International Journal of Scientific Research in Science and Technology
Available online at : www.ijsrst.com
Print ISSN: 2395-6011 | Online ISSN: 2395-602X
doi : https://doi.org/10.32628/IJSRST52310628

Assessing the Impacts of Solar *PV* Plants on Distribution Systems using DigSilent

Moilwa S[1*], Setlhaolo D[2], Sakala J. D[3]
[1,2,3]Department of Electrical Engineering, University of Botswana, Private Bag UB 0061,Gaborone, Botswana

ARTICLEINFO

Article History:

Accepted: 10 Nov 2023
Published: 24 Nov 2023

Publication Issue
Volume 10, Issue 6
November-December-2023
Page Number
162-171

ABSTRACT

The purpose of this paper is to evaluate the effects of integrating solar PV plants on distribution systems using Botswana Power Corporation greater Gaborone distribution system as a case. The study compares and analyses the system baseline to solar integrated system using DIgSILENT Powerfactory software. The system studies conducted in this paper include short circuit and effects on active and reactive power losses at different penetration factors. This research found out that integrating solar PV plants to the distribution network caused a decrease in grid losses and the extent of power losses decrease vary. Fault level contribution from the PV systems is generally low. In conclusion, the effects of these interconnections on line losses and fault level contribution differs in all circuits under study, therefore network assessment must first be thoroughly conducted before interconnecting solar PV plants with distribution systems as some areas indicated some reverse power flow that could affect the protection systems because initially the distribution system was designed to operate on a single source voltage.

Keywords: Photovoltaic (PV), Penetration level, DigSilent, Short Circuit Current, Distribution, Active and Reactive Power Losses

I. INTRODUCTION

The global community is increasingly transitioning to clean and low carbon energy sources. In line with this, countries are adopting Distributed Generation (DG) as integral part of their primary and secondary distribution systems. The purpose being to leverage on the decreasing capital cost of Renewable Energy Sources (RES) and the global drive on reduction in carbon foot print. However, the exponential integration of RES into the grid requires an extensive analysis because it comes with a number of technical, quality, economic and research related challenges [1]. Most distribution system networks were designed on the assumption that the system has a single source of voltage on each feeder. The inclusion of multiple RES departs from this original notion. Therefore, an extensive research is currently ongoing at a global scale to ensure a robust operation of the grid in the presence of these DGs.

Botswana has a significant solar potential receiving over 3,200 hours of sunshine per year with an average insolation on a flat surface of 21 MJ/m. This rate of irradiation is among the highest in the world [2]. Despite this, the solar industry in Botswana remains largely untapped. Since the early 1990, the country has been making some attempts to integrate solar in the energy mix but to date nothing much has been achieved as depicted by the reduced participation of renewable energies in the country's energy mix [3]. In an effort to increase participation in the solar energy sector, the country recently put into effect a net metering solar rooftop program. The program system-wide aggregate capacity of 10 MW for the first 12 months of the program was rolled out by BPC in 2020 [4].The country has also amended its electricity supply act to allow Independent Power Producers (IPPs) participation in the electricity sector. This great development provides an opportunity for IPPs to participate in the largely monopolistic Botswana electricity market and further drive it towards liberalization. Renewable energy capacity of more than 300MW has been projected for the planning period 2020-2040 [5]. It is envisaged that by 2030, 18% of Botswana's power be generated from renewables [6].

Botswana is a party to the United Nations Framework Convention on Climate Change (UNFCCC). Having adopted the Paris Agreement, in 2015 the government has made a voluntary commitment through its first Nationally Determined Contribution (NDC) to reduce the country's total greenhouse gas (GHG) emissions by 15% by the year 2030, with reference to 2010 emissions. Furthermore, the country is working towards providing affordable and clean energy to its general population in order to align with UN 2030 Agenda for Sustainable Development Goals, especially SDG7 [7]. In an effort to meeting the above goals, a table below shows some solar energy based projects that are anticipated by 2030. Other projects on biomass, concentrating solar-thermal power (CSP), wind and Coal Bed Methane (CBM) also in the pipeline.

Location/Plant Name	**Capacity**	**Year launched**
Phakalane	1.3MWp	2012
Botho University	200kWp	2020
AirPort Junction Mall-Gaborone	2.2 MWp	2021
Bobonong	3MWp	2022
Shakawe	1MWp	2022
BUAN	1MWp	2022
Diamond Trading Company Botswana (DTCB)	950kWp	2022
BPC Tati	50MWp	2026
BPC Jwaneng	50MWp	2026
University of Botswana	6MWp	2025

Therefore, it is with this background that this detailed study is conducted to determine effects of the integration of RES in Botswana system using the Greater Gaborone distribution network as a case study. In particular, determining how much, what should be the guiding principles. The system active and reactive power losses and fault levels at different PV penetration levels are determined and analyzed. The findings of this research provide knowledge to address the implications of connecting solar Photovoltaic systems to the distribution system. The research outcome can be used as an input into the procedures for connection of PV plants in distribution networks. Also the research can contribute in the operational and performance margins of the solar generation plants.

