Stability Evaluation of Non-ideal Grid-tied Photovoltaic on IEEE-9 Bus System

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Abstract – *The integration of photovoltaic in power systems has proved its capability of being a viable source of power to be considered in grid-tied power systems. However, in some cases various electrical challenges may arise when high photovoltaic power is integrated into power systems at the time the voltage collapse caused by an increase in the load consumption. In case of non-ideal grid-tied photovoltaic due to inappropriate or absence of control strategies to regulate the power dispatch between the microgrid and the grid, the photovoltaic power may negatively further affect the grid voltage stability instead of restoring it to the stability level of the electrical grid. This paper investigates the challenge of solar power integration in the grid by demonstrating that due to its randomness and intermittent nature, the photovoltaic power is likely to be associated with voltage disturbance and low power quality that occurs on the electrical grid. Data from simulation of a non-ideal grid-tied photovoltaic are collected to demonstrate the characteristics and negative effects of high photovoltaic integration on the IEEE-9 bus system.*

Keywords: *dynamic load, photovoltaic integration, power quality, voltage profile, voltage stability*

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I. Introduction

With the global energy demand climbing, the necessity of using renewable energy is increasing constantly, although at a slower rate than energy consumption. Renewable energy sources require a way that improves their technical integration into power systems [1]. Grid-tied photovoltaic systems are also growing fast worldwide with an estimated total of 705 Giga Watts (GW) of power generated in the year 2021 [2], and the generation capacity is expected to grow steadily according to the International Renewable Energy Agency. Considering that the issue of power shortage which affects the electrical network has become a major concern with economic implications, microgrid photovoltaics has grown to become an effective alternative way when it comes to power shortage [3]-[4]. The strain on the transmission network is increasing at a considerable rate due to the increasing power demand. Since the negative impact of power shortage on the electrical grid turns to be a serious concern that affect the economic growth, microgrids in this regards have been recognised as an appropriate alternative way in dealing with power shortage [5]-[6]. In a smart grid, microgrids are commissioned with the idea that power can still directly flows from the traditional generators to the load without having to disturb the operation of the transmission network [7]. Microgrid in this regard serves as a palliative solution to alleviate the burden on the transmission network when generators can no longer supply the amount of power needed [7].

Unfortunately, the integration of PV into power systems does not always relieve the power system from the stress caused by the extensive load demand. Integrating photovoltaic power to the power system brings some challenges that need to be addressed for the safe operation of the electric grid [7]-[9]. The potential problem that occurs is that the high penetration of solar energy generation will probably increase the possibility of system disturbances especially when no adequate control of power flow is considered [9]-[10]. One of those disturbances is described as voltage instability, which is defined in the power system as the potential of the electric grid to re-establish the initial working voltage level after being exposed to a disturbance [11].

II. Literature Review

The challenges of microgrid integration are mainly attributed to effort leading to control the penetration of renewable energy into the power system. In this paper, the microgrid is affected by the instability of voltage caused by the increase in the load demand. The paper presents an investigation of the operation of a microgrid-tied power system, where the PV system with a non-ideal controller is used to respond to the voltage instability after the power system is subjected to the disturbance caused by a total of 35% increase in load consumption in the stage of 5%. The IEEE 9-Bus transmission system is considered as a test benchmark model for the investigation on the influence of microgrid power on the voltage stability in the power system under disturbances.

The Real-Time Digital Simulator (RTDS) environment is used to design a grid-tied solar power generation plant. The increase in load consumption is simulated as disturbances leading to voltage instability. The integration of the photovoltaic system as the generator of a microgrid into the transmission network represents many challenges when the PV power is not regulated. The power generated by the PV plant has proven to be an essential contributor to voltage instability if adequate control strategy to assure that the operation of the grid remains safe and the quality of the power increases to the permissible index for stability as per grid code is not put in place [11]. The paper investigates the grid disturbance caused by the impact of high photovoltaic penetration without proper regulation.

The challenges and issues of integrating the photovoltaic energy has been a significant area of study with focus on the control of power dispatch between the photovoltaic and the grid. Various research works manage to develop some algorithms to deal with the disturbance caused by such integration. These algorithms, which in some sort demonstrate the need for having an adequate controller scheme used as a solution in restoring the system stability when voltage collapse in the power system. The following is a short description of several algorithms that were developed by previous researchers in retribution for the consequence of not having proper control strategies for grid integration.

