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Voltage Stability Margin-Based Approach for Placement of Distributed Generators in Power Systems

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***Abstract*—**Voltage stability analysis is crucial to the reliable and economic operation of power systems. The power system of developing nations is more susceptible to failures due to the continuously increasing load demand which is not matched with generation increase and efficient transmission infrastructures. Thus, most power systems are heavily stressed and the planning of extra generation from distributed generation sources needs to be efficiently done so as to ensure the security of the power system. In this paper, the performance of a relatively different approach using line voltage stability margin indicator, which has proven to have better accuracy, has been presented and compared with a conventional line voltage stability index for distributed generators (DGs) siting using the Nigerian 28 bus system. Critical Boundary Index (CBI) for voltage stability margin estimation was deployed to identify suitable locations for DG placement and the performance was compared with DG placement using Novel Line Stability Index (NLSI) approach. From the simulation results, both CBI and NLSI agreed greatly on suitable locations for DG on the test system; while CBI identified bus 18 as the most suitable at system overload, NLSI identified bus 8 to be the most suitable. Considering the effect of the DG placement at the selected buses on the voltage magnitude profile, the result shows that the DG placed on bus 18 identified by CBI improved the performance of the power system better.

***Keywords*—**Voltage stability analysis, voltage collapse, voltage stability index, distributed generation.

I. Introduction

POWER networks are complex and highly dynamic in nature due to the non-linearity of the interactions between the various active and passive system components [1]. The challenges of modern power system operation are further complicated by the various technical and operational standards and conditions that must be taken into consideration, especially under a deregulated market environment [2]. Hence, efficient and optimal planning of additional power injection from DGs must take into consideration the technical and operational specifications of the existing grid infrastructures especially for heavily loaded power systems of developing countries like Nigeria.

Introduction of localized generators, otherwise known as DGs has been identified as a way to improve the steady state operating condition of power systems and also improve the energy and environmental sustainability [3]. Dispersed or distributed generation is a concept where smaller, clean-burning and highly efficient power plants are built around the existing grid infrastructure, close to the customers [4]. DG technologies are rapidly developing and gradually changing the face of power generation all over the world. This is essentially attributed to the cheapness (sometimes free) of the primary energy sources and the closeness of the produced energy to the load centers. Properly designed DG systems can reduce the risk of stressing the overloaded transmission lines and also improve the Nigerian steady state power system operation security [5]. Different classifications of existing DG technologies, their output characteristics and common examples are listed in Table I.

TABLE I
CLASSIFICATIONS AND EXAMPLES OF DGS BASED ON POWER OUTPUT CHARACTERISTICS [4]

DG Type	Property	Examples
I	Inject P only	PV, Battery energy storage system, microturbines, fuel cells etc.
II	Inject Q only	Static capacitor, synchronous condensers
III	Inject P and Q	Synchronous machines (Open-cycle, combined heat power gas-turbines)
IV	Inject P and absorb Q	Induction generators (Wind turbines)

One of the most important features of power system operational planning which put a limit on the siting and sizing of DGs is the voltage stability criteria. For instance, the existing Nigerian power system is grossly inefficient as a result of system overload and aging infrastructures. Thus, on the average, there are 23 system collapse occurrences (both partial and total collapses) experienced yearly over the past 31 years as shown in Fig. 1 [6]. Hence, while planning to increase generation to meet the growing electricity needs, adequate consideration should also be given to the available transmission capacity along with the need for sufficient reactive power (volt-ampere reactive, VAR) support at the load end to ensure adequate voltage stability on the grid.

In this paper, the investigation of an approach for DG siting in a heavily loaded power system is discussed. The proposed approach is compared with a conventional voltage stability index approach using the Nigerian 28 bus system, under a system overload condition, as the test case. The effects of the DG at identified injection points (buses) are analyzed and

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compared on the system's voltage profile and voltage stability condition.