II. LITERATURE REVIEW

The integration of solar in the grid has brought many advantages mainly clean energy and reduction of energy bill. It however comes with a number of challenges that includes technical, quality, economic and research [1].

Author in [8] found out that solar PV integration in the distribution grid decreases voltage drop and percentage line losses of feeder cables. The voltage drop is as a result of conductor resistances. These power losses and voltage drops are usually brought about by the use of inverters and the non-linearity of the load. The interconnection of PV in the LV distribution system is carefully analyzed in [9]. The authors concluded that buses with a greater probability of causing disturbances to the grid are those connecting a higher number of consumers in their different phases. When a small-scale generation is being injected into the network, these buses and their adjacent ones will have a higher voltage fluctuation. Uneven distribution of consumers across phases and the distance to the transformers are also a contributing factor to grid disturbances. In order to determine which penetration levels create voltage or current distortions,[10] presented simulation results for a class of typical distribution feeders with different levels of PV penetration. And it was noted that the maximum PV penetration generally decreases with an increase in distance from the feeder source to the PV system, but most feeders still tolerate moderate to high PV penetrations even for PV systems placed almost at the end of the feeder. [11] presents an analysis approach that uses a cloud shadow model to recreate the variable output power of both distributed & large, centralized PVs at various locations on a feeder [12]. This is done to help distribution planners better understand & predict these likely impacts on voltage quality and avoid overly conservative decisions on the amount of PV installed on a feeder. This study, however contributes in analyzing the effects of solar PV penetration on both active and reactive power line loses and short circuit penetration factor in different locations in Botswana distribution network.

III. PROBLEM DEFINITION

The study is conducted by collecting input data from Botswana Power Corporation, modeling and simulation of distribution system using DIgSILENT Powerfactory software with and without interconnection of solar PV plants. Four distribution grid areas with PV plants are studied in order to make comparative analysis. Different penetration levels of the solar plants are considered for further analysis of the performance.

3.1 Location and Description of the Network under Study

The Greater Gaborone area in Botswana, lies between Longitude 250 45′ 17. 76“ E and 260 11’ 01.04” E and Latitude 240 41′ 15.44“ S and 240 42’ 45.96” S. It covers a surface area of 669 km2. To the east, the area includes the tribal villages of Tlokweng, Oodi and Modipane; to the west, it includes Mogoditshane and Gabane; to the south, it includes Mokolodi; and to the north, Gaborone is bordered by the Kgatleng district land whilst in the south it is mostly surrounded by freehold farms [13, 14].

The electrical connections for greater Gaborone distribution system (GGDS) is provided in Figure 1. The greater Gaborone BPC area is mainly supplied from transmission substations; Sub 500 (Mogoditshane 132/33/11kV) and Sub 1700 (Phakalane 132/11kV) Sub 400(132/11kV) and Sub 1300 amongst others. Sub1300 which supplies Tlokweng village is currently being supplied through a 132kV overhead line (OHL) that also carries the load of Segoditshane amongst others [14].

