Voltage Stability Control in Grid-Tied Photovoltaic Systems Considering Loading Effects

Sampi Denis Lumina
Electrical, Electronic and Computer Engineering
Cape Peninsula University of Technology
Cape Town, South Africa
luminas@cput.ac.za

Mkhululi Mnguni
Electrical, Electronic and Computer Engineering
Cape Peninsula University of Technology
Cape Town, South Africa
mngunim@cput.ac.za

Yohan Darcy Mfoumboulou
Electrical, Electronic and Computer Engineering
Cape Peninsula University of Technology
Cape Town, South Africa
mfoumboulouy@cput.ac.za

2024 32nd Southern African Universities Power Engineering Conference (SAUPEC) | 979-8-3503-7134-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/SAUPEC60914.2024.10445040

Abstract—**This paper addresses the crucial challenge of voltage instability in grid-connected photovoltaic (PV) systems, especially under increased load consumption. The proposed control method introduces an innovative approach based on the Load Margin (LM) violation condition to optimize control strategies. The study evaluates the feasibility and effectiveness of this approach through simulations on the IEEE 9-bus system, utilizing Real-Time Digital Simulator (RTDS) technology. The research contributes valuable insights into mitigating voltage stability issues, offering a sophisticated control strategy tailored to the specific challenges posed by grid-connected PV systems. The findings have significant implications for advancing the integration of renewable sources of energy into traditional electrical grids while ensuring stable and sustainable power supply.**

Keywords— Voltage stability, Distributed photovoltaic power, Dynamic load, sequence collapse, cascade power quality dispatch.

I. INTRODUCTION

Voltage stability in a power system is known as the stability of the electrical grid to stand stable with a tolerable voltage at every single bus of the electrical grid during standard operation of the grid as well as after being subjected to a disruption [1]. Previously, most power systems were fitted with reactive power compensators to contribute to power stability when voltage instability was a concern. Recent studies have shown that distributed energy resources (DERs) such as photovoltaic power have proven to be a contributing source of secondary power added to the traditional grid with the sole objective of mitigating voltage instability, especially when the loading factor is a key cause.

Under normal condition, an electrical power system's grid is planned for radial service, with a centralized electrical power generation system delivering power to the loads. However, as decentralized renewable energy is added progressively to the electrical system to match the increasing load demand, the electrical grid is undergoing dramatic changes in power flow which may affect the stability of the voltage [1].

As solar power operates in parallel to traditional kinds of synchronous generators, the grid encounters further challenges related to the dispatch control of power, preventing stability of the entire photovoltaic-grid-tied system. Voltage stability increasingly becomes a challenging task due to the stochastic generation of solar systems and the dynamic characteristics of the loads associated with it[2]. As such the photovoltaic system requires an adequate preventive and adaptive control strategy that updates the transfer of photovoltaic power to the electrical grid based on the loading condition that causes voltage instability.

The impact of load margin conditions on system voltage instability has attracted some form of interest that has seen numerous researchers investigate how the two are related and how a mitigation solution can be achieved. Previously, little research has been carried out to obtain detailed and adequate methods that monitor the stability of the power grid by providing suitable control mechanisms that ease the challenge of grid integration. Various contributions could be brought forward[3].

In their study [4], the authors emphasize voltage collapse as a serious threat to power system stability and safety, occurring when the power supply falls short of peak demand, resulting in a gradual voltage drop and eventual grid collapse. They introduce a novel approach, the collapse prediction index (NCPI), designed to detect and mitigate voltage collapse by assessing the voltage stability of the power systems and critical conditions on transmission lines. Using the IEEE 30-bus and 118-bus systems, the authors compare NCPI with established voltage indices like Line stability indicator (LMM), Fast voltage stability index (FVSI), Line stability factor (LSP), New line stability index (NLSI), and Voltage stability line index (VSLI) under various power system conditions. Simulation results demonstrate that NCPI outperforms traditional methods by swiftly detecting critical lines, weak buses, and potential maximum load ability. The method's comprehensive consideration of sensitive phenomena enhances the accuracy of collapse prediction, yielding more precise results compared to conventional stability indices[4]

In [5],the authors present a sensitivity analysis-based preventive control method described as voltage stability assessment (VSA) as a real approach for anticipating voltage instability based on the effect of load demande increase. The method uses a fixed voltage sensitivity approach that monitors the voltage profile for any minor deviation possibly caused by load increase. The approach consists of considering the load impedance modulus margin (IMM), which depends on the measurement of the nodal voltage and current set at each bus of the system. With this approach, the sensitive fluctuation in the power profile can be obtained precisely and more rapidly than the traditional way based on load margin (LM). This method prevents the power system from collapsing since the precautionary control is intended to take control action to convert the critical contingencies with the inadequate voltage stability margins (VSM) into negligible ones in the minimum possible time.