The work in [12] describes how the size and location of the PV plant can affect the operation of the power system. Bearing in mind that the penetration of PV power in a power system may increase the voltage stability of the grid, it is therefore critical to emphasize that connecting a PV plant can create unwanted situations like overvoltage, distribution losses, harmonics, and flickers appearing during the operation of the power system[12]-[13]. Analyzing the influence of the PV on the IEEE 14 bus system, the researchers demonstrate that the size of the PV in grid-tied mode may have the possibility of negatively influencing the parameter of the grid when not carefully regulated. A downsized PV plant integrated into the grid may contribute to more overloading troubles, whereas an oversized PV supplying active and reactive power can negatively affect the operations of the grid by creating overvoltage and more instability. While the size matters, it is important to also consider the position of the PV plant since this may positively influence the magnitude of the voltage when placed closer to the problematic area of the network.

In [14], although renewable energy is regarded as an appropriate solution to the global energy crisis, the importance of PV energy security and reliability when integrating with power systems still needs to be considered carefully. The researcher goes on to explain how the power supplied by solar panels can result in uncontrolled power, this may in turn cause significant network disruption. To avoid disturbance of the power system, the researcher proposed a central controller algorithm located at the microgrid level to improve and boost the attributes functions. The role of the controller is to determine the rentability of the microgrid based on the condition of the load on the grid side. The well-defined mechanism for the safe operation of the grid is implemented by synchronizing the transmitted grid signal with the set parameters of the microgrid controller. By doing so, the proposed control ensures that the energy exchange through the microgrid and the grid is equally balanced between load consumption and microgrid energy production.

In [15], the authors explain the importance of regulating PV penetration in the power system. The researchers described a PV plant control system that can aid in solving various challenges related to the interconnection of large PV power plants with the utility grid. The proposed control strategy consists of monitoring the overall operations of the generation plant at the point of common coupling and based on the conditions adjusts the PV plant operation to meet the grid performance requirements. The proposed architecture is based on the implementation of strong control communication to be integrated into both the PV plant and the power system. To achieve a reliable and efficient control system, it is recommended that the use of communication protocols such as SCADA and others be made available as part of grid architecture. These control systems provide a reliable communication monitoring system that ensures the power system voltage stability remains monitored at any given time of the operation of the grid. By doing so, the utility continuously maintains a safe and reliable electrical grid integrated with renewable energy.

The work in [16] proposes a synchronous algorithm method that deals with the uncontrolled injection of reactive power from the PV microgrid to the power system. The impact of the non-ideal PV power plant is known in some conditions to have an unwelcomed impact on the safe operation of the grid. When the electrical grid is subjected to an uncontrolled flow of PV power, its operation is disturbed to an extent of producing voltage instability in the power system. The researcher demonstrates that an uncontrolled flow of active and reactive power to the grid has a diminishing effect on the voltage profile. To solve the problem caused by the uncontrolled injection of reactive power into the electrical grid, the researchers propose a method of active power filtering which is controlled by the synchronous algorithm method based *d-q* frame. The *d-q* frame is used to compare the phase angle between the voltage and the current of the PV plant with those of the grid. Once synchronization is achieved between the PV plant and the grid, the inverter of the solar plant can then positively regulate the amount of power needed to restore the voltage profile of the power system.

This paper is a detailed and comprehensive review of the impact of photovoltaic integration in power systems without considering a control strategy that regulates the exchange of power between the microgrid and the electrical grid. The disturbance in voltage stability is namely caused by uncontrolled high photovoltaic penetration. The investigation into the power system disturbances caused by high photovoltaic penetration is reviewed.

The structure of the paper is presented as follows: Section II covers the comprehensive theorical related to the integration of photovoltaic in the power system. Section III introduces the case studies to be covered in the investigation and section IV presents the results based on the case studies carried out. In section V, the findings based on the results are thoroughly discussed before a conclusion is made in section VI.

III. Case Studies

This section presents three case studies as follow;

- Case 1- Performance of IEEE-9 under Load increase
- Case 2- Design of the Photovoltaic Power Plant
- Case 3- IEEE-9 Transmission network with PV at bus 5

The investigation steps are carried out and validated using the IEEE-9 bus test systems. Simulations and validation of results are performed using RTDS. The network represents a transmission network made of 9 buses, six lines, three generators, three loads, and three transformers. Fig.1 below is the representation of the One-Line Diagram illustration of the IEEE-9 Bus Power System. Because of its radial structure and the ideal placement and sizing of the generators, the network is likely to develop a deteriorated voltage profile, which is ideal for a perfect test benchmark for voltage stability study.