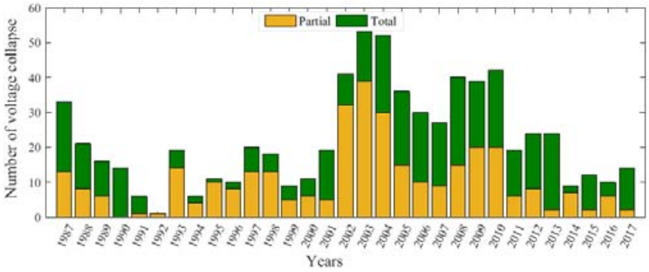


Fig. 1 Voltage collapse incidences in Nigeria from 1987-2017 [6]

II. Case Study Description

Nigeria is one of the most promising economies in Africa and it is the most viable market in the sub-Saharan African region by the virtue of its location and population advantage. However, the poor condition of the power sector has constituted the greatest impediment to the maximization of Nigeria's potentials for adequate socio-economic growth and development. The combined installed generating capacity of Nigeria electricity system currently stands at 12,522 MW, and the average available daily generation is often less than 4,000 MW [7]. The all-time peak generation was recorded as 5,375 MW in February 2019. Nigeria's total daily electricity demand currently stands at above 20,000 MW and it was projected to have reached up to 90,000 MW by the turn of 2020 going by the estimated yearly economic growth rate of 7% to 13%, and an urbanization rate of 3.8% [8]. Going by this abysmal condition of the electricity sector of Nigeria, only about 59.3% of the population currently has access to electricity and the existing infrastructure is heavily loaded. Nigeria is blessed with both renewable and non-renewable energy resources that can be properly harnessed for DG technology. This can go a long way in bridging the energy supply and demand gap that currently exists in Nigeria [9]. Devising efficient technological and market policy model for the significant adoption of clean-burning fuels such as natural gas, biofuels, etc., alongside the renewable energy resources, can help to meet the short term energy needs as further steps are being strategically devised and implemented towards a possible all-green energy future.

III. Voltage Stability and DG Planning

Voltage stability is essentially described as the ability of the power system to remain within a satisfactory voltage range at all buses under no-fault, fault, fault-cleared conditions [10]. Heavily loaded (stressed) power systems are at the risk of voltage instability due to insufficient capacity to provide reactive power (VAR) support at the local load points. This can be empirically noticed by the dip in the voltage profile at critical buses within the power system. If this situation persists, it can lead to voltage collapse and wide-area power system blackouts; which is a common experience in many developing countries. Hence, increasing the share of DGs especially at the low and medium voltage sub-transmission/distribution level of the power system can help improve the voltage stability [11].

Voltage stability problems are actively dynamic in nature; however, for simplicity and time-efficiency, static analysis involving the power flow solution have been found to be sufficient for predicting the voltage stability level of a power system [12]. Thus, the assessment of power system voltage stability has been effectively carried out by using some set of power flow-based mathematical models collectively referred to as voltage stability indices [13]. Voltage stability indices based on real and reactive power sensitivities such as L-index, P-Index, Lmn, LQP; and others such as Novel fast voltage stability index (FVSI), Voltage Collapse Proximity Index (VCPI), NLSI, CBI, Simplified Voltage Stability Index (SVSI) etc. can be used for monitoring the stability condition and criticality of the major components of a power system of different topologies and sizes; and for planning effective enhancement of power system steady-state performances [14].

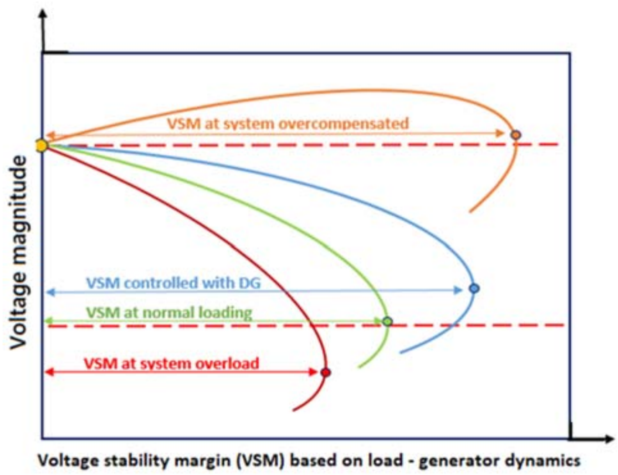


Fig. 2 Voltage stability margin at different loading conditions

One important issue to be considered when adding DG units to power systems is the effects it will have on the effective voltage stability margin (VSM) of the power system. This can be observed by monitoring the relationship between the voltage magnitude of the most critical bus and the power increment under a continuous DG power injection.