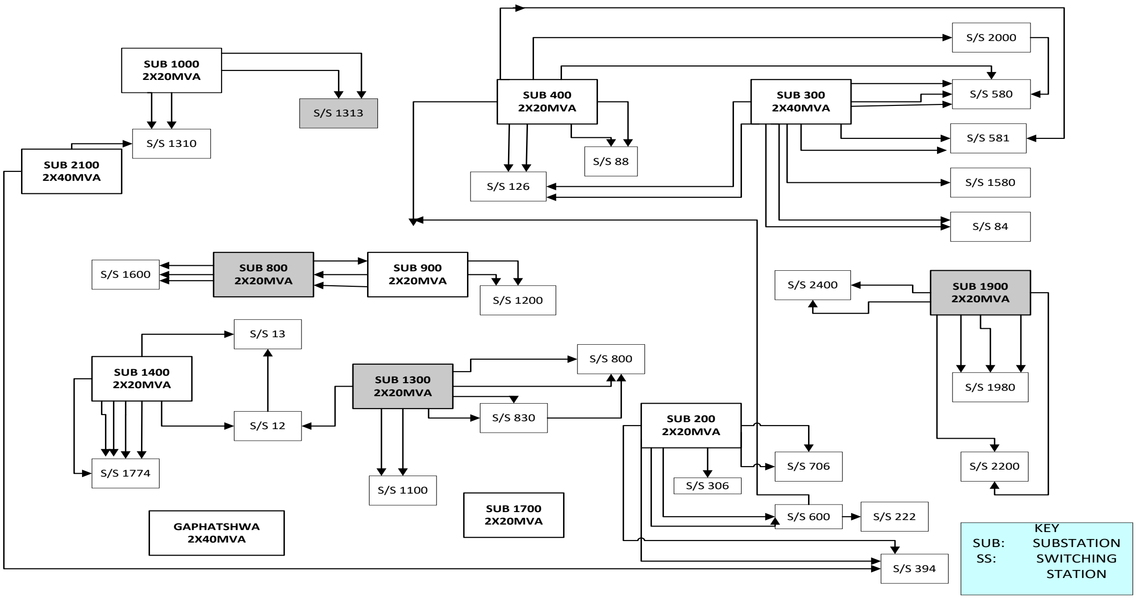


Figure 1: *Layout of the distribution grid of Greater Gaborone*

3.2 System Studies with Solar PV Integrations

The distribution network of BPC is studied and modelled as follows.

Case 1: Grid only, (without PV connection): This is taken as a base case to obtain base electrical quantities.

Case 2: Grid with PV Integration: The connected PV models are set to operate at unity power factor. The percentage PV penetrations are 0%, 30%, 60% and 90% of the maximum feeder load.

3.3 Greater Gaborone Grid Areas

For better analysis, the area network, GGDS is divided into four grid areas namely; three of which are commercial and industrial namely, Gaborone Block 8 Industrial (Sub 1900), Gaborone Government Enclave (Sub 800), Gaborone Kgale View (s/s 1313) where the solar PV plants are already installed. Tlokweng Residential Feeder (From Sub1300) is also chosen to further analyze a purely residential feeder. These areas are all indicated in grey in Figure 1. The data (infeed MVA, no. of buses and lines) for the grid areas is presented below where a typical case of Gaborone Block area has been expanded further.

3.3.1 Gaborone Block 8 Industrial Grid Area 1

In Figure 2, the PV capacity is connected at the 11 kV busbars of Switching stations 2200 and 581. The solar plants are physically located at Airport junction mall (APJ) diamond park (Diamond Trading Company (DTCB) and Okavango Diamond Company (ODC) will install one in the near future.,. Each of these PV plants has its own rated capacity o, but for purposes of this study, PV penetrations are estimated as a percentage of the maximum feeder load assuming that BPC cannot allow solar PV plants to exceed the maximum permissible feeder loading. Moreover [4] guides that , the Rooftop system (RTS) should be sized such that it generates no than 110% of the previous 12 months consumption.

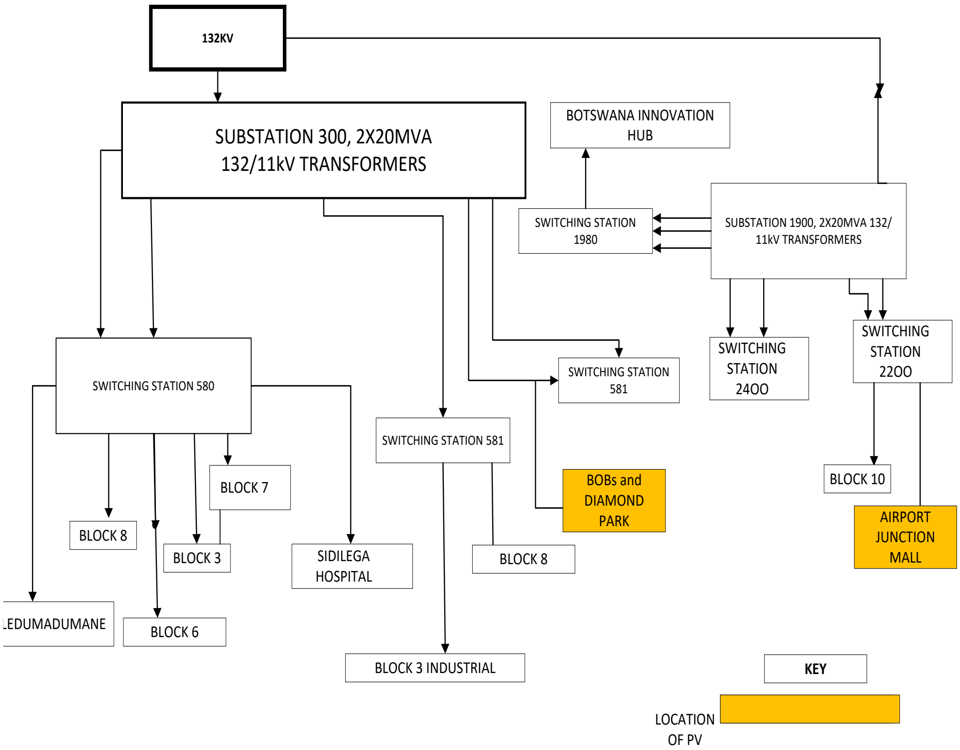


Figure 2 : Block Diagram of the Block 8 Industrial area with installed solar plants