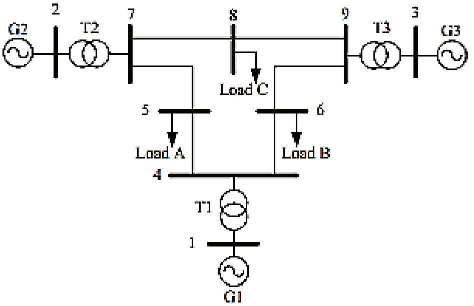

Fig. 1. IEEE-9 bus power system

IV. Simulation results and discussions

This section focuses on the effects of load consumption increase in the power system, and the introduction of the photovoltaic system used for simulation. The results of the impact of the load increase are presented in Table I, Table III and Fig. 3 to Fig. 10.

A. Case 1- Performance of IEEE-9 under load increase

In any given moment, a consistent power system voltage stability is not continuously possible in practice. In most cases, the electrical grid is exposed to variations in its load and operating conditions [1]. Known as the ability of the power system to preserve or regain voltage magnitudes to an adequate level after a contingency event [13]-[14],the voltage stability study in RSCAD is performed using a common phenomenon described as the load event mechanism which will allow the load of a given power system to be directed to simulate a particular disturbance that leads to voltage collapse.

In the RSCAD environment, dynamic loads can be adjusted by turning a build control logic, where P and Q setting inputs are fully set for the external logic for tuning. Fig. 2 shows the dynamic load control logic in RSCAD.

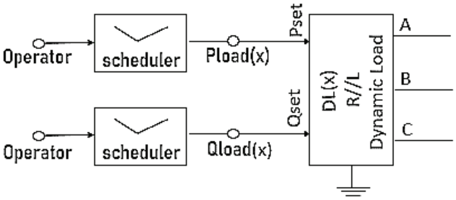

Fig. 2. Control logic for dynamic load control

The signal names PloadX and QloadX represent the active and reactive power respectively. These are used to control the consumption of load X (DLoadX). The signal called Operator is used to control the state (ON/OFF) of the scheduler component. The component "scheduler" in the RSCAD plays the role of increasing the load consumption by multiplying the given multiplier percentage with the initial values of power. Voltage stability is investigated using a disturbance describes as a load event, where the demand of all three loads has been increased from the initial value by 35% during 10 seconds in the step of 5% every 2 seconds.

The result of load events following the disturbance in the power system is presented in Table I and Fig. 3 to Fig. 5. Table I summarises the results of real-time simulation of the IEEE-9 bus system under the disturbance of a 35% increase in load demand. The disturbances in the electrical power system create a voltage drop in the network with bus 5, bus 6, and bus 8 dropping beyond the threshold limit of 0.95 p.u. Fig. 3 to Fig. 5 show the voltage collapse of bus 5, bus 6 and bus 8 respectively which drops from 0.9777 p.u. to 0.9199 p.u. for bus 5, from 0.9984 p.u. to 0.9463 p.u for bus 6 and 0.9957 p.u. to 0.9442 for bus 8.

The recorded violation at these 3 buses indicates that the permissible voltage post contingency at these buses exceeded the standard limit of 0.95 p.u of the nominal voltage. Furthermore, this indicates that when there is a voltage collapse happens after contingency, meaning the voltage in the power system or part of it is driven beyond the threshold of 0.95 p.u which determines the steady nominal voltage, a spike in the reactive power is about to happen as more of it will be injected in the power system [19].

The reactive power is expected to restore the voltage profile to an acceptable voltage magnitude. The same scenario is required in case of voltage rise above the limit of 1.05 p.u., and a drop in reactive power is expected to occur. More reactive power will be absorbed by the power system to maintain the nominal voltage acceptable for the buses [20].

TABLE I
VOLTAGE PERFORMANCE OF THE IEEE-9 BUS SYSTEM BEFORE AND AFTER DISTURBANCE

Bus (Nbr)	Normal Voltage (p.u)	Voltage after Disturbance
1	1.030	1.025
2	0.994	0.9704
3	1.018	0.9878
4	1.012	0.9872
5	0.977	0.9199
6	0.998	0.9363
7	1.001	0.9598
8	0.9957	0.9444
9	1.0201	0.9744