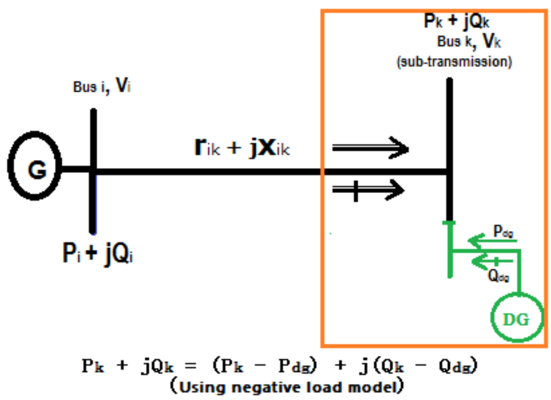


Fig. 3 Equivalent circuit of a sub-transmission system with DG

VSM is directly estimated as the maximum load increase that the power system can withstand without violating the voltage stability limits at the most critical part of the network [12]. The illustration of the impacts of DG on power system VSM under different conditions of power system loading is illustrated in Fig. 2. The generating capacity of DG is quite small compared to the main generators; hence, DG output is often modeled as a negative (real and reactive, PQ)-load at the point of current injection for steady-state load flow analysis [4]. Considering the two-bus equivalent circuit of a sub-transmission system shown in Fig. 3, the net load demand at the point of DG power injection and the line flow equations are derived accordingly.

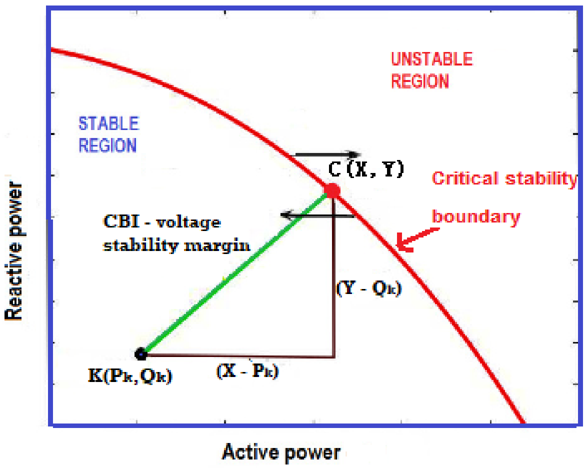
$$V_k^4 + 2V_k^2(P_k r_{ik} + Q_k r_{ik} - 0.5V_i^2) + (P_k^2 + Q_k^2)(r_{ik}^2 + x_{ik}^2) = 0 \qquad (1)$$

By finding the unique positive and stable roots (solutions) of (1), the condition for keeping the power system within the voltage stability margin/limit is derived as given by (2) [15]:

$$\left(\left(r_{ik}P_k + x_{ik}Q_k - 0.5V_i^2\right)^2 - \left(r_{ik}^2 + x_{ik}^2\right)\left(P_k^2 + Q_k^2\right)\right) \geq 0 \qquad (2)$$

Static voltage stability indices are often derived from the approximated simplification of (2). In this study, the NLSI formulation given in [13] will be used for comparative siting of DG. The criticality of a line increases as the NLSI value increases; i.e., Voltage stability of the power system deteriorates as the NLSI increases.

$$NLSI = \frac{P_k r_{ik} + Q_k x_{ik}}{0.25(V_i^2 \cos^2 \delta)} \qquad (3)$$



Fig, 4 Critical stability boundary/VSM

A new direct approach for measuring the optimal VSM of transmission lines was derived in [16]; this is called the Critical Boundary Index (CBI) as shown in Fig. 4. The stability boundary is governed by (2) and the effective voltage stability margin (called CBI) is calculated as the distance between the current operating point (K) and a critical point (C) as described in Fig. 4.

$$F(X,Y,\lambda) = \sqrt{(X-P_o)^2 + (Y-Q_o)^2} + \lambda\left[\left(r_{ik}X + x_{ik}Y - 0.5V_i^2\right)^2 - \left(r_{ik}^2 + x_{ik}^2\right)\left(X^2 + Y^2\right)\right] \qquad (4)$$

$$CBI = \sqrt{(X-P_o)^2 + (Y-Q_o)^2} \qquad (5)$$

The critical real and reactive load points (X and Y) are obtained from simultaneously solving the set of equations derived from the partial derivatives of (4). Low CBI value indicates limited VSM. Hence, for DG siting, the CBI value for all the transmission lines is arranged in ascending order and the most critical lines are taken from the top (i.e., from the lowest). The significant difference between the proposed CBI and the conventional NLSI approach for voltage stability condition marking is the level of simplification involved in their derivation. While NLSI is an approximate approach, CBI is more of a direct measure of the stability margin (in per unit, *pu*).

