# Assessment of the Steady State Voltage Stability of the Ghanaian Transmission System with the Integration of Renewable Energy Sources

M. W. Asmah, R. Baisie, B. K. Ahunu, J. M. A. Myrzik

***Abstract*--The increasing demand for electric power and the resulting need for new generating stations and grid reinforcement have led to an increased complexity in the Ghanaian power system. Power generation in Ghana is dominated by hydro and thermal generation with only 0.6% solar PV generation. Albeit, plans are underway to increase the share of renewable power generation (solar PV and wind) to 10% by the year 2020. The location of the proposed PV plants in the north, where there is less load demand with a likelihood of leading to an imbalance in the system during periods of high PV generation. Long transmission lines are therefore needed to transport power from PV units in the north to load centers in the south. This situation translates into high reactive power demand and very high voltages in the north, which eventually leads to the operation of the Ghanaian power system near its voltage stability limits. In view of the ongoing renewable energy integration, assessing the voltage stability limit becomes necessary in the planning of the Ghanaian power system. This paper thus analyzes the steady state voltage stability of the Ghanaian transmission system using simple power flow algorithms based on the Newton-Raphson method. The continuation power flow method is specifically employed to develop the nose curves of critical buses in an attempt to determine the steady state stability limit of the system. To investigate the effect of increased PV generation on the voltage stability, different simulation scenarios, which represent different percentages of PV generation, are developed for the simulations.**

***Keywords*: Ghanaian power system; nose curves; renewable energy integration; steady state voltage stability**

## I. Introduction

POWER systems in developing countries today are facing diverse challenges due to the rampant growth in electricity demand and the resulting increasing complexity of the power systems. The Ghanaian power system for instance with a peak demand of 2,500 MW and a total installed generation capacity of 3,700 MW [1] experiences various technical challenges. These challenges, which include transmission line and equipment overload, inadequate reactive power supply and the violation of set voltage limits [1] occur as a result of the increasing load demand and the inability of the power system to meet the demand. The reliability and quality of supply in the Ghanaian power system have therefore reduced leading to outages and subsequent load-shedding.

Due to the national target to increase the share of renewable energies (RE), voltage stability has become one of the important design criteria for the safe operation of the Ghanaian power system. Based on the geographical location of the country, higher solar irradiation is recorded in the north where the demand is less (light load). The availability of large expanses of land in the north also makes the north appropriate for the solar panel installation. Consequently, power generated from the solar PV units in the north will have to be transported to load centers in the south. The longitudinal structure of the Ghanaian power system and the light load in the north results in several cases of Ferranti effect and a high utilization of the transmission infrastructures with resulting increase in the operational voltages in the north. Diverse compensation devices have thus been installed in the north to manage the existing high voltages which endangers the system stability.

Although voltage instability is not new in the Ghanaian power system, it has recently received much attention with the expected increase in renewable power generation. Against the backdrop of the above mentioned challenges, the transmission system operator in Ghana together with other key players in the Ghanaian power sector have taken keen interest in carrying out system stability studies, which are limited to only transient stability analysis [2], [3], [4]. Despite voltage instability being a major problem in the Ghanaian power system, few system studies have been carried out on the impact of the planned renewable power generation on voltage stability. It is in this regard that this paper seeks to investigate the steady state voltage stability limit of the Ghanaian national interconnected transmission system (NITS) and how the proposed increase in PV generation affects the stability of the network.

The organization of the paper will be as follows: Section II presents a brief review of selected techniques for analyzing steady state voltage stability while section III presents a concise overview of the Ghanaian power system. The methodology implemented to develop the nose curve in this paper is explained in section IV. Section V discusses the simulation scenarios developed for the system simulations in this paper. The results of the simulation are then presented in section VI with the conclusion drawn in section VII.

