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Dynamic voltage stability of a distribution system with high penetration of grid-connected photovoltaic type solar generators

This paper presents the impact of grid-connected photovoltaic (PV) generator on dynamic voltage stability of a power distribution system by considering solar intermittency, PV penetration level, and contingencies such as line outage and load increase. The IEEE 13 node test feeder is used as a test system, and a solar PV of 0.48 kV/0.5 MVA is integrated into the test system. Test results show that system voltage is stable at high PV penetration levels. Increase in load causes voltage instability, in which voltage drops below its allowable operating limit. Thus, increase in PV penetration level does not improve system voltage stability because the system experiences voltage collapse during line outage.

Keywords: dynamic voltage stability; power distribution system; grid-connected PV system.

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1. Introduction

One of the widely used renewable energy sources for the generation of electrical power is solar energy. Photovoltaic type solar generation is considered as one of the fastest growing power generation in the world. A properly utilized solar energy can supply power needed by consumers. However, integrating large scale PV generation into a power distribution network may cause significant impact on the flow of power, voltage level and fault current and also potential impact on system stability. Voltage stability which is concerned with the capacity of a power network to maintain acceptable voltage levels after enduring any form of disturbance is a major concern in power system operation [1]. A power system is regarded as voltage unstable if the voltage magnitude of at least one bus in the system decreases and, the fallout is voltage collapse which happens when the system operates at maximum load.

Numerous studies have investigated the impact of grid-connected PV systems on static and dynamic voltage stabilities [2-5]. The effect of a grid-connected PV system with various penetration levels of active power on the voltage profile of a network and static voltage stability have been studied. Previous studies showed that increasing PV penetration levels increases voltage stability margin [2,3]. Voltage stability indices such as line stability and fast voltage stability margin have been used as indicators for determining proximity to voltage collapse. Penetration of PV generators and location of the dispatch generator also affect transient stability of a power system [6]. Moreover, high penetration of PV with low-voltage ride-through capability negatively affects transient stability [7–9]. High penetration of grid-connected PV generation into a power distribution network may cause dynamic voltage instability problems due to intermittent solar radiation from the PV array and dynamic behaviour of inverter and step up transformer. Voltage instability may occur because a PV system only provides additional active power into the network and the reactive power is supplied from the conventional generators. Based on the IEEE 929-2000

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standard, a small-scale PV system is not allowed to deliver reactive power to a network for voltage regulation purposes [10]. Thus, this will result in reverse power flow which consequently leads to dynamic voltage instability which is evaluated using time-domain analysis. Dynamic voltage stability is affected by loading condition in which if a network operates under heavy load condition, the reactive power consumption increases and system voltage decreases. Disturbances such as increase in load, action of tap-changing transformer, line tripping and generator outage increase the reactive power demand beyond the capacity of the available reactive power sources and thus create a dynamic voltage instability condition.

PV parameters such as solar radiation and temperature, and dynamic modelling of a PV system considering power electronic converters need to be considered when analysing dynamic voltage stability of grid-connected PV systems [4,5]. Intermittent PV output power leads to unwanted voltage rise in a power system which may cause major damage to household equipment and unnecessary temperature rise in motor windings [11]. Factors such as cloud shading effect and rapid fluctuation in solar radiation play a role in dynamic voltage instability. Cloud transient affects dynamic stability of power systems at high penetration levels whereas cloud sweep for a few seconds induces drop in PV power which result in voltage fluctuation and voltage drop [12]. During heavy loaded condition in a power network, system voltage will drop below acceptable limit which leads to voltage instability. Thus, cloud transient and cloud sweep are considered in dynamic voltage stability study because distribution systems are usually installed with dynamic loads and characterised with high X/R ratios [13,14]. In this paper, the effect of a grid-connected PV system on dynamic voltage stability of an unbalanced power system is studied by considering the following factors: (i) intermittent solar radiation and temperature, (ii) high PV penetration level, (iii) increase in load and (iv) line outage.

2. Notation

The notations used throughout the paper are stated below.

Constants:

PV	Photovoltaic
G	Solar irradiance
TC	Solar operating temperature
VOC	Open circuit voltage
ISC	Short circuit current
NPV	PV modules number
TA	Ambient temp
NOCT	Nominal operating cell temperature
K_i	Short circuit current coefficient
K_v	Open circuit voltage coefficient
T_{ref}	Reference operating condition (25°C)
STC	Standard test condition

3. System Modelling

Modelling of loads and PV system are described in this section.

