and Orust energy distribution (10/0.4kv and 130/10 kV) grids," Master's thesis in Electric Power Engineering, Dept. Ener. Envir., Chalmers Univ. of Tech., Gothe., Sweden, 2015.
v. R. Yan and T. K. Saha "Investigation of Voltage Stability for Residential Customers due to High Photovoltaic Penetrations", IEEE Transactions on Power Systems, Vol. 27, No. 2, pp. 651–662, May 2012.
vi. E. A, E. Kwofie, G. Mensah and V.S. Antwi, "Post Commission Grid Impact interfacing," 2019.
vii. Balamurugan, K., Srinivasan, D., & Reindl, T. (2012). Impact of distributed generation on power distribution systems. Energy Procedia, 25, 93–100.
viii. Parthiban Perumal, Agileswari K. Ramasamy and Au Mau Teng, "Performance Analysis of the DigSILENT PV Model Connected to a Modelled Malaysian Distribution Network," International Journal of Control and Automation Vol. 9, No. 12 of 2016.
ix. J. Widen, E. Wäckelgård, J. Paatero and P. Lund, "Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids," Electric Power Systems Research, vol. 80, pp. 1562–1571, 2010.
x. Peter Esslinger and Rolf Witzmann, "Improving Grid Transmission Capacity and Voltage Quality in Low-Voltage Grids with a High Proportion of Distributed Power Plants", in ICSGCE 2011: 27–30 September 2011, Chengdu, China, 2011.
xi. Bravo, R. J. (2018, April). Solar PV power plants have harmonic impacts. In 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D) (pp. 1–9). IEEE.
xii. E.A. Kwofie, G. Mensah and V.S Antwi, "Post Commission Grid Impact Assessment of a 20 MWp Solar PV Grid Connected System on the ECG 33 kV Network in Winneba, IEEE/IAS Power Africa", 2019.
xiii. [13] Anderson Hoke, Rebecca Butler, Joshua Hambrick, and Benjamin Kroposki, "Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders", IEEE Transactions on Sustainable Energy, 2012.
xiv. Kamaruzzaman, Z. A., Mohamed, A., & Shareef, H. (2015). Effect of grid-connected photovoltaic systems on static and dynamic voltage stability with analysis techniques—A review. Przeglad Elektrotechniczny, 1, 136–140. Zetty.
xv. Abobakr, H., Diab, A., Hassan, Y. B., & Khalaf, A. A. (2021). Performance analysis of a small-scale grid-connected photovoltaic system: a real case study in Egypt. Journal of Advanced Engineering Trends, 40(1), 79–96.
xvi. Statutory Instrument No. 52 of 1988, ELECTRICITY (SUPPLY) ACT (Cap. 73:01) ELECTRICITY (SUPPLY) REGULATIONS, 22 April 1988. Available at: https://www.botswanalaws.com/StatutesActpdf/ELECTRICITY (SUPPLY) REGULATIONS.pdf
xvii. Botswana Rooftop solar program brochure: https://www.bera.co.bw/downloads.php: Botswana rooftop solar programme, Accessed, February 2023.
xviii. Verband der Elektrotechnik (VDE) Standard, https://www.vde-verlag.de/standards/0102006/din-iec-60909-3-vde-0102-3-1997-06.html, Acessed March 2023.