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# Static Voltage Stability Analysis in a Distribution System with High Penetration of Photovoltaic Generation

***Abstract**. This paper analyses the effect of grid-connected PV systems on static voltage stability using the IEEE 69 radial distribution system. The effect of integrating PV generators into power systems with higher PV penetration level and multiple numbers of PV generators is analyzed using P-V curve and improved voltage stability index (IVSI). The P-V curve data show that grid-connected PV systems improve loading margin and voltage magnitude. The IVSI gives a positive output because systems with integrated PV generators reach the voltage collapse point.*

***Streszczenie.** W artykule analizowany jest wpływ podłączenia systemu fotowoltaicznego na na stabilność napięcia w radialnym systemie energetycznym IEEE 69. Analizowane są zależność P-V oraz indeks stabilności napięciowej IVSI. Podłączenie systemu fotowoltaicznego poprawia margines obciążenia sieci.* ***Analiza statycznej stabilności napięciowej systemu energetycznego wzbogaconego o system fotowoltaiczny***

**Keywords:** Static voltage stability; Voltage collapse; solar PV generator; P-V curve; IVSI index.
**Słowa kluczowe:** statyczna stabilność napięciowa, system fotowoltaiczny

## Introduction

Modern infrastructures demand high-energy consumption with high quality and reliable electric power supply. Electric power utilities have difficulty answering these requirements due to the deficiency of conventional energy sources. Fossil fuels are a dense form of energy and thus requires millions years to develop. Therefore, renewable energy sources (RES) are introduced as a reliable form of energy to replace conventional energy sources. Wind power, solar energy, and hydropower are some examples of mainstream renewable technologies. Among those, solar energy has received much attention due to its promising energy, low installation cost, and lack of environmental pollution.

Power system network design initially does not integrate any RES including solar PV. Small scale solar PV may not affect this network. However, integrating large scale solar PV might raise several technical issues such as power quality and power system stability. Among those, power system stability has become major attention where the main focus is on voltage stability. Voltage stability is defined as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to some form of disturbance that leads to voltage collapse [1].

For the last few years, studies on the effects of solar PV system on transmission and/or distribution systems have attracted the attention of researches [2-4]. Studies show that integrating a solar PV system into a power network improves loading margin and voltage stability limit [5, 6]. The active power generated by PV generators can be penetrated either by a generation base or a load base. A higher PV penetration level shows a reduction in voltage magnitude and improves loading margin with minimum grid loss observed at 30% PV penetration level [7]. Moreover, research shows that at 20% PV penetration level, an overvoltage of +10% is observed at certain buses [8]. At high PV penetration levels, the effects on voltage stability are supported by few additional factors such as solar radiation, solar temperature, cloud shedding effect, and the distinct design of the power system network [9-12]. Cloud shedding leads to PV power drop and voltage fluctuation; for distribution systems, this factor is considered because these systems have exclusive characteristics such as dynamic loads and high X/R ratios [13, 14]. Solar irradiance relates equally to PV power output. The sudden drop in solar irradiance results in a drop in PV power; the voltage may drop below the tolerable limits [2]. Operating a system below statutory limits may cause voltage collapse. However, intermittent PV power output causes fluctuations in system voltage. A voltage unbalance of 1% is observed [15], where this unwanted event can damage household equipment. The various PV parameters contribute to voltage drops and therefore affect system voltage stability.

This study focuses on the impacts of integrating PV generator on radial distribution system static voltage stability. IEEE 69 radial distribution system is used as a test system while P-V curve and voltage stability index are used for analysis. The objective of this paper is to extend the application of IVSI index towards the voltage stability improvement of grid connected PV generator.

## Static Voltage Stability Index

Voltage stability index have been developed to anticipate the voltage collapse phenomenon in a power system. The Line Stability Index (Lmn) is developed based on the power flow in a single line [16]. Stability of each single line in a network is first assessed before considering the network system stability. The Lmn equation gives value between 0 to 1. The system is said to have voltage stable if the Lmn index value closer to 0. The Fast Voltage Stability Index (FVSI) is developed considers the margin of a single line under loading condition [17]. If the FVSI index value for a line approaches 1, the line is in a critical condition and might leads to voltage collapse. The Line Stability Index (LQP) is proposed by [18]. A line is stable if the LQP index value maintains less than 1. The Line Stability Indices (VCPI) is developed based on the maximum active power or reactive power transfer through a line [19]. The VCPI index must be maintained below 1 to avoid voltage collapse. The Line Collapse Proximity Index (LCPI) is developed based on power flow in a line and exact model of transmission line described by a two-port equivalent circuit of ABCD-matrix [2]. The LCPI index must be less than 1 to maintain the system voltage stability.