Table 1: Summary data for the Four Grid Areas

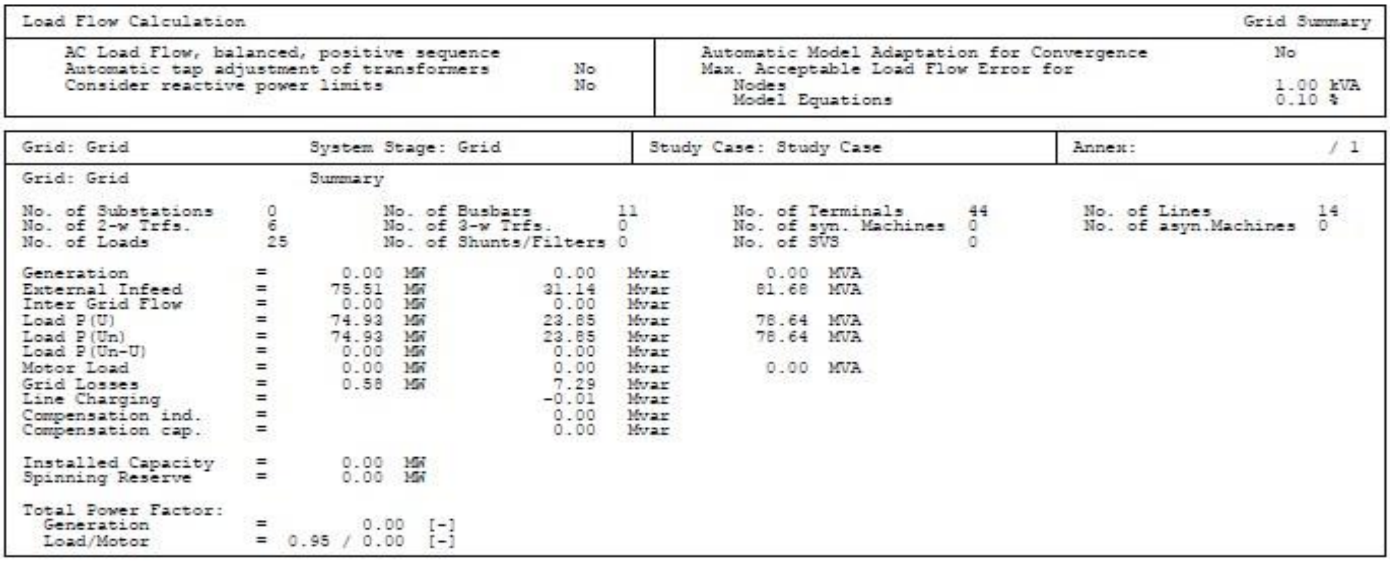
Area	*No. of Buses*	*No. of Lines*	*In-feed (MVA)*
Gaborone Block 8 Industrial	*15*	*22*	*45.5*
Gaborone Government Enclave	*11*	*14*	*81.68*
Gaborone Kgale View	*9*	*15*	*46.41*
Tlokweng Residential Feeder CB11L5	*102*	*146*	*4.97*

IV. RESULTS AND DISCUSSION

In this section, the findings of impacts of solar PV plants on distribution systems are presented and analyzed. These results are system active and reactive power losses and fault levels at different PV penetration levels. The results of both scenarios are presented.

(i) 4.1 Baseline Scenario

4.1.1 Line Losses: For the existing system, the grids were simulated at the maximum load demands received from BPC. The DigSilent baseline typical simulation results are presented in Figure 3 while Table 2 shows the results for all areas.