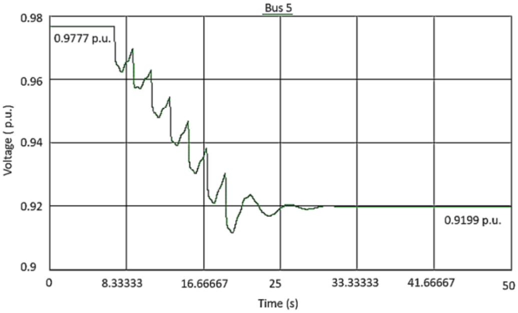

Fig. 3. Impact of 35% load increase on the voltage profile of bus 5

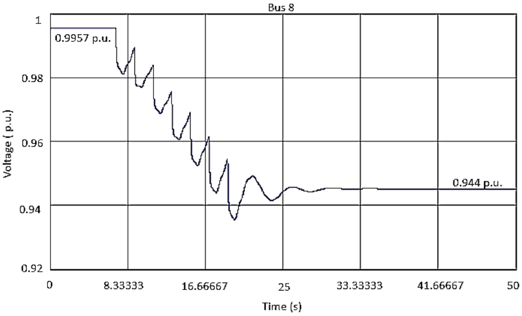

Fig. 4.impact of 35% load increase on voltage profile at bus 6

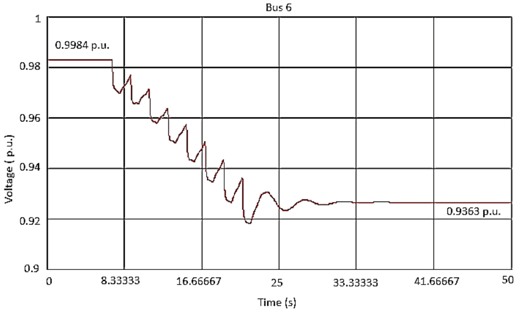

Fig. 5. Impact of 35% load increase on voltage profile at bus 8

The simulation results indicate that there is a voltage collapse when the load demand is increased. A PV can then be integrated into the power system to improve the stability of the load voltage profile.

B. *Case 2-Design of Photovoltaic Plant*

Microgrid modelling is generally known as the representation and integration of a power generation unit, either islanded or connected to the power system. Such representation is usually mathematical, circuit-based, or physical-based, which describes the parameter of the microgrid, its rated voltage and power [15]. The microgrid under consideration in this paper is a photovoltaic plant built using equations (1) to (4) with monocrystalline modules' parameters as listed in Table II.

N-number series modules are expressed in terms of

$$N_s = \frac{V_{OCA}}{V_{OC}} \tag{1}$$

where V_{OCA} is the estimated DC output open voltage expected to be delivered by the solar system and V_{OC} is the open-circuit voltage per single series module datasheet. From the equation, the number of series modules can be determined. The current is determined from the formula below.

$$I_T = \frac{P}{V_{OCA}} \tag{2}$$

where P is the DC output power expected from the PV array. V is the DC voltage of the Solar plant and I_T is the total intensity of the solar plant. The number of modules in parallel is determined by:

$$N_{PP} = \frac{I_T}{I_{MP}} \tag{3}$$

where N_{PP} is the number of parallel modules, I_T is the total intensity of the solar plant and I_{MP} is the current of the solar plant at maximum power.

Therefore, the overall power of the PV power plant is expressed by the total number of all modules, and the respective parameters in Table II are used in RTDS to computerize the total power of the photovoltaic system.

TABLE II
PHOTOVOLTAIC PARAMETERS FOR SIMULATION IN RTDS

Parameters Symbol	Value	Unit
V_{OCA}	11	kV
V_{oc}	43.5	V
V_m	37.2	V
P	90	W
I_{MP}	9.41	A
I_{scref}	10.15	A
$INSr$	1000	W
T_{ref}	25	deg
$Pmodule$	410	W

The 80 MW photovoltaic plant is designed as a large-scale plant for high penetration of power into the electrical grid. The advantage of high output power is to minimize losses of power in the transmission line, which connects the PV plant to the 230 kV node of the IEEE-9 transmission network.

C. Case 3-Impact of Non-ideal Photovoltaic Integration

Various studies indicate the advantages to integrate photovoltaic power into the existing grid where local generators are available but not able to stand the increase in load consumption [16]. The balance of power, regulation of voltage and load-following capability of the grid are some of the factors that determine the expected contribution of solar energy to the electrical grid [8]. In this section, a photovoltaic system is integrated into the electrical grid at $time = 0s$ considering the voltage collapse due to load increase. The contribution of the photovoltaic system is expected to restore the voltage profile of the grid to an admissible level of grid stability. Due to the absence of appropriate control algorithm, the injection of solar power into the grid contributes to further disturbance in the grid creating voltage rise in some part of the grid [17]. In Fig. 5 below, the PV is integrated at bus 5, which is the crucial bus with lowest voltage of 0.9199 p.u.. The lower voltage at bus 5 is likely to keep the rise of voltage within the safe range of stability once the photovoltaics is integrated.