Further in [6], the impact of high photovoltaic penetration is investigated on a power system when the load consumption increase causes the voltage to drop beyond the permissible voltage stability index. Because solar power can generate up to 100MW, it is imperatively important to regulate the power dispatch to the grid. The authors analyzed the effectiveness of adding a STATCOM on the power system voltage and the capacity of loading to get to the optimal system quality. The key point in the investigation is to examine the effect of PV energy on the voltage when there is an unexpected rise in loading conditions in the electrical grid. A controller module based on STATCOM for enhancing the voltage quality and ensuring continuous operation of a self-sufficient power system is presented. The logic controller is required to work in sequence mode that matches the profile of the loads.

This paper also emphasizes the simulation procedures involving the controller logic module, utilizing the Real-Time Digital System (RTDS). These simulations aim to assess the impact of photovoltaic integration on power system voltage and loads condition, by keeping the desired voltage stability within the adequate limit of 0.95 and 1.05 p.u, as stipulated by the grid code.

The paper comprises several key sections. In Section 2, different case studies that constitute the research based on the IEEE-9 bus systems are presented to be performed in RTDS. Moving to Section 3, the focus shifts to power flow analysis during the stable state operation of the distribution grid, with a specific simulation case highlighting the impact of increased load consumption on voltage stability. Section 3 also delves into the control mechanism for voltage stability, taking loading conditions into account. The paper provides results and discussions on the efficacy of the proposed control method, culminating in overall conclusions presented in Section 4.

II. EXPERIMENTAL

The laboratory experiment was performed in real real-time digital system demonstrating a voltage collapse instigated every two second by an increment of 50% loading consumption in step of 5% from the initial load condition. The projected method which is based on the load margin condition has the task of monitoring changes in the voltage magnitude that occurs at the point of common coupling. The logic controller in Fig.7 is designed to react instantaneously to the change by providing an adaptative amount of power that will restore the voltage stability as soon as a risk of power collapse is detected in the system. Basically, in the situation of an unexpected rise in load demand in the power system, there must be appropriate sensitive , preventive and adaptive control strategy in the injection of power delivered by the PV plant to the electrical system [6]. This paper concentrates on the development and implementation of a control logic module aimed at monitoring and enhancing voltage quality considering unexpected change of loading profile. Additionally, it addresses strategies to ensure consistent stability in the operation of an autonomous power system.

Three simulation case studies are completed using the IEEE-9 bus system are conducted as follows:

Case 1- Computing load flow analysis for all load buses of the electrical grid to determine the steady state condition.
Case 2- Determining the critical voltage stability margin by increasing the consumption of all loads without integrating the photovoltaic system.
Case 3- Integrating the PV system with operational ability depending on the loading margin. Lastly, analyze the performance of power systems and acknowledge the effectiveness of the method. The steps of the case studies are presented in Fig. 1.