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## II. Voltage Stability Analysis Techniques

Voltage stability is defined as the ability of the power system to maintain steady voltages at all busbars in the system after being subjected to a disturbance [5]. The system's ability to maintain equilibrium between supply and demand also influences the stability of the system. On the other hand, voltage instability is often experienced in the power system in the form of increasing or decreasing bus voltages with resulting loss of load, tripping of transmission lines, generators, etc. The analysis of voltage stability in the power system encompass several methods with and without the use of power flow solutions [6]. The P-V and Q-V curves (nose curves) are the most considerable methods, which utilize power flow solutions for determining the load margin (active and reactive power) of the system. A typical nose curve (P-V curve) of a 2-bus system with the various operation points and regions is presented in Fig. 1.

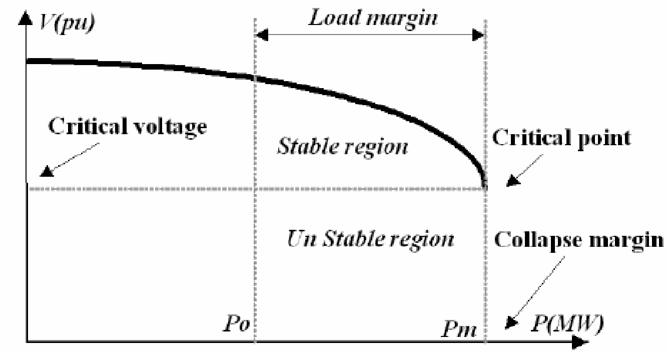


Fig. 1. P-V Nose Curve of a Two-bus System [7]

Fig. 1 shows the active power and corresponding voltage levels at which different operating regions in the power system is possible. Maximum loading occurs at the critical point, beyond which any loading increases the risk of voltage collapse in the power system. Voltage collapse in the power system is an uncontrollable process, which leads to very low voltages in the power system. It is for this reason that the maximum loading point (critical point) is also known in literature as the voltage stability limit of the system. The voltage stability limit is however influenced by other factors in the power system such as the network impedance. Compensation devices are thus installed in the system to improve the voltage profile.

Analyzing the steady state voltage stability using load margin as the voltage stability index, which by far is the simplest stability index to implement includes the use of the direct and continuation methods [6]. Continuation methods such as the continuation power flow (CPF) allows the solution of a nonlinear system to be developed using the prediction and correction of a parameter $\lambda$, introduced into the load flow equation. The CPF involves the prediction of the next solution point and the correction of the predicted value to get the next point on the nose curve [8]. The prediction and correction processes in this technique earns the technique its name, the 'predictor-corrector' method. The CPF method also eliminates the singularity of the Jacobian matrix, which occurs during the conventional power flow. In the CPF, the Jacobian matrix remains well conditioned even at the saddle node bifurcation point. The direct methods on the other hand are used to directly determine the singular bifurcation points of nonlinear systems [6]. The load margin to the voltage collapse at any defined operating point is directly determined using this method. This technique however has the disadvantage of a high computational requirement for large systems. Thus, based on the large size of the Ghanaian transmission system, which is used for the analysis in this paper and the advantages the CPF method offers, the CPF method will be employed to develop the nose curve.

## III. Overview of the Ghanaian Power System

The Ghanaian power system just like any power system is divided into the generation, transmission and distribution sub-sectors with different mandates. The power market in Ghana takes the form of an unbundled power system with vertical governance, which allows for separate markets in the three different sub-sectors as well as immediate and fair competition in the respective sub-sectors. While the generation sector is currently unbundled, i.e. open for both government and private investors, the open access power transmission is still carried out by a single transmission system operator, the Ghana Grid Company. Power distribution on the other hand is by two separate institutions, which are responsible for the southern and northern parts of the country.

### A. *Generation Sub-Sector*

Ghana relies on two main energy sources for power generation: hydro and thermal with respective percentage shares of 44.3% and 55.1% [1]. Power generation from RE, currently only solar PV accounts for 0.6% of the total installed generation. The total installed generation capacity amounts to 3,700 MW [1] with only about 70% (2,600 MW) available for supply due to unanticipated fuel supply challenges. 72% of the total installed generation belongs to the Volta River Authority (VRA) – a government owned institution while the remaining 28% belongs to four independent power producers (IPP).