The proposed voltage stability index is useful in assessing voltage collapse based on line stability. However, the drawback of these indexes is that the system stability is based on the line stability ranking. PV systems give active power support the power system. Therefore, PV generators must be integrated at the weakest bus in a system. To determine the weakest bus in a system, an Improved Voltage Stability Index (IVSI) is developed by [21]. The IVSI equation is formulated based on Newton-Raphson power flow equation. Each line connecting two buses is added to determine the weakest bus. The bus is considered as having unstable voltage if the IVSI value approaches 1 and voltage collapse is said to occur. The IVSI is defined as

$$(1)\quad IVSI=\frac{-4\sum_{j=0}^{n}\left(G_{ij}-B_{ij}\right)\left(P_i+Q_i\right)}{\left[\sum_{j=1}^{n}\left|V_j\right|\left[G_{ij}\left(\cos\delta_{ij}+\sin\delta_{ij}\right)-B_{ij}\left(\cos\delta_{ij}-\sin\delta_{ij}\right)\right]\right]^2}\le 1.0$$

where Pi + Qi is the load at receiving end bus. The Vj is the voltage at sending end bus whereas δij is the angle difference between sending end and receiving end bus. The Gij – Bij is the elements in bus admittance matrix.

### P-V Curve

A P-V curve is useful to analyse the effect of PV generators on system voltage stability because PV generators actively support the power of the system and consequently expends the active power margin. A P-V curve illustrates the steady state relation between injected real powers and the voltage magnitude of the selected bus as shown in Fig. 1. The curve provides sufficient information regarding the maximum active power with minimum voltage magnitude that a bus or a system can uphold before it collapses due to some form of disturbances. Thus, the P-V curve helps in analysing the effect of PV system on network stability.

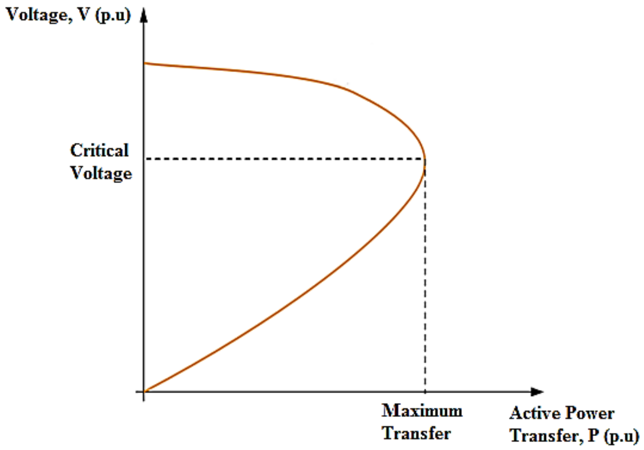


Fig.1. P-V Curve

### Test System Description

The IEEE 69 radial distribution system is used in this study. The system consists of 69 buses with a 12.66 kV rated voltage and 100 MVA rated power. The total system losses are 0.22 kW/0.10 kVar.

The PV generator is designed with 0.95 pf, no reactive power limits and integrated at the busbar with a 2.5 MVA 12.66/0.4 kV transformer. For the base case, the active power offered by the PV generator is set at 0.95MW. Figure 2 shows the IEEE 69 radial distribution system with grid-connected PV generator simulated in the DIGSILENT PowerFactory.