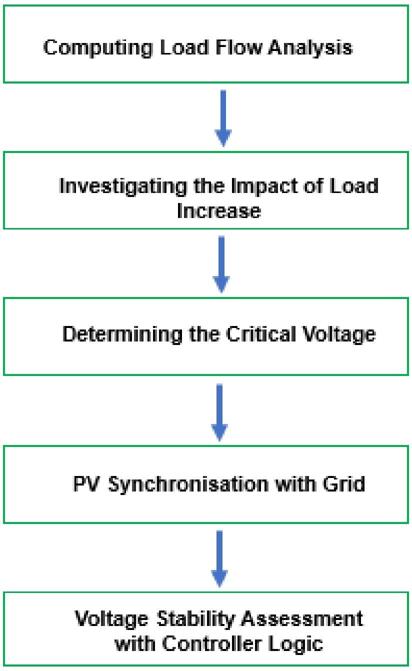

Fig. 1. Steps leading to the investigation of the Voltage stability index

III. RESULTS AND DISCUSSION

A. *Case study 1: Stability analysis through power flow*

The first case study is the load flow simulation of the IEEE-9 bus system to demonstrate that the load margin and voltage index of the system are both within the acceptable limit for system stability. Load flow analysis is critical as it gives a clear image of the performance of the grid. Table 1 below is a summary of the voltage margin of the grid before the voltage instability is induced in case study two. The stability analysis and voltage control results of the IEEE-9 bus systems in RTDS are presented in Table 1 below.

TABLE I. STABILITY CONTROL WAY OF THE IEEE-9 BUS SYSTEM

IEEE-9 bus system simulation Data			
Bus	Voltage p.u.	Type	Stability index
1	1.040	SLACK	Long-term
2	1.025	P-V	Long-term
3	1.025	P-V	Long-term
4	1.026	P-Q	Long-term
5	0,996	P-Q	Long-term
6	1.013	P-Q	Long-term
7	1.026	P-Q	Long-term
8	1.016	P-Q	Long-term
9	1.032	P-Q	Long-term

The quality of voltage stability can be described using various criteria. However, in essence, voltage stability in the system refers to its capability to keep its voltage magnitude within predefined parameters under all loading conditions and at any given moment for all buses within the system [5],[6]. From a load perspective, voltage is considered stable when its magnitude falls within the limit of 0.95 p.u to 1.05 p.u, as indicated in table 1.

B. Case study 2: Stability problem in the system. Load Impact

Testing the effect of the load consumption on the voltage profile is carried out using a load scaling factor of 50% increase from the initial load. By increasing the load consumption, the voltage magnitude at various buses of the electrical grid is monitored. The simulation Data of the case study not only come in support of the aim of this paper by providing a clear understanding of the effect of the loading condition on the voltage stability but also more as a supporting argument to the idea of integrating renewable energy in the electrical grid. The case study consists of increasing the load consumption to the instance where the grid will no longer be able to provide enough power for the load. This phenomenon can be further supported by examining the PV curve in Fig. 2 below where one can see how the loading profile of the system can drive the voltage deep to the level of instability.

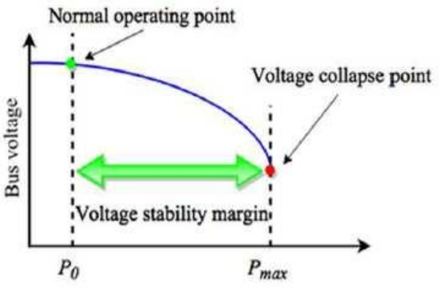

Fig. 2. PV curve for loading capability[7]

A representation of a standard voltage stability monitoring and detection system is created in RTDS, employing the IEEE-9 bus system for simulation purposes. The grid's stability is evaluated by tracking the voltage magnitude and applying a meticulously selected stability index, which is determined based on the voltage collapse point, as outlined in Fig. 2 above.

The outcomes of the RTDS simulation reveals that the voltage magnitude at nodes 5, 6, and 8 declined below the authorized limit for voltage stability. This vividly illustrates how the loading pattern directly influences voltage stability. The simulation results undeniably highlight the adverse consequences of heightened load consumption in power systems.

Table 2 describes the loading condition of the system while Fig. 3 to Fig. 5 show the collapse of voltage on the affected bus of the system. Fig. 6 is the actual state of the entire system after the load increase.

TABLE II. LOAD CONSUMPTION PROFILE

Loading profile of the IEEE-9 bus systems						
Load Range	Load 5		Load 6		Load 8	
	MW	Mvar	MW	Mvar	MW	Mvar
Initial condition	125	50	90	30	100	35
Full load	187.5	75	135	45	150	52