A total of 16 generating stations exist in the country, three of which are hydro plants, two solar PV plants and the remaining eleven, thermal power plants as presented in Figs. 2 and 3 below. A 225 MW wind park is currently under construction, which when completed will be the largest in the West African sub-region. All generating units are located in the south with only two; 400 MW hydro and 2.5 MW solar PV located in the north of the power system.

### B. *Transmission Sub-Sector*

Ghana's high voltage transmission network, which is presented with single line diagrams in Figs. 2 and 3 consists of four voltage levels; 330 kV, 225 kV, 161 kV and 69 kV [1], [9]. The 161 kV serves as the main transmission voltage in Ghana, while the 69 kV serves as the higher sub-transmission voltage in some parts of the network. The 225 kV is the voltage of the existing interconnecting transmission line between Ghana and Cote d'Ivoire. The network currently has two main 330 kV double circuits with ongoing plans and expansion projects to eventually make the 330 kV the main transmission voltage. The network is made of approximately 5,440 km of high voltage transmission lines [9] connecting the generating stations to various load centers across the country. Due to the nature of the power system (concentrated generation) and the need for long transmission lines, compensation devices (represented with orange figures in Figs. 2 & 3) have been installed in the power system to deal with the existing reactive power imbalance.

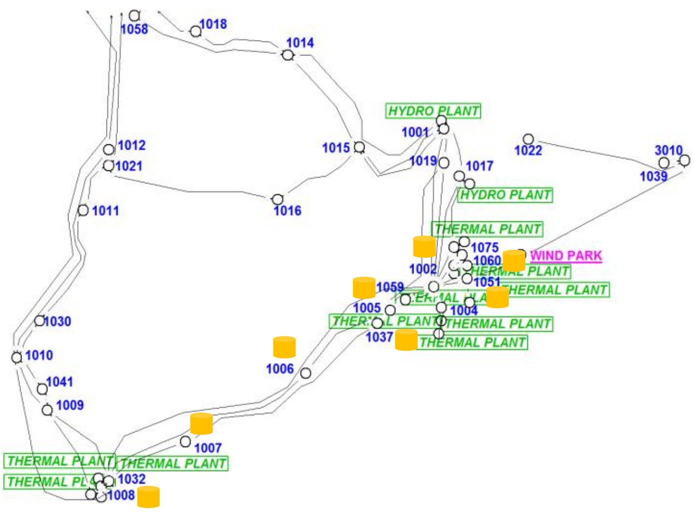


Fig. 2. Single Line Diagram of the Southern Transmission Grid

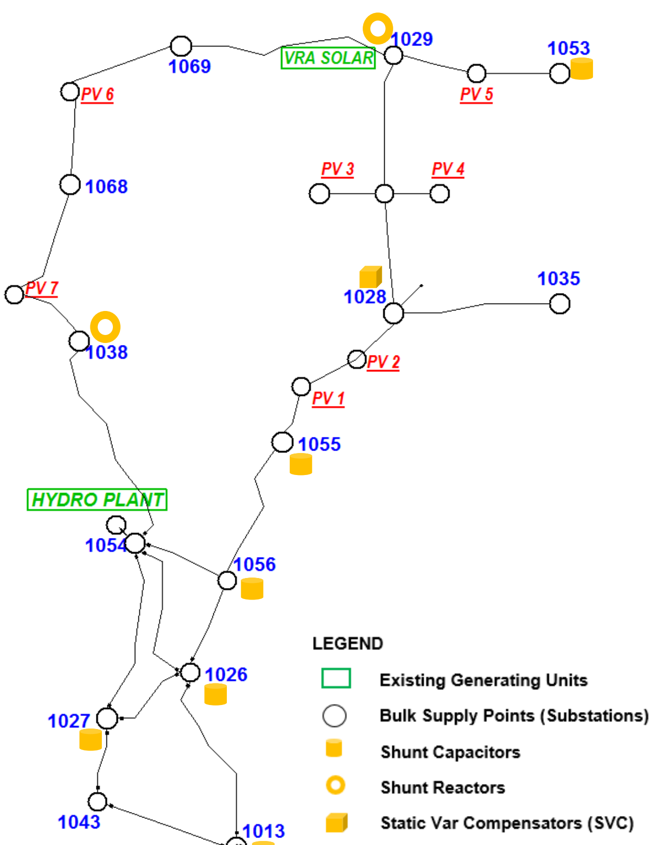


Fig. 3. Single Line Diagram of the Northern Transmission Grid with PV Units

Fig. 3 shows the location of the proposed PV units in the northern transmission system. A total of 150 MW solar PV generation is expected in Ghana by the end of the year 2017. The Ghanaian NITS is made up of interconnections of the power systems of Ghana and its neighboring countries, Cote d'Ivoire to the west, Burkina Faso to the north and Togo/Benin to the east.

### C. Distribution Sub-Sector

Ghana's distribution network is divided into two parts; northern and southern grids, which are managed by two different institutions. The Electricity Company of Ghana (ECG) manages the southern distribution grid, while the Northern Electricity Distribution Company (NEDCo) manages the northern grid. The total demand in ECG's network constitute 64% of the total system peak, while the demand in NEDCo's network amount to only 8% of the system peak. The remaining 28% is distributed among the loads in the mines, VALCO[1] all located in the south as well as power exports to Burkina Faso and Togo/Benin. All proposed PV plants are located in the northern part of the transmission network, which is part of NEDCo's operational region (on the distribution level). There is however a 20 MW solar PV plant in the south, which is connected directly to the distribution grid.