### Simulation Procedure

All results presented in this paper are simulated in the DIGSILENT PowerFactory and MATLAB. The IEEE 69 radial distribution system and PV generator is designed in the DIGSILENT PowerFactory. The power flow and P-V curve are also simulated in DIGSILENT PowerFactory. However, the IVSI is calculated in MATLAB. First, the balanced, positive sequence Newton-Raphson power flow is run to test the system availability. The P-V curve is then simulated with all loadings increase simultaneously until the power flow stop converging. The IVSI calculation is based on the power flow thus power flow results from DIGSILENT PowerFactory are transferred into MATLAB. Bus admittance matrix is performed to obtain the Gij and Bij elements. In the meantime, IVSI index is calculated for all 69 buses with increasing loads and the iteration stops when one of the buses reaches voltage stability limit. The simulation procedure is similar for the grid-connected PV system.

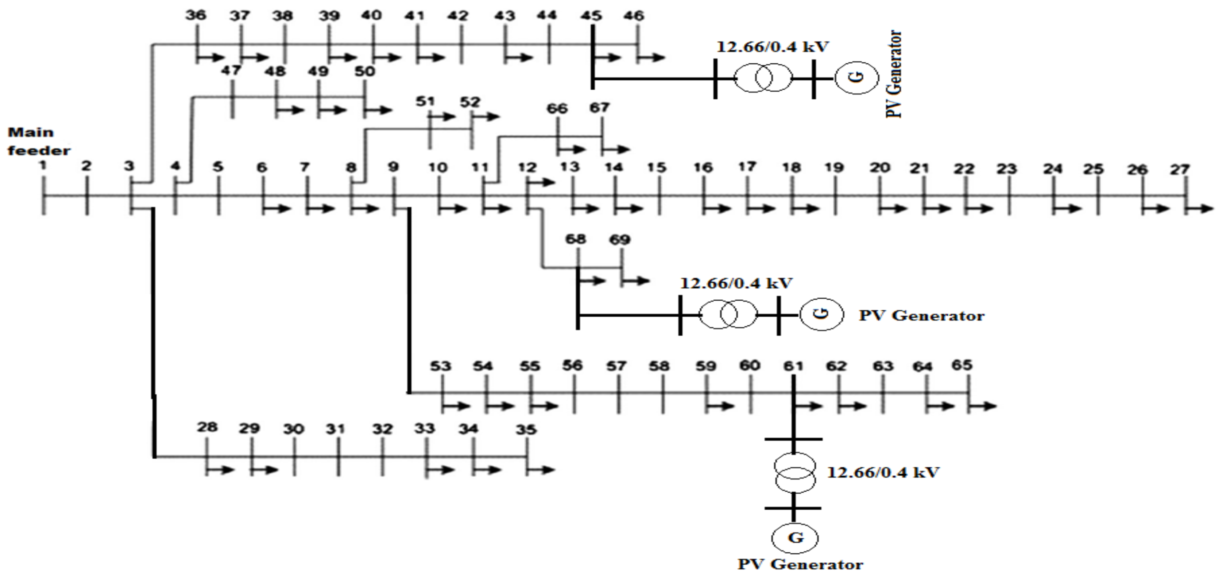


Fig.2. IEEE 69 radial distribution system with grid-connected PV generator

**Weakest Bus in the IEEE 69 Radial Distribution System**

IEEE 69 radial distribution system is a distribution system with 12.66 kV rated voltage. To study the effect of PV generators on distribution system voltage stability, the weakest bus is first determined. The PV generator is integrated at the weakest bus since voltage collapse usually starts at the weakest bus in a system. The system is segregated into seven sub-feeders with one main feeder of Bus 1 to Bus 27 as shown in Table 1. The IVSI for every bus in this system is calculated by expanding all loads simultaneously until one of the buses from each feeder reaches collapse point, which is 1.0.

Table 1 and Figure 3 show the weakest bus in every sub-feeder evaluated using IVSI. Based on Figure 6, Bus 61 is the weakest bus among all followed by Bus 68, Bus 45 and Bus 17. IVSI index of Bus 68 and Bus 45 shows slightly different value and both buses are considered to collapse at the same time. In this study case, PV generators are integrated at Bus 61 as it is the weakest bus of the IEEE 69 radial distribution system.