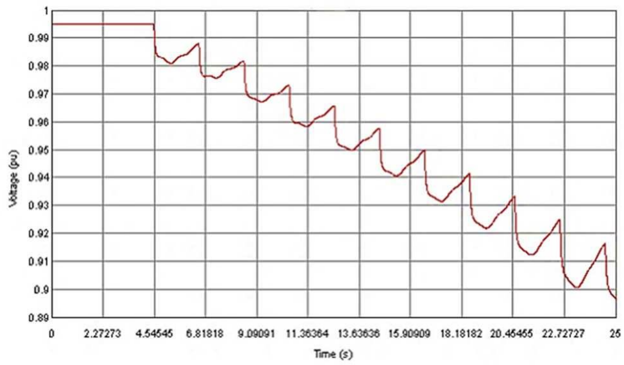

Fig. 3. Voltage drops at Bus 5 due to load increase

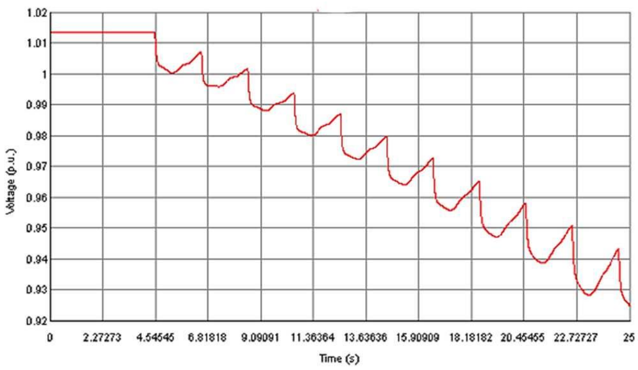

Fig. 4. Voltage drops at bus 6 due to load increase

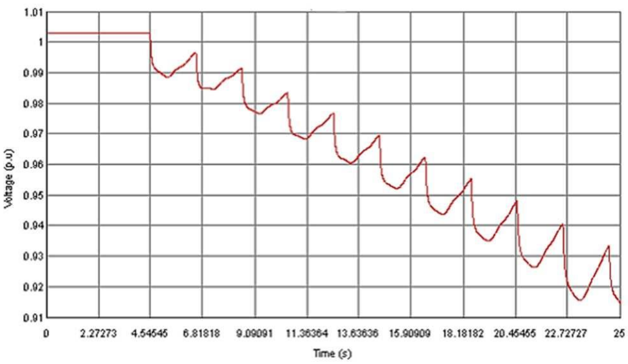

Fig. 5. Voltage drops at bus 8 caused by load increase.

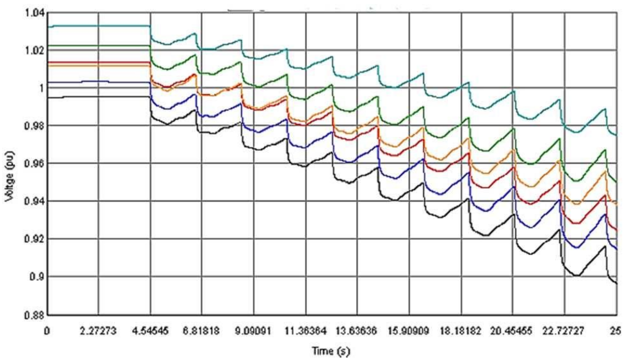

Fig. 6. Voltage drops at bus 4,9,7,6,8, and 5 of the IEEE-9 bus system

C. Case study 3.Controller design and Integration of Pv power

Considering the influence of the load escalation on voltage stability, the incorporation of the photovoltaic power into the grid is implemented as a countermeasure to prevent voltage collapse. Specifically, an 80 MW solar power source is linked to bus 5 to alleviate the risk of grid instability. The choice of bus 5 as the location for the PV plant is motivated by the tendency for voltage levels to rise at the point of connection. Drawing from the findings obtained in case study two, it is anticipated that the solar power injection at bus 5 will have a limited impact due to the relatively low voltage magnitude recorded at this location following the load increase.

To ease the secure integration of solar energy into the electrical grid, an RTDS-based PID logic controller, illustrated in Fig 7, has been developed. This controller serves the purpose of monitoring the grid's performance, reacting to voltage fluctuations, and tracking the voltage magnitude patterns across all system buses [7],[8]. Furthermore, the controller's logic is responsible for ensuring that the voltage remains within a predefined and acceptable stability range[9],[10].