## IV. Implemented Methodology

The continuation power flow method (CPF) using a simple Newton-Raphson power flow algorithm is used to develop the nose curve. The Newton-Raphson method is used here due to its high accuracy in approximation [10], which is essential to the analysis of voltage stability. A continuation parameter λ and an additional equation are introduced into the power flow equation of a system assumed to have $n$ nonlinear equations as illustrated in [8] and given as follows:

$$g(x) = \begin{bmatrix} P(x) - P^{inj} \\ Q(x) - Q^{inj} \end{bmatrix} = 0 \quad (1)$$

$$x \in R^n \text{ and } x \equiv (\Theta, V_m) \quad (2)$$

The load flow equation of the system is modified as

$$f(x,\lambda) = g(x) - \lambda b = 0 \quad (3)$$

where $b$ is the power transfer vector $b = \begin{bmatrix} P_{target}^{inj} - P_{base}^{inj} \\ Q_{target}^{inj} - Q_{base}^{inj} \end{bmatrix}$ (4)

Using the continuation power flow method allows the solution to the system, $x$ to be traced through the change in $\lambda$, which is the continuation parameter. The continuation parameter introduced into the load flow equation $\lambda$, represents the increase in demand (loading parameter) and is used as the horizontal axis in the nose curve. The nose curve is then traced by varying the demand of the busbars from the base load

[1] VALCO, the Volta Aluminum Company is a government owned aluminum smelter in Ghana. VALCO's demand represent 3% of the total system demand.

condition (minimum) to the maximum or critical loading point [11] as seen in Fig. 1.

The nose curve in this paper was developed through the step-wise increment of the load demand on all buses in the system by 1.35% while recording the corresponding bus voltage. A curve of the load increment λ and the bus voltage (nose curve) was then produced for selected buses.

### A. *Description of Simulation Model*

The power system model used in this study is the static model of the Ghanaian NITS, which consists of approximately 430 buses. The model consists of 100 generator buses with about 500 branches, which includes all transformers, compensating devices, line impedances, resistances, etc. For the purpose of this analysis, the influence of the transformer on-load tap changers (OLTC) and switched capacitors in the network are not considered.

To analyze the voltage stability of the Ghanaian network, the following critical buses were selected from the northern and southern transmission systems for further investigation:

- Bus 1005 – Bus of one of the largest load centers in the south
- Bus 1013 – Bus of a large load center and a major bus between the north and south
- Bus 1028 – Bus of a major load center in the north, which is equipped with a 40 MVAr SVC and also serves as connection point for three PV plants
- Bus 1032 – Bus of thermal generating units in the west
- Bus 1068 – Connecting bus to a 20 MW PV plant

Buses 1013, 1028 and 1068 are located in the northern transmission system while the buses 1005 and 1032 are located in the south as shown in Figs. 2 and 3.