IV. Result and Discussion

The Nigerian 28 bus system used in this study is shown in Fig. 5. The system has 28 buses and 52 lines; some of the buses are connected by more than one line (i.e., multiple circuits).

A. Line Severity Ranking Comparing NLSI and CBI

The NLSI and CBI value for each line is estimated, according to (3)-(5), at normal load and at a loading point close to voltage collapse. The line severity ranking considering the 10 worst lines are presented in Tables II and III for CBI and NLSI, respectively.

From Tables II and III, three candidate buses are selected for evaluating the superiority of CBI in optimal DG placement for voltage stability enhancement. The selected DG power injection buses are the receiving end buses of the identified lines as shown in Table IV. In order to obtain the point of system overload that is close to the voltage collapse, the system real power (megawatt, MW) was step-wisely increased and the bus voltage magnitude, the line NLSI and CBI values are monitored to the last loading point where their values are technically reasonable.

TABLE II
Line Severity Ranking Using CBI

	Normal load		Overload	
RANK	CBI [pu]	Line	CBI [pu]	Line
1	0.2331	L32	0.1174	L32
2	0.2331	L33	0.1174	L33
3	1.7454	L49	0.2921	L7
4	1.7454	L50	0.2921	L8
5	1.7687	L23	0.6723	L34
6	1.7687	L24	0.6723	L35
7	1.7687	L25	1.3912	L5
8	2.0461	L7	1.3912	L6
9	2.0461	L8	1.9797	L31
10	2.5497	L31	1.9821	L49