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Load Flow Calculation                                                                              Grid Summary
    AC Load Flow, balanced, positive sequence               Automatic Model Adaptation for Convergence     No
    Automatic tap adjustment of transformers      No        Max. Acceptable Load Flow Error for
    Consider reactive power limits                No           Nodes                                       1.00 kVA
                                                               Model Equations                             0.10 %

Grid: Grid                  System Stage: Grid          Study Case: Study Case          Annex:              / 1
Grid: Grid                  Summary

No. of Substations     0          No. of Busbars        11       No. of Terminals      44      No. of Lines           14
No. of 2-w Trfs.       6          No. of 3-w Trfs.      0        No. of syn. Machines  0       No. of asyn.Machines   0
No. of Loads           25         No. of Shunts/Filters 0        No. of SVS            0

Generation             =      0.00  MW            0.00   Mvar      0.00  MVA
External Infeed        =     75.51  MW           31.14   Mvar     81.68  MVA
Inter Grid Flow        =      0.00  MW            0.00   Mvar
Load P(U)              =     74.93  MW           23.85   Mvar     78.64  MVA
Load P(Un)             =     74.93  MW           23.85   Mvar     78.64  MVA
Load P(Un-U)           =      0.00  MW            0.00   Mvar
Motor Load             =      0.00  MW            0.00   Mvar      0.00  MVA
Grid Losses            =      0.58  MW            7.29   Mvar
Line Charging          =                         -0.01   Mvar
Compensation ind.      =                          0.00   Mvar
Compensation cap.      =                          0.00   Mvar

Installed Capacity     =      0.00  MW
Spinning Reserve       =      0.00  MW

Total Power Factor:
  Generation           =         0.00  [-]
  Load/Motor           =  0.95 / 0.00  [-]
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Figure 3 : Total System baseline losses for Gaborone Government Enclave Area

A summary of all grid areas, the system losses are summarized in Table 2. Government Enclave grid area has 0.58MW and 7.29 MVAr at maximum demand. As for Gaborone Kgale view area the losses are 1.29 MW and 4.5MVAr and Gaborone Block 8 Industrial area has 1.22MW and 9.05MVAr.Tlokweng residential grid area has 0.3MW losses. The line charging values are -0.01MVAr, -0.09MVAr, 0.03MVAr and 0.021MVAr for the grid areas respectively. These are monitored in order to determine the impacts of PV power.

Table 2: *Baseline Power Losses*

		Power Losses	
No	**Area/Location**	**Active Power, P (MW)**	**Reactive Power, Q (MVar)**
1	Gaborone Block 8 Industrial	1.22	9.05
2	Gaborone Government Enclave	0.58	7.29
3	Gaborone Kgale View	1.29	4.5
4	Tlokweng Residential Feeder	0.3	0.38

4.1.2 Fault Level Analysis: Fault level analysis based on the VDE 0102 standard [5] is performed at the distribution and substation busbars (BBs) and Maximum three phase fault levels are evaluated.

Table 3 presents three phase fault levels of the selected buses of the existing selected areas. These are also monitored and compared with PV integrated system in order to determine the impacts of PV power in fault levels of the system.

The three-phase fault current for Gaborone Block 8 Industrial is 12.48 kA and 5.103 kA for the two buses (APJ & Diamond Park). For the Government Enclave grid area, the fault current is 11.853 kA. As for Tlokweng residential feeder the fault current ranges from 1.70kA to 9.11kA. These results are monitored in order to determine the impacts of PV power.

Figure 4 shows the DIgSILENT short circuit simulation sample for Gaborone Kgale view area which was one of the figures used to populate Table 3.

Table 3 : Three phase fault current for selected buses of existing case.

Area	Substation	Load	Rated Voltage (kV)	3Phase fault current (kA)
Gaborone Block 8 Industrial	Sub 2200	Airport Junction Mall	11	12.480
	Diamond Park SS	DTCB	11	5.103
		ODC		
Government Enclave Grid	Sub 800	BOBs	11	11.853
Gaborone Kgale view	Sub 1310	Botho College	11	2.679
Tlokweng Sub 1300 CB 9L5 Feeder	Tx172 LV BB	Residential	0.4	9.11
	Tx 2632 LV BB	Residential	0.4	1.71
	Tx 87 LV BB	Residential	0.4	1.70
	Tx 228 LV BB	Residential	0.4	2.95
	Tx 204 LV BB	Residential	0.4	7.24

4.2 Effects of PV Plants on the Existing Grid

The performance of the BPC distribution system integrated with solar PV plants is determined using different penetration levels for the four studied areas.

4.2.1 Impacts on Losses

Tables 4 and 5 show active (P) and reactive power (Q) losses for the grid areas under study at different penetration levels. The percentage decrease provides a percentage variation between the 0% penetration level, which is the base case, and the 90% penetration level.

***Table 4 :** Grid P&Q Losses for Gaborone Block 8 Industrial area*

Power	**Penetration levels (%)**				**% Decrease**
	0	**30**	**60**	**90**	
P (MW)	1.22	0.79	0.58	0.57	53.23
Q (MVar)	9.05	4.59	1.92	0.81	91.05

The active and reactive grid losses for all the considered areas decreased with an increase in photovoltaic penetration level in all areas as shown in Tables 4& 5. For example, in Table 4 for the Gaborone Block 8 grid area, in order of the penetration levels from 0-90%, the active power decreased from 1.22 to 0.57MW, a 53.23% decrease, while the reactive power from 9.05 to 0.81MVar.(91.05% decrease). Comparatively, a decline in reactive power (91%) is significant compared to the active power (53.23%). The 0% penetration level gives the baseline values as presented in Table 2.