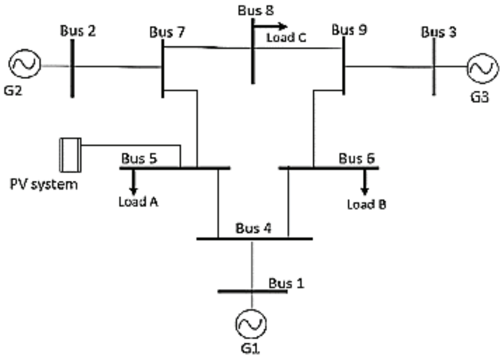

Fig. 6. PV integration at bus 5 of the IEEE-9 bus system

The investigation focuses on the impact of the penetration of the PV-microgrids in the power system considering the load demand disturbance. The voltage magnitude of the system network, power losses of the grid, and PV performance are also considered. Because the power system is subjected to some disturbance, the voltages in the system are negatively affected where the voltage magnitude at bus 5, bus 6, and bus 8 drop beyond the acceptable level of voltage stability indicators in the power system.

The lower magnitude of the voltage at these buses triggers the necessity of integrating the microgrid PV to support the grid in restoring the voltage stability [18]. But the integration of the microgrid to the grid is also known for its possibility to create over-voltage when proper regulation for integration is not followed. The simulation results obtained in the RTDS demonstrating the influence of the photovoltaic power on the IEEE-9 bus system are presented in Table III and Fig. 6 to Fig. 8.

TABLE III
IMPACT OF NON-IDEAL PHOTOVOLTAIC INTEGRATION

Bus (Nbr)	Normal Voltage (p.u)	Voltage after Disturbance
1	1.030	1.044
2	0.994	0.9976
3	1.018	1.022
4	1.012	1.051
5	0.977	1.062
6	0.998	1,025
7	1.001	1.067
8	0.9957	1.015
9	1.0201	1.033

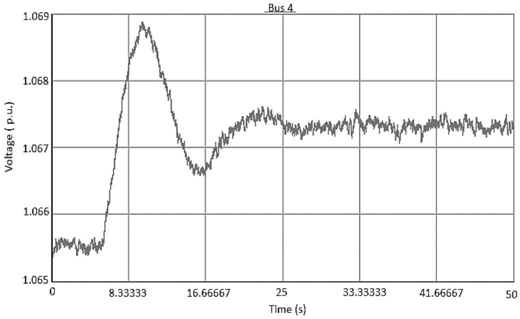

Fig. 7. Over Voltage at bus 4 due to high penetration of photovoltaic

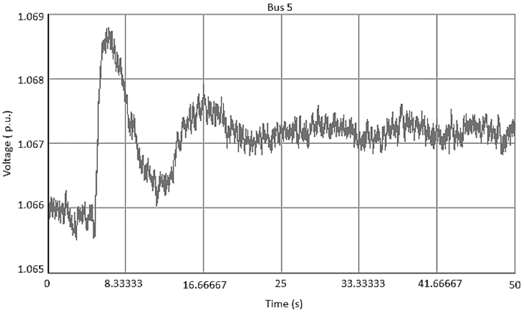

Fig. 8. Over Voltage at bus 5 caused by non-ideal photovoltaic

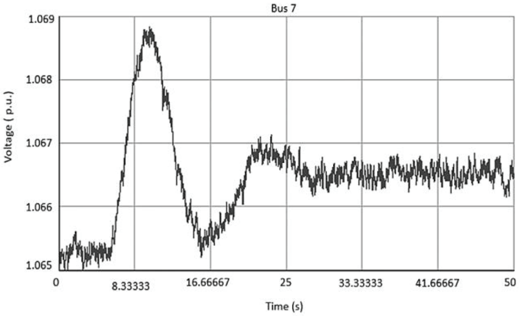

Fig. 9. Influence of non-ideal photovoltaic penetration on bus 7

V. Finding and Discussions

The data of photovoltaic parameters in Table II and voltage profiles illustrated in Fig. 7 to Fig. 9 show a surge in magnitude when the 80 MW PV is integrated without an ideal control strategy. The rise of the voltage represents the poor quality of power at the point of common coupling and some parts of the power system. The integration of the microgrid into the power system has the potential to cause an alternation of the system parameters beyond or below the operation limit fixed by the power utility. This concern leads to the common term of the hosting capacity of a power system, which is defined as the measure of how much renewable energy a power system can accept for it to stay stable [19].