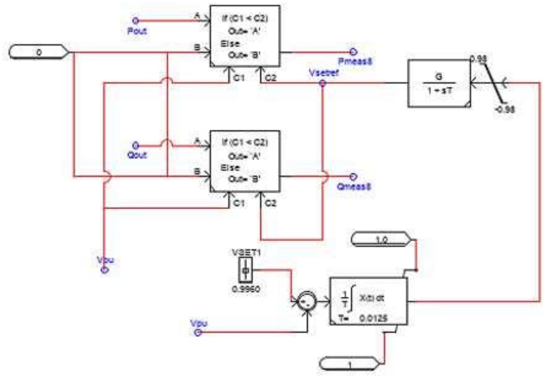

Fig. 7. PID Logic controller for grid synchronization in RSCAD

In the control loop of the PID, the voltage V_{SET1} is set at 0.95 p.u as reference by the power utility, V_{pu} is the voltage profile at the point of coupling. The voltage V_{pu} which reflects the performance of the grid between the range of 0.95 p.u and 1.05 p.u is compared to V_{SET1} to obtain the margin error which is processed through the PI controller to get the susceptance V_{setref} . The role of V_{setref} is to trigger the ON/OFF function of the inverter. By doing so, the inverter can inject P_{out} and Q_{out} from the PV in accordance with the variation of the voltage magnitude caused by the increase of load consumption. The operation of the inverter depends on the value of V_{SET1}. For a value of V_{SET1} less than the susceptance, the inverter will let the transfer of PV power to the grid, but for a value of V_{SET1} greater than the susceptance, the inverter will stop sending P_{meas8} and Q_{meas8} power into the grid. This is where the injection of PV power into the power systems is adaptive.

The simultaneous introduction of active and reactive power into the electrical grid in a step-by-step manner is depicted in Fig. 8 and Fig.9. Meanwhile, the simulation outcomes of the grid's synchronization with the photovoltaic plant, detailed from Fig.10 to Fig. 13, demonstrate the efficiency of the employed approach in controlling voltage stability while accounting for the load characteristics.

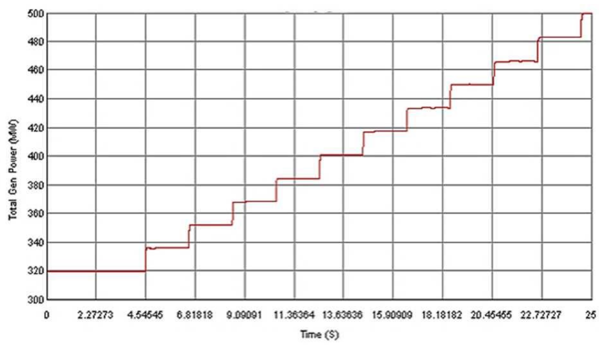

Fig. 8. Impact of photovoltaic power integration on the IEEE-9 bus system.