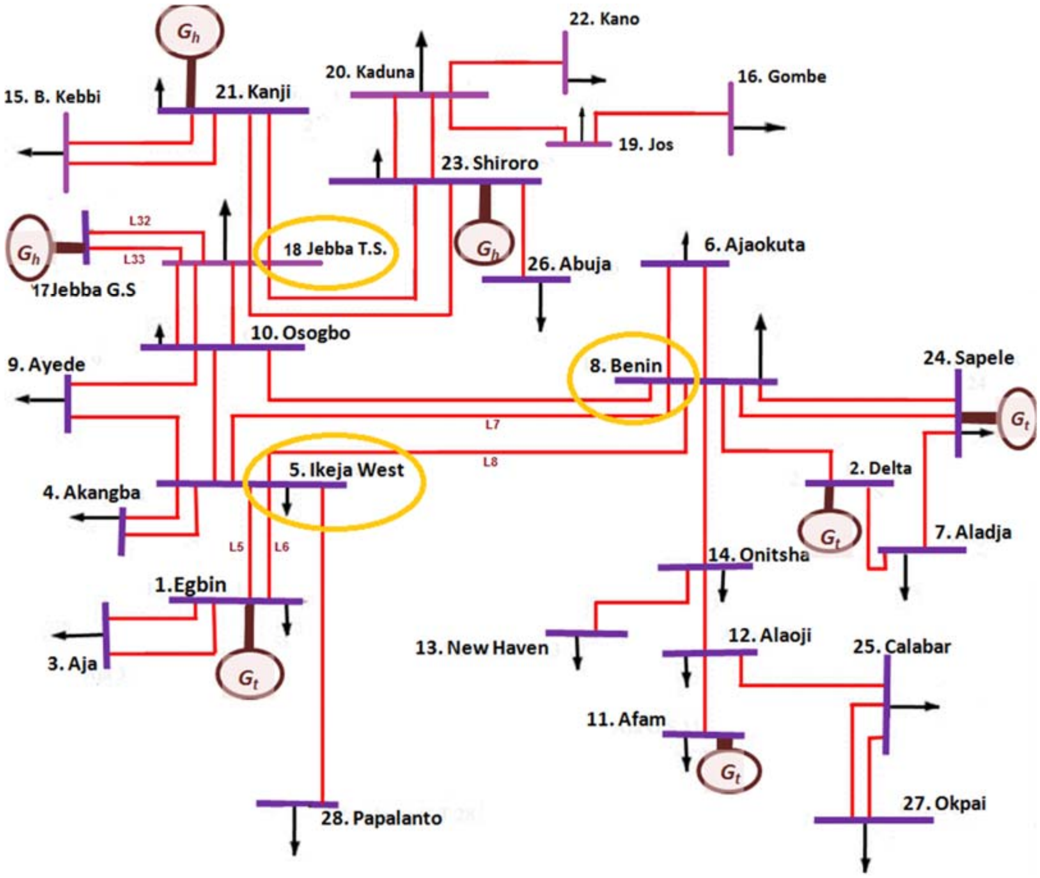


Fig. 5 Nigerian 28 bus system and the selected DG locations

TABLE III
LINE SEVERITY RANKING USING NLSI

	Normal load		Overload	
RANK	NLSI value	Line	NLSI value	Line
1	0.3630	L5	0.9199	L7
2	0.3630	L6	0.9199	L8
3	0.3222	L23	0.7118	L23
4	0.3222	L24	0.7118	L24
5	0.3222	L25	0.7118	L25
6	0.2876	L45	0.4614	L5
7	0.2876	L46	0.4614	L6
8	0.2513	L7	0.368	L28
9	0.2513	L8	0.3021	L10
10	0.1957	L39	0.2743	L34

TABLE IV
SELECTED CANDIDATE BUSES FOR DG

CASES	Identified lines	Candidate buses
I	L32	Bus 18
	L33	Bus 18
II	L7	Bus 8
	L8	Bus 8
III	L5	Bus 5
	L6	Bus 5

The selected Lines are L32 and L33 (connecting bus 17 and bus 18) which are ranked the most critical by CBI under both the normal loading and system overload, Lines L7 and L8 (connecting bus 5 and bus 8) which are ranked to be the most critical by NLSI at system overload and lines L5 and L6 (connecting bus 1 and bus 5) which are ranked to be the most critical by NLSI at normal loading condition. More so, the four lines (L7 and L8 at overload and L5 and L6 at normal load) ranked to be critical by NLSI are also ranked to be among the top ten most critical lines by CBI while NLSI does not recognize the two lines that are consistently ranked to be the most critical lines by CBI under both loading conditions.

B. Effect on Voltage Magnitude and Voltage Stability

Equal MW of DG power is introduced at each of the candidate buses identified (the receiving end buses of the selected lines), one after the other. The effect on the voltage profile for each DG power injection point is monitored, and the plot of the voltage profile at system overload without DG and the voltage profile when DG power is injected at each of the selected buses is shown on Fig. 6. Though there is a significant improvement in the voltage profile at all the system buses with DG power at the three selected buses, the performance of the DG power injection at bus 18 (identified by CBI at both loading conditions) is more effective. Significantly, there is a remarkable improvement in the voltage values at bus 9 and bus 13 from below the minimum voltage limit of 0.95 pu (i.e., 0.9321 pu at bus 9 and 0.9372 pu at bus 13) to 0.9693 pu at bus 9 and 0.9543 pu at bus 13. This trend was recognized with other DG sizes.