The other 3 considered areas are presented in Table 5. Note that under each area active and reactive power are indicated, for example Government enclave, at 0% penetration, there is 0.58MW and 7.29MVAr losses while at 30% penetration level, 0.42MW and 4.86MVar, etc.

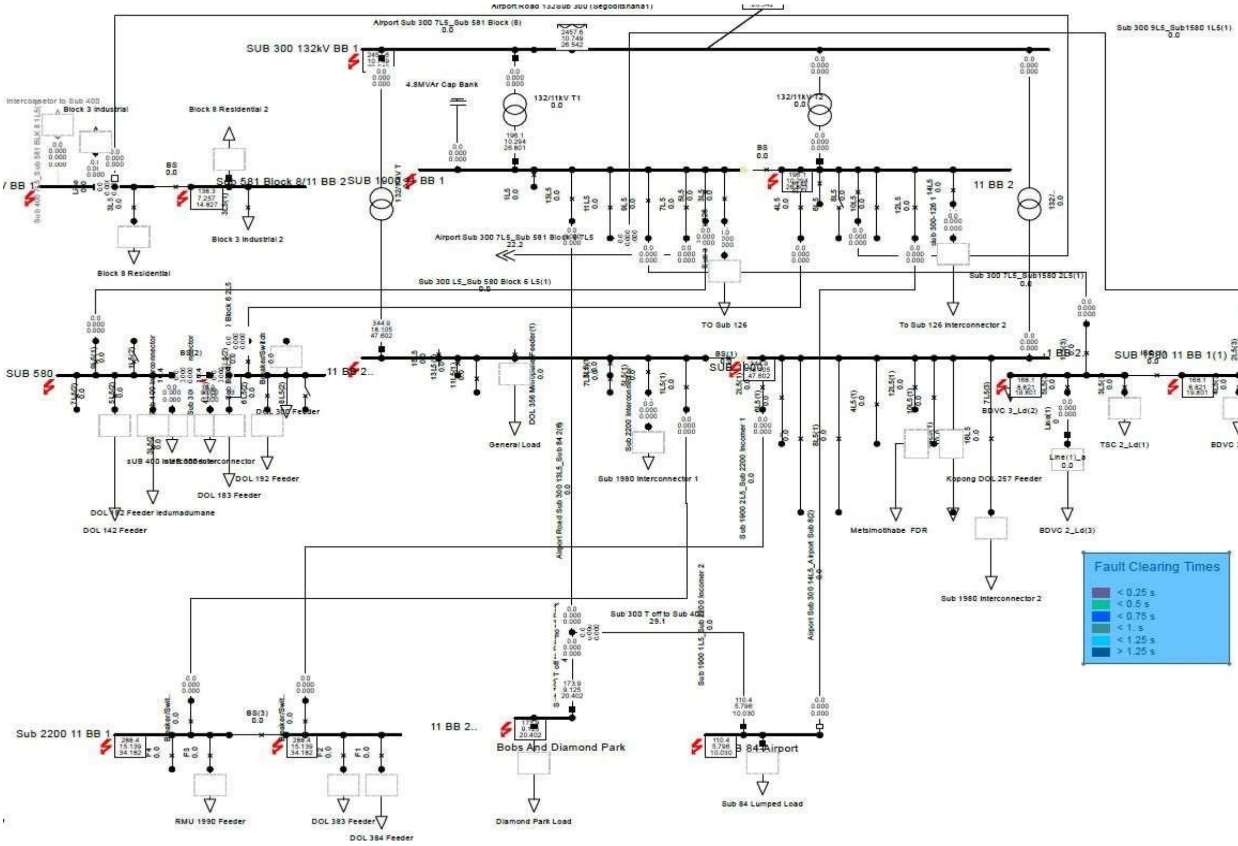
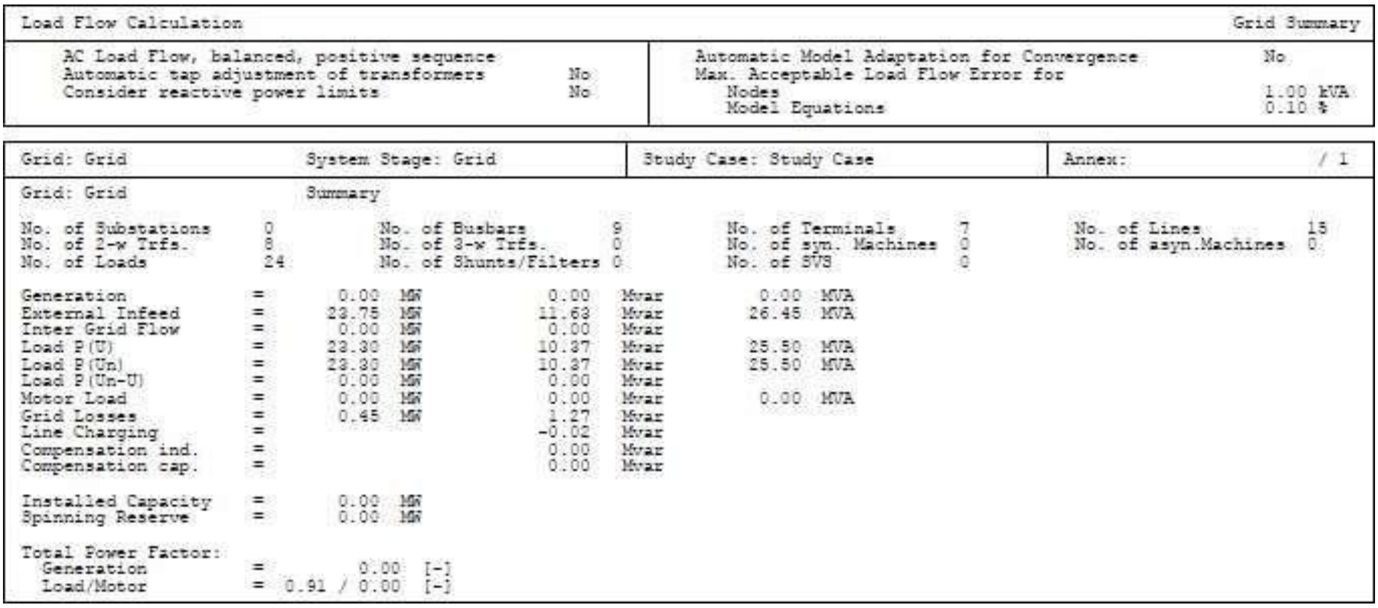