Table 1: Weak bus ranking for different feeders of the IEEE 69 radial distribution system using IVSI index

| IEEE 69 radial distribution system | Weak bus evaluated using IVSI index |
|---|---|
| Main feeder with Bus 2-27 | Bus 17 |
| Sub-feeder with Bus 28-35 | Bus 34 |
| Sub-feeder with Bus 36-46 | Bus 45 |
| Sub-feeder with Bus 47-50 | Bus 49 |
| Sub-feeder with Bus 51-52 | Bus 51 |
| Sub-feeder with Bus 53-65 | Bus 61 |
| Sub-feeder with Bus 66-67 | Bus 66 |
| Sub-feeder with Bus 68-69 | Bus 68 |

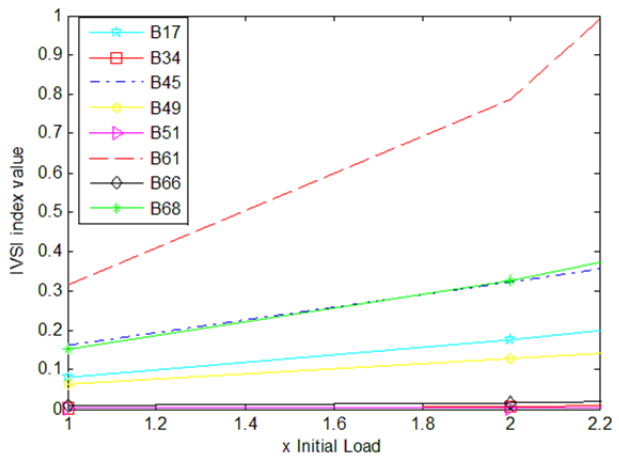


Fig.3. IVSI for the weakest bus in every sub-feeders of the IEEE 69-radial distribution system

**Effect of PV Generator**

Voltage instability and voltage collapse starts at the weakest bus in a power system. Therefore, PV generators are most likely integrated into the weakest bus. The PV generator gives active power support to the system and changes the power flow in the radial distribution system since the system initially does not equipped with power generator. To study the voltage stability effect of PV generator on IEEE 69 radial distribution system, PV generator with 0.95 MW active powers is integrated at the weakest bus that is Bus 61. In real operating condition, load increments are unpredictable as it may increase in several buses while others remain constant. It is however challenging to perform analysis with such complex loading pattern. Hence, in this study, all loads are increase simultaneously with a constant loading factor until power flow stop converging for P-V curve analysis and the IVSI reaches its collapse point.

P-V curve is performed to analyse the effect of PV generator on power margin and voltage magnitude. Figure 4 shows the comparison of active power margin in Bus 61 between base case and integrated PV generator. The maximum loading margin for base case is 0.12 p.u with voltage magnitude of 0.50 p.u. With integrated PV generator, the loading margin increases by 11.71% while the voltage magnitude increases by 1.54% from base case value.

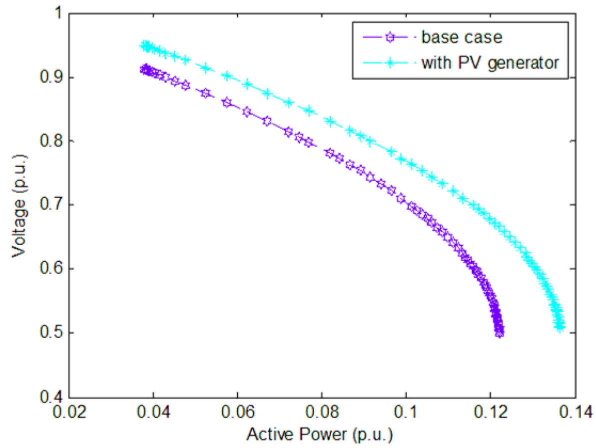


Fig.4. P-V curve of Bus 61 with integrated PV generator

Table 2: IVSI value at Bus 61 with PV generator

| x100% | IVSI index value | |
|---|---|---|
| S Load | base case | with PV generator |
| 1.0 | 0.32 | 0.29 |
| 2.0 | 0.79 | 0.70 |
| 2.2 | 1.00 | 0.85 |