## V. Simulation Scenarios

To analyze the influence of solar PV generation on the steady state voltage stability of the Ghanaian power system, the following scenarios were developed for the simulation. Each scenario portrays a condition of the network with a different PV penetration level.

**Scenario 1**: This is the base case scenario, which describes the proposed network conditions for the end of the year 2017. A total of 150 MW PV generation is installed, which represents approximately 4% of the total installed generation capacity.

**Scenario 2**: Scenario 2 mimics the network in the year 2020, where the network will have 10% renewable power generation. In this scenario, PV generation is increased to 370 MW to make up the targeted 10%.

**Scenario 3**: This scenario exhibits the 'post-2020' situation, where network conditions beyond the year 2020 are simulated. With plans to increase the RE generation beyond the year 2020, it is appropriate to also consider the voltage stability in the event when PV generation exceeds 10%. PV generation in this scenario is increased to 15%.

The PV units in Ghana would be operated just like conventional power plants as far reactive power and voltage support are concerned. As specified in Ghana's RE sub-code for the transmission system, PV units are required to operate within their reactive capability limits at power factors of 0.95 lagging and 0.925 leading [12]. Table 1 below thus summarizes the active and reactive power generation in each of the scenarios at a specified operational power factor of 0.95. For each of the scenarios, load demand in the system is increased and the resulting bus voltage recorded to develop the nose curve, which represents the relationship between the load increase of a bus and the corresponding bus voltage.

TABLE I
Overview of PV Generation in the Different Scenarios

| PV Unit | Scenario 1 | | Scenario 2 | | Scenario 3 | |
|---|---|---|---|---|---|---|
| | P (MW) | Q (MVAr) | P (MW) | Q (MVAr) | P (MW) | Q (MVAr) |
| PV 1 | 20 | -6.57 | 50 | -16.4 | 73 | -23.9 |
| PV 2 | 30 | -9.86 | 75 | -24.7 | 113 | -37.2 |
| PV 3 | 20 | -6.57 | 50 | -16.4 | 73 | -23.9 |
| PV 4 | 20 | 6.32 | 50 | 15.8 | 73 | 23.1 |
| PV 5 | 20 | -6.57 | 50 | -16.4 | 73 | -23.9 |
| PV 6 | 20 | -6.57 | 50 | -16.4 | 73 | -23.9 |
| PV 7 | 20 | -6.57 | 50 | -16.4 | 73 | -23.9 |
| **Total** | **150** | **-36.4** | **375** | **-90.9** | **551** | **-133.6** |

Due to the prevailing high voltage conditions in the north, where the PV units will be installed, the PV units are set to absorb reactive power from the system. Notwithstanding, the defined reactive limits (maximum and minimum) of the PV units allows them to either absorb or generate reactive power depending on grid conditions. To comply with this regulation, PV operators, whose units do not meet this requirement are obliged by the law to install additional compensation devices.

## VI. Simulation Results

The results obtained from simulating the system under the different network conditions described in the three scenarios are presented in this section.

### A. *Scenario 1*

Fig. 4 illustrates the relationship between the bus voltage and the change in active power with 4% PV generation.

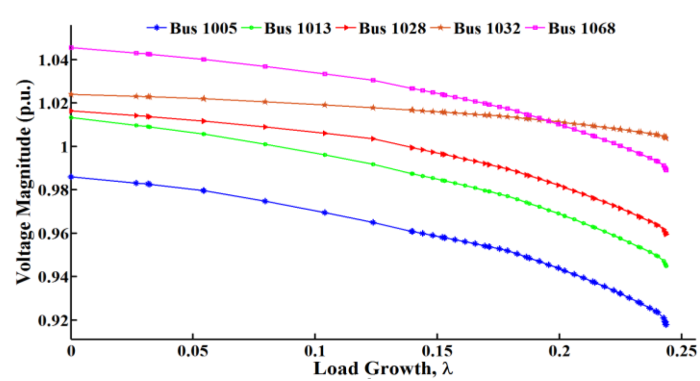

Fig. 4. Nose Curves of Selected Buses for Scenario 1

An observation of Fig. 4 indicates that a steady increase in the load demand results in the variation of the bus voltage, which cannot be sustained beyond a load increase of 0.244 p.u., where the nose of the curve occurs. This point represents the critical point of the system, which is also the maximum power transfer that the system can handle.