Figure 4 : Short Circuit Analysis for Gaborone Kgale View area

Table 5 : Grid P&Q Losses for the other three Areas at different penetration levels

No	Area	Penetration Levels (%)				% Decline
		0	30	60	90	
2	Goverment Enclave	0.58	0.42	0.34	0.27	53.45
		7.29	4.86	3.73	2.50	65.71
3	Kgale View	1.29	0.64	0.45	1.0	22.48
		4.50	2.67	1.27	1.98	56.00
4	Tlokweng CB 9L5 Residential	0.3	0.27	0.25	0.22	26.67
		0.38	0.33	0.29	0.34	10.53

In all areas, the losses were simulated at maximum load demand for the grids. It is observed that both results for P & Q losses generally decreased with an increase in PV penetration levels. It also reveals that percentage decline in power losses is generally more significant for reactive power than active power. The computations are performed using the extreme cases of 0% and 90% penetration levels. Government Enclave provides 65.71% decline in Q losses against 53.45% of P losses. Kgale View; 56% compared to 22.48%, while Tlokweng it is 10.53% against 26.67%. It is noted that for Kgale View, minimum P&Q losses are realized at 60% penetration rather than at 90% penetration level whereas for Tlokweng minimum Q losses are at 60% penetration level. The implications of these are that in these feeders, the high level of PV penetration significantly improves the reactive power losses more than active power losses. After the 60% penetration levels, the losses (active and reactive power and energy) started to increase with an increase in penetration levels. As a result, this indicates a limit to PV integration, the maximum penetration levels.



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Load Flow Calculation                                                                    Grid Summary

    AC Load Flow, balanced, positive sequence                 Automatic Model Adaptation for Convergence     No
    Automatic tap adjustment of transformers        No        Max. Acceptable Load Flow Error for
    Consider reactive power limits                  No           Nodes                                        1.00 kVA
                                                                 Model Equations                              0.10 %

Grid: Grid                System Stage: Grid        Study Case: Study Case               Annex:              / 1

Grid: Grid                Summary

No. of Substations     0        No. of Busbars          9     No. of Terminals       7     No. of Lines           15
No. of 2-w Trfs.       8        No. of 3-w Trfs.        0     No. of syn. Machines   0     No. of asyn.Machines   0
No. of Loads          24        No. of Shunts/Filters   0     No. of SVS             0