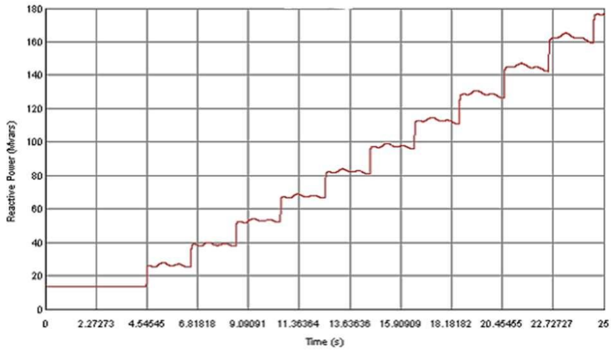

Fig. 9. Reactive power injection after PV integration on the power systems

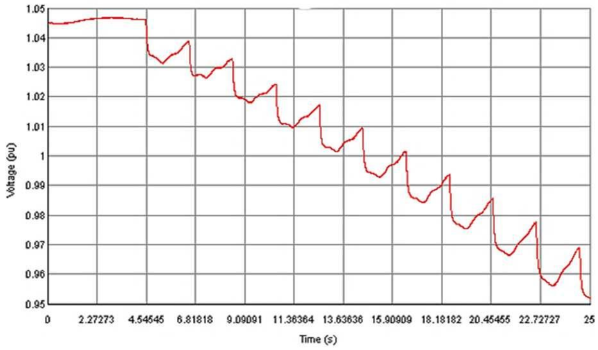

Fig. 10. Restoration of voltage to its stability after integration of PV

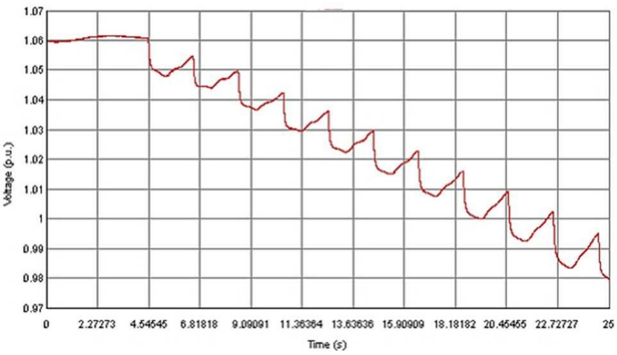

Fig. 11. Bus 6 voltage profile restored

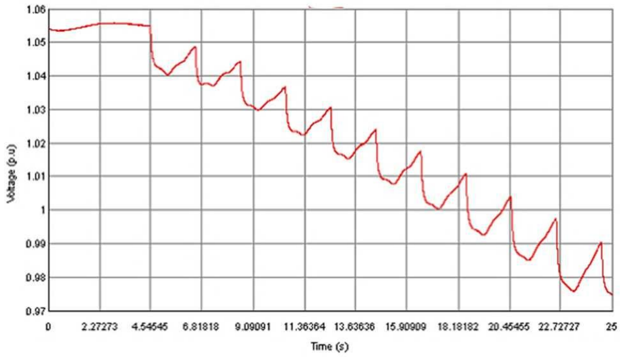

Fig. 12. Voltage profile restored at bus 8

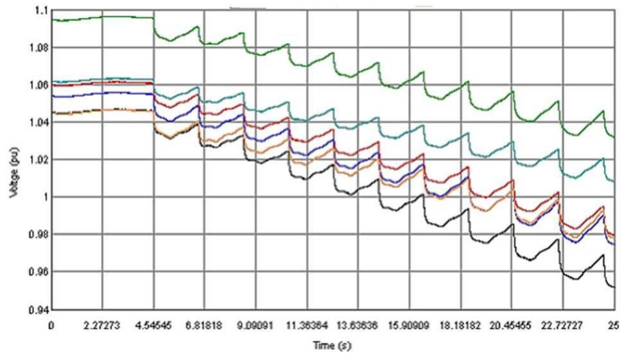

Fig. 13. All bus voltage is kept within acceptable range of voltage stability

As illustrated in Fig.13 above, the allocation of power between the photovoltaic system and the grid follows a pattern that aligns with the voltage decrease caused by the load characteristics. Consequently, the control mechanism is closely linked to the voltage magnitude, which is influenced by the load profile.

The validation of the load margin method becomes relevant when the voltage magnitude is impacted by the load profile[11]. The success of the proposed control method has significantly mitigated the impact of load consumption, a primary contributor to voltage collapse. The issue of voltage stability in the integrated grid becomes a significant concern in the absence of a well-established control strategy for ensuring smooth synchronization.

IV. Conclusion

In conclusion, the research paper highlights the effectiveness of the proposed method-based loading margin approach and controller logic system in monitoring and preventing voltage instability within power systems. The comprehensive case studies, particularly on the IEEE-9 bus system, illustrate the system's ability to respond effectively to a substantial increase in load consumption, preventing grid collapse. The results emphasize the adaptability and responsiveness of the control system to dynamic grid characteristics, offering a promising contribution to enhancing the reliability and stability of power systems under varying load conditions.

V. Future Work

The future work recommended in alignment with the current study aims to explore voltage profile enhancement by integrating Electric Vehicles (EVs) into the grid using Vehicles to Grid (V2G) technology. The research will involve theoretical and simulation analyses, conducted in RTDS, to showcase the potential of V2G technology in supporting voltage stability within power systems, particularly those with microgrids. Furthermore, the recommendation includes the development of a smart management communication solution utilizing the IEC 61850 communication standard protocol to facilitate effective communication between various components of the smart grid.

AUTHOR CONTRIBUTIONS

Sampi Denis Lumina realised the study concept, completed the investigation, and drafted the paper. Mkhululi Mnguni and Yohan Mfoumboulou entirely overseen the research, reviewed, and corrected the research paper.

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