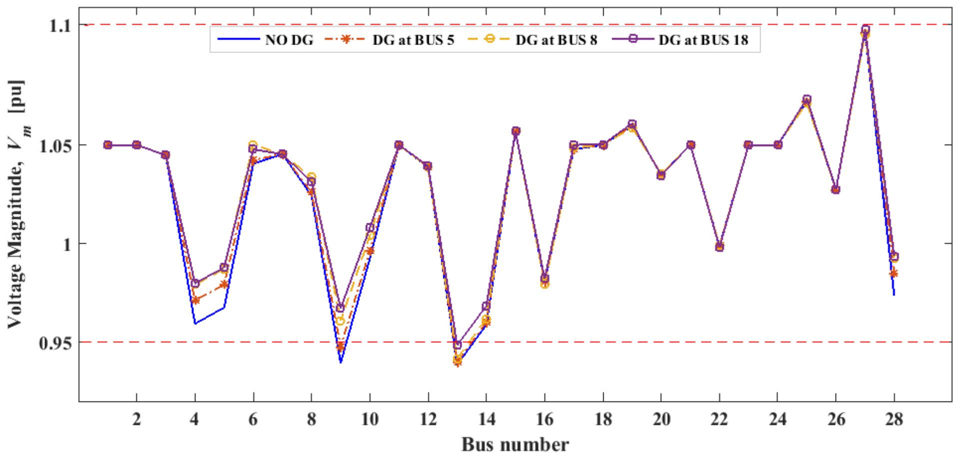


Fig. 6 Effects of DG on bus voltage profile

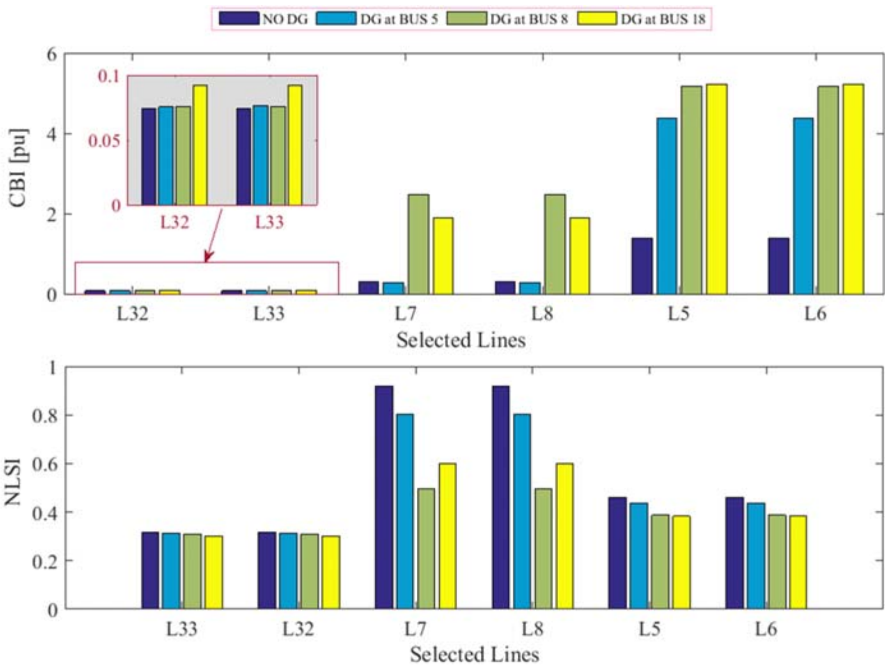


Fig. 7 Effects of DG on voltage stability

In order to analyze the effect of DG power injection at each of the selected buses on the voltage stability of the power system, the CBI and NLSI values for all the six selected lines according to Table IV are computed and recorded under system overload condition, without and with injected power from DG at each of the selected buses and plotted as shown in Fig. 7. According to the CBI, the VSM increases as expected for the six lines, with the DG placement at bus 18 performing better than at the other buses. The voltage stability of the system, as indicated by the NLSI, improved for the six lines as seen by the decrease in the NLSI values. The performance of the DG placement at bus 18 is consistent and seen to be more effective in four of the monitored lines (L32, L33, L5, L6). For lines L7 and L8, a DG installed at bus 8 performs slightly better than at bus 18, principally due to the DG location advantage. However, among the three critical buses investigated for DG power injection, the performance of bus 18 (identified by CBI) is shown to be more consistent and effective.

V. Conclusion

In this study, the performance an approach for power system VSM estimation known as CBI has been compared with the conventional voltage stability index (NLSI) for siting DG for overloaded power system. The Nigerian 28-bus system was used for the demonstration study reported in this paper. From the obtained results, the supremacy of CBI over NLSI in identifying the most critical components of the power system and consequently, the suitable point for DG power injection was confirmed. Unlike most of the existing voltage stability indices, CBI involves less approximation of the power system parameters and it is directly measured in per unit; hence the reason for its better accuracy. However, the required computational time for CBI is higher than that of NLSI due to the more detailed mathematical procedures involved in computing CBI.

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