The acceptable capacity is the safe amount of Solar PV power allowed to be supplied to an existing power system. Such an amount of power can be determined by software simulation and system monitoring to establish when a voltage violation occurs in the system. The hosting capacity of the power system also depends on the capability of the inverter to regulate the correct amount of power needed to flow to the grid. Unfortunately, due to the lack of a proper control algorithm, the flow of power from the inverter is not related to the dynamic change of the voltage within the power system. The exchange of power between the PV system and the power system is continuous rather than reliant on the dynamic change of the load consumption.

Fig. 10 below shows the ON state of the inverter which does not wait for the voltage at the point of common coupling to drop below 0.95 p.u. but the ON state of the inverter is constant because of the lack of proper control algorithms to determine when mode ON and OFF of the inverter valve is needed.

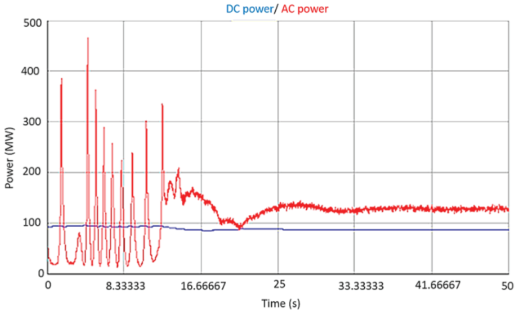

Fig. 10. Non-ideal photovoltaic power dispatch to the grid

The injection of power from the inverter is not controlled by any regulator. The flow of the power is consequently related to the time of the simulation and not to the change in the operation state of the grid. Because of the missing adequate controller for the integration of the PV, the inverter valve delivers excessive and disorganized power to the grid. Even though the flow of power stabilizes itself after ten seconds of the simulation, the considerable power sent to the grid is above the host capacity of the grid. The transfer of power between the grid and the microgrid PV as shown in Fig. 10 demonstrates that the controller from the RTDS library which has been used to integrate the PV to the grid shows that the valve for the inverter is constantly in ON mode by allowing the power of the PV to be injected to the grid. Because of this, there is an overvoltage on bus 5. Consequently, this violates the standard for grid code for the integration of renewable power into the grid.

The negative impacts of the integration of PV system in the power system includes voltage rise and voltage unbalance [1]. Such a voltage violation may depend on the capacity of the photovoltaic system, on the hosting capacity of the grid [19]-[20] with the absence of an appropriate control mechanism to regulate the flow of power from the microgrid to the electrical grid [21]. In this paper, the investigation carried out with a PV control shows that the absence of proper control can create further voltage unbalance in the network by injecting the full amount of power produced by the PV into the grid.

The importance of having a gradual injection of power is to prevent damage to the power system. Unfortunately, with the absence of an adequate control mechanism, the flow of the power from the PV is correlated to the start of the simulation and not to the need for the grid. The behaviour of the PV system violates the grid code of safe integration of the microgrid into the power system. The critical point here is to acknowledge that the lead overvoltages that happen at the point of common coupling and another buses close to the PV system are very serious and dangerous violation of voltage stability that needs an appropriate control scheme that can keep the voltage level to an acceptable limit rather than create further disturbance to the safe operation of the electrical grid [22].

VI. Conclusion

The investigation on the effect of integration of microgrid PV into the power system without proper control of power exchange between the microgrid and the electrical grid reveals that integrating a PV with no ideal control into the power system can cause more harm to the grid than resolve the voltage stability.

The simulation results show that the penetration level of the microgrid PV creates an uncontrolled voltage surge that disturbs the power system. Such overvoltages led to voltage instability in power systems even though the level of voltage in part of the grid remains within the acceptable level for voltage stability. The finding of this investigation may be used as preamble for research with interest in photovoltaic integration where voltage stability is a concern.

Therefore, to restore the stability of the grid after the integration of a non-ideal photovoltaic, an adequate algorithm for voltage control will be required whenever a photovoltaic is integrated in power system. This will ensure that high penetration of photovoltaic in power system bring voltage stability into the affected grid.

Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

Author S.D.Lumina conceptualized the research, performed the analysis, and wrote the paper. E.S Mnguni and Y.D. Mfoumboulou fully supervised the research, reviewed, and edited the paper. All authors have approved the final version.

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