Generation           =      0.00  MW           0.00   Mvar      0.00  MVA
External Infeed      =     23.75  MW          11.63   Mvar     26.45  MVA
Inter Grid Flow      =      0.00  MW           0.00   Mvar
Load P(U)            =     23.30  MW          10.37   Mvar     25.50  MVA
Load P(Un)           =     23.30  MW          10.37   Mvar     25.50  MVA
Load P(Un-U)         =      0.00  MW           0.00   Mvar
Motor Load           =      0.00  MW           0.00   Mvar      0.00  MVA
Grid Losses          =      0.45  MW           1.27   Mvar
Line Charging        =                        -0.02   Mvar
Compensation ind.    =                         0.00   Mvar
Compensation cap.    =                         0.00   Mvar

Installed Capacity   =      0.00  MW
Spinning Reserve     =      0.00  MW

Total Power Factor:
  Generation         =         0.00  [-]
  Load/Motor         =  0.91 / 0.00  [-]
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Figure 5 : P&Q losses for Kgale View Grid Area at 60% Solar PV Penetration

Figure 5 presents a typical DigSilent simulation output for Kgale View area at 60% penetration level.

4.2.2 Effects on Fault Levels

Integration of solar PV plants more especially in distribution network can result in reverse power flow which may affect the performance of existing protection relaying schemes. This can potentially lead to increased fault levels in the network that may require uprate specifications of switchgears. Solar PV integration to the selected distribution grids resulted in a slight increase in fault levels as shown in Table 6 below. The fault levels were determined at different selected buses in each area.

***Table 6**: Fault Current Levels (KA) for Selected Buses-The four study areas*

Area	***Bus***	***Penetration Levels (%)***			
		0	***30***	***60***	***90***
Gaborone Block 8	Sub 2200 11kV BB	12.480	12.478	12.483	12.483
	Diamond Park Switching Station	5.103	5.103	5.153	5.153
Government Enclave	Sub 800 BOOBS Feeder Panel	11.853	11.903	11.903	11.903
Kgale View	Sub 1310 11 kV BB	2.679	2.829	2.859	2.859
Tlokweng	Tx 172 LV BB	9.11	9.11	9.13	9.13
	Tx 2632 LV BB	1.71	1.72	1.71	1.72
	Tx 87 LV BB	1.70	1.70	1.70	1.70
	Tx 228 LV BB	2.95	2.95	2.95	2.95
	Tx 204 LV BB	7.24	7.25	7.25	7.24

In this case, fault level contribution from the PV systems is generally low since the size of the installation is very small and the contribution is not significant. The increase in the fault levels due to contribution from the PV system is not expected to exceed existing equipment ratings. The injection of the solar PV plant will mean that electric power will flow in the two directions between the solar plant and the substation. This will require the protection to be capable of successfully isolating the faults regardless of the power contribution of each source.

V. CONCLUSION

The study was conducted to evaluate the performance of the greater Gaborone Distribution system (GGDC) with four 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 is a combination of radial and meshed network distribution systems. Hence, the effect of solar PV on the distribution system differs from one grid area to another.

The main conclusions formulated for the selected grid areas where the pilot projects are being implemented using the grid data received from BPC are as follows.

- Integrating solar PV plants to the greater Gaborone distribution network causes a decrease in grid losses for the grid areas. Relatively, reactive power has a more significant decrease relative to the active power.
- Fault level contribution from the PV systems are generally low. The increased fault levels due to contributions from the PV systems are not expected to exceed existing equipment ratings. The injection of the solar PV plant may result in electric power flowing in the two directions of a feeder and this will require the protection to be capable of successfully isolating the faults regardless of the power contribution of each source.
- A decrease in losses, both real and reactive was also noted in most grid areas. The exception is for the Tlokweng radial Distribution grid, where increasing the PV penetration level in the area up to 90% increases the reactive power loses. For this distribution grid area, initially, the grid losses decrease with increasing penetration level up to a certain penetration level. After this penetration level, the reactive losses increase with increase in PV penetration.
- 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.

VI. ACKNOWLEDGMENTS

Our profound acknowledgement to Botswana Power Corporation for permitting us to conduct research on their system and providing us with all the necessary support to complete this work.

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Cite this article as :

Moilwa S, Setlhaolo D, Sakala J. D, "Assessing the Impacts of Solar PV Plants on Distribution Systems using DigSilent ", International Journal of Scientific Research in Science and Technology (IJSRST), Online ISSN : 2395-602X, Print ISSN : 2395-6011, Volume 10 Issue 6, pp. 162-171, November-December 2023. Available at doi : https://doi.org/10.32628/IJSRST52310628

Journal URL : https://ijsrst.com/IJSRST52310628