A further observation of Fig. 4 shows the existing high voltages on the buses in the north, buses 1028 and 1068. The voltage on bus 1032, which is a generator bus, does not vary widely as a result of the reactive power support provided by the generators connected to it. Apart from the effect of the PV units installed at bus 1028, the impact of the control action of the installed SVC is also made clear from the relatively lower voltage variation margin of that bus. The relatively lower voltage on bus 1005 is as a result of its very heavy loading.

### B. Scenario 2

In simulating scenario 2, an amount of conventional generation in proportion to the increase in PV generation was taken out of service. The relationships between the loadability of the system and the bus voltages with a PV penetration of 10% are illustrated in Fig. 5.

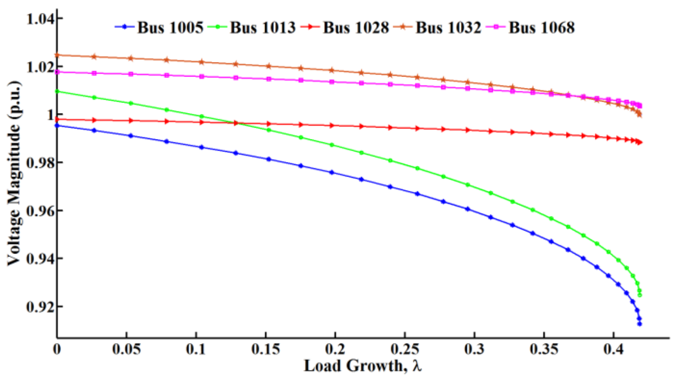


Fig. 5. Nose Curves of Selected Buses for Scenario 2

The results presented in Fig 5 show an obvious increase in the loadability of the system with increasing PV generation (from 4% to 10%) as also depicted in [14]. With an increased PV generation, the critical loading was recorded at a $\lambda$ of 0.418 p.u.

An observation of Fig. 5 depicts a faster decline in voltages on buses 1005 and 1013 as the load increases. The reason for this is that these buses are among the heavily loaded buses in the Ghanaian power system and as such slight load increases result in large voltage drops. Furthermore, with increasing amount of PV generation, the high voltages on the PV buses: 1028 and 1068 decreased (seen in the relatively flatter curves of buses 1028 and 1068) as compared to scenario 1. This is attributed to the reactive power contribution of the PV units, which were set to act as reactive power absorbers due to the high voltage condition in the north, where they are connected. The high voltage recorded at bus 1032 is as a result of the reactive power support provided by the generating units on that bus.

### C. Scenario 3

Increasing the PV penetration level from 10% in scenario 2 to 15% in scenario 3 further stabilizes the bus voltages on the PV buses 1028 and 1068 as seen in Fig. 6 below.