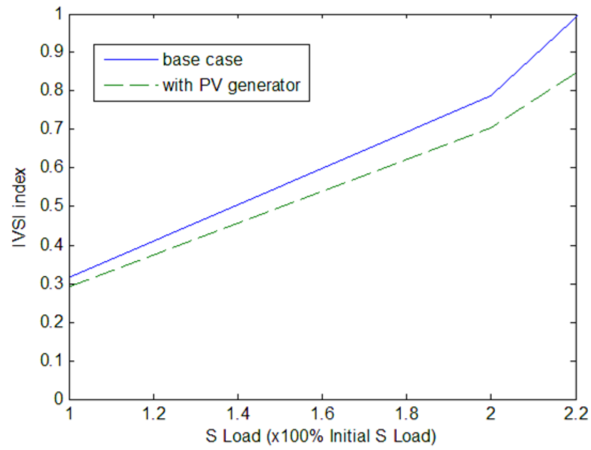


Fig.5. IVSI at Bus 61 with PV generator

Table 2 and Figure 5 show the IVSI for Bus 61 with the effect of integrated PV generator. Results show that at load 2.2 higher than the original loading, Bus 61 experiences voltage collapse while Bus 61 with integrated PV generator remains stable. Results from both P-V curve and IVSI show that integrating PV generator at the weakest bus improves voltage stability at that bus with higher loading margin and voltage stability limit.

**Effect of Higher PV Penetration Level**

Active power from PV generator can be penetrated to a point that the increment effects voltage stability. Higher penetration level of PV generator affects the power flow of the system and thus might have a significant effect on the power system voltage stability. PV penetration level depends either on total generation or the total load in a system. In this study, PV penetration level is referred to the ratio of PV generation to the total generation in a system. The equation is as follow:

$$\text{PV penetration level}\,(\%) = \frac{\sum \text{PV generation (MW)}}{\sum \text{PV generation (MW)} + \sum \text{system generation (MW)}} \tag{2}$$

Table 3 shows the various penetration level of the PV generator integrated at Bus 61. The P-V curve and IVSI analysis is performed by increasing the loading margin of all loads until Bus 61 reaches its voltage stability limit.

Table 3: PV penetration level

| PV penetration level (%) | PV generation (MW) |
|---|---|
| 20% | 0.95 |
| 40% | 2.53 |
| 60% | 5.70 |

Figure 6 shows the effect of higher PV penetration level on Bus 61 using P-V curve. At 60% PV penetration level, the loading margin is 0.20 p.u which is 64.40% increment, meanwhile the voltage magnitude improves to 0.54 p.u from the base case value. This shows that higher PV penetration level offers fair loading margin and voltage magnitude to the system.

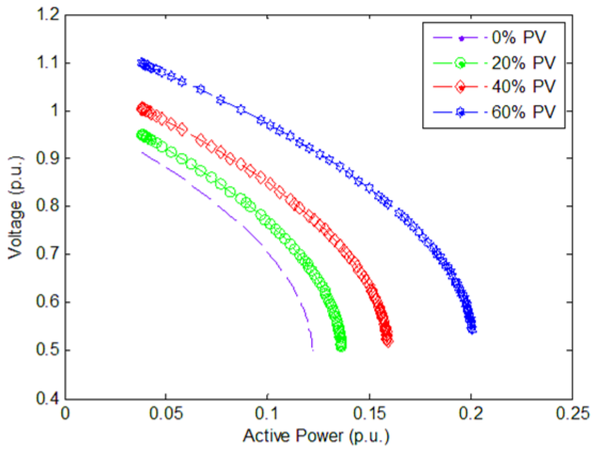


Fig.6. P-V curve of Bus 61 with various PV penetration level

On the other hand, results from IVSI display the same pattern with the results from P-V curve. Table 4 and Figure 7 show the IVSI of Bus 61 with various PV penetration levels. At load 2.2 higher than the original loading, Bus 61 reaches its voltage collapse point. However, at the same loading margin, Bus 61 integrated with various PV penetration level has voltage stable and far reaches its voltage collapse point. With 60% PV penetration level, the load at Bus 61 can be expended until it is 3.3 higher from its original load before it collapses.