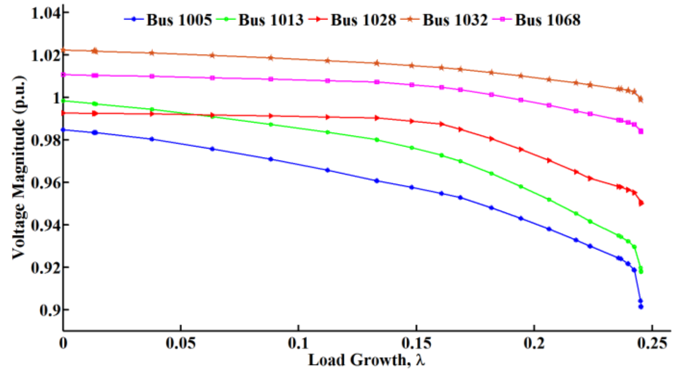


Fig. 6. Nose Curves of Selected Buses for Scenario 3

Also in this scenario, conventional generation was reduced by an equivalent of the 15% PV generation increase. With increased PV generation in the north and reduction of conventional generation in the south, the network in the south became deficient of real and reactive power. As loads in the south are generally larger than in the north, the slightest increase in load resulted in major reduction in the bus voltage as seen in Fig. 6. The transmission of real power and the associated reactive power all the way from the north to the south over very long transmission lines resulted in low voltages depicted by the voltage profiles of buses 1005 and 1013 in Fig. 6. On the other hand, the voltage profiles of buses with a form of generation; buses 1068 and 1032 were rather stable due to the reactive power support of the connected generating units. Even with the installed SVC and PV units, the large load on bus 1028 (exceptional case of large load in the north) affected its voltage profile compared with the voltage profile of bus 1068, which has a lighter load. The system in scenario 3 became relatively unstable as more conventional generation was replaced with PV generation.

### D. Discussion of Results

The results presented in this paper indicate that increasing percentages of PV generation have a positive influence on different system parameters based on the amount of PV generation as well as the settings and control mode of the PV units. For the simulations in this paper, the PV units were set to absorb reactive as they were located in a part of the network with high voltages. As per the Ghanaian RE grid code, the units were set to operate at their minimum reactive power limit (power factor of 0.95 lagging) in this paper. As was expected, the reactive power absorption of the PV units resulted in improved voltages at the corresponding busbars.

Analysis of the simulation results show that the increasing percentages of PV units in the Ghanaian power system lead to improvement of the voltage profile and an enhancement of the overall power quality of the system. This observation relates to the findings of the analysis carried out in [13]. The improvement in the voltage profile in the long term leads to an enhancement of the static voltage stability of the system, which corresponds to the findings in [13], [14].

The PV units in this paper were set to operate in the voltage control mode by choice of the authors. As it was the case in the researches of [15] and [16], the operation of the PVs in the voltage control mode resulted in an increased voltage stability as compared to operation in the other control modes.

The installation of PV units in the north of Ghana, where only two generating units are currently installed is strategic in relieving the transmission congestions in the power system due to the transmission of power over very long distances (from south to north of Ghana). Congestion relief in the transmission system consequently leads to a general reduction of transmission losses, which is confirmed by the simulation results of this paper as well as findings in the researches of [13] and [14].

To further investigate the role of the PV units in the voltage control of the network, the reactive power generation of the PV units were reduced to half of the minimum allowed to assess their effects on the voltage. The results indicated that the PV units worked exactly in response to the network conditions of the part of the network they were installed. In this case, the PV units continued to absorb more reactive in proportion to their minimum reactive power limits.

## VII. Conclusions

The aim of this paper was to investigate the effect of PV generation on the static voltage stability of the Ghanaian power system. The motivation of the contributions is seen in the challenges that are likely to be introduced in the voltage stability through power generation from RE sources. This paper therefore presented an analysis of the steady state voltage stability of the Ghanaian power system using the continuation power flow method.

The nose curve obtained in this paper provides a visual information to system operators and offers a general overview of the steady state stability limit of the Ghanaian power system. The simulation results indicate that the maximum power transfer (loading margin) of the system was improved by a certain percentage increase of PV generation. Again, based on the results, it was observed that the operation of the PV units in the voltage control mode resulted in an improved stability compared to other control modes. Furthermore, increasing the percentage share of PV generation improved the voltages of the busbars the PV units were connected to. The persistent high voltage condition in the north of the Ghanaian power system was reduced to acceptable limits through the operation of the PV units as reactive power absorbers. The installation of the PV units in the Ghanaian power system did not only improve voltages of the PV connected buses but also voltages of neighboring buses as seen from the voltage profile of bus 1013 in the three scenarios. Due to the nature of the Ghanaian power system, it can be concluded that a certain amount of conventional generation is always required in the south to ensure system stability, a condition, which limits the amount of PV generation in the north of Ghana.

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