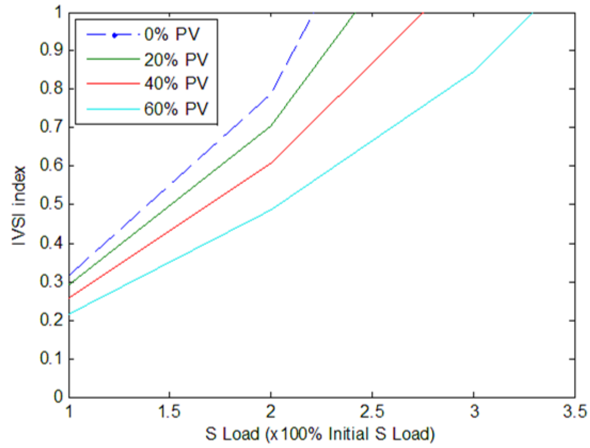


Fig.7. IVSI at Bus 61 with various PV penetration level

Table 4: IVSI value at Bus 61 with various PV penetration level

| x100% S Load | IVSI index value | | | |
|---|---|---|---|---|
| | 0% PV | 20% PV | 40% PV | 60% PV |
| 1.0 | 0.32 | 0.29 | 0.26 | 0.22 |
| 2.0 | 0.79 | 0.70 | 0.61 | 0.49 |
| 2.2 | 1.00 | 0.85 | 0.71 | 0.56 |

**Effect of Integrating Multiple PV Generators**

To study the effect of multiple PV generators on system voltage stability, PV generator is integrated at different location in the system. Referring to the IVSI index in Fig. 3, Bus 61 has been recognized as the weakest bus followed by Bus 68 and Bus 45. Therefore, PV generator is first integrated at Bus 61. The second PV generator is integrated at Bus 68 followed by third PV generator which is integrated at Bus 45. The system voltage stability is analysed using the IVSI by taking Bus 61 as a reference bus. Table 5 and Figure 8 shows the IVSI for Bus 61 (reference bus) with multiple PV generators integrated at different location in the system.

Table 5: IVSI value at Bus 61 (reference bus) with multiple PV generators

| No. of PV generator in the system | IVSI index value (at load 2.2 x 100% of initial S load) |
|---|---|
| 0 | 1.00 |
| 1 | 0.85 |
| 2 | 0.83 |
| 3 | 0.83 |

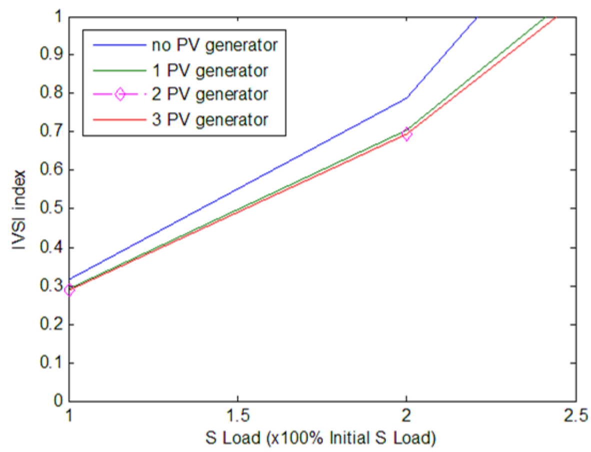


Fig.8. IVSI at Bus 61 (reference bus) with multiple PV generator

Increasing number of PV generator integrated in the system improves the voltage stability limit. Bus 61 reaches its voltage stability limit at load 2.2 higher than the original load. With one PV generator integrated in the system, the loading margin increases to 2.4 higher than the original load before Bus 61 experiences voltage collapse. However, the IVSI for the second and third PV generator integrated in the system shows no difference since Bus 68 and Bus 45 share the same IVSI value and are said to collapse at the same time.

**Conclusion**

This study presents the effect of PV generators on system voltage stability. Two analysis techniques that are P-V curve and IVSI are used in this study. First, the system voltage stability is analysed by integrating a PV generator at the weakest bus in the system. Then, the PV penetration level and the number of PV generator are increased to observe their effect on system stability. Results show that integrating PV generator on the weakest bus improves the loading margin and have significant effect on system voltage stability. Similar positive results are presented when increasing PV penetration level and the number of PV generator in the system. The system experiences far-reaching voltage collapse compared to the base case. Thus, integrating PV generator into distribution system enhances system voltage stability.

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