3.1. Load model

A complex load model is represented with combined dynamic and static loads. The static load is represented by a polynomial model as shown in Equations (1) and (2) and it consists of industrial, household, and commercial parts. The exponential parameters are shown in Table 1. Motor load significantly affects dynamic voltage stability and therefore it is considered in the study. In case of voltages lower than the nominal value, disconnection of motor loads may reduce system voltage, thus resulting in system voltage instability. Motor load is represented by an asynchronous machine and modelled similar to an induction motor model Type 6 with a single cage. The parameters of the induction motor load model are listed in Table 2.

$$P = P_0\left[aP\left(\frac{V}{V_0}\right)^{e\_aP} + bP\left(\frac{V}{V_0}\right)^{e\_bP} + cP\left(\frac{V}{V_0}\right)^{e\_cP}\right] \tag{1}$$

$$Q = Q_0\left[aQ\left(\frac{V}{V_0}\right)^{e\_aQ} + bQ\left(\frac{V}{V_0}\right)^{e\_bQ} + cQ\left(\frac{V}{V_0}\right)^{e\_cQ}\right] \tag{2}$$

Table 1: Exponential parameters for polynomial load

	Industrial (a)	**Commercial (b)**	**Household (c)**
P	0.1	0.6	1.7
Q	0.6	2.5	2.6

Table 2: Induction motor load parameters

Induction motor load Type 6	
Rs =	0.035 pu
Xs0 =	0.094 pu
Xm =	2.800 pu
Rr =	0.048 pu
Xr0 =	0.163 pu

3.2. PV system model

In this study, the PV system considers the built-in PV model in the DIGSILENT PowerFactory. The PV model is based on a single-diode equivalent circuit shown in Figure 1 and the PV output power is described in Equation (3).

$$P_{PV}(t) = N_{PV} \cdot V_{OC}(t) \cdot I_{SC}(t) \tag{3}$$

in which,

$$I_{SC}(t)=\left[I_{SC,STC}+K_i\left[T_C(t)-T_{ref}(t)\right]\right]\frac{G(t)}{1000} \tag{4}$$

$$V_{OC}(t)=V_{OC,STC}+K_v\left[T_C(t)-T_{ref}(t)\right] \tag{5}$$

where,

$$T_C(t)=T_A(t)+\frac{NCOT-20}{800}G(t) \tag{6}$$

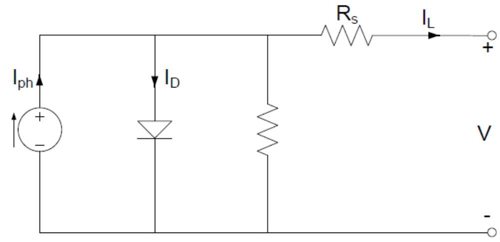

Figure 1: Equivalent circuit of a solar cell

All the electrical characteristics at STC are taken from the PV datasheet provided by the manufacturer. The input data for solar irradiation and cell temperature were obtained from the grid-connected 3 kW PV system installed at the rooftop of the Faculty of Engineering, Universiti Kebangsaan Malaysia. Input data in terms of solar radiation and cell temperature are shown in Figure 2.

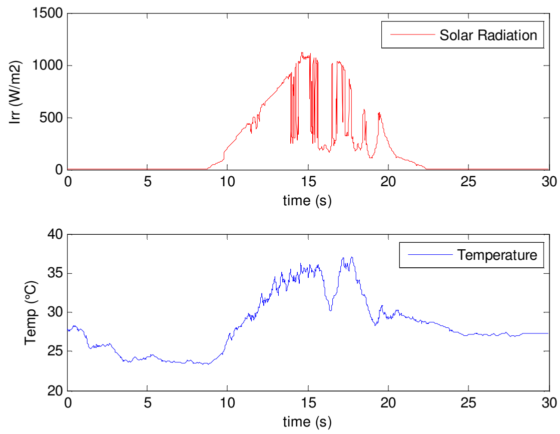

Figure 2: Input data for PV system

Figure 3 shows the simulation model of a grid-connected PV system developed for time-domain simulation. Due to the architectural limitation of the software, the connection is translated into few blocks. First, the 'Solar Radiation' and 'Temperature' block represents the input data, imported into the DIGSILENT PowerFactory from excel sheet. The 'Photovoltaic Model' block represents the algorithm for calculating the voltage and current at MPP where all electrical calculations are represented by Equation (3) to Equation (6). The 'Power Measurement' block is used to represent the active power measurement whereas the frequency from 'Slow Frequency Measurement' block is regardless of instantaneous disturbances, over a period of time. In the system, the 'DC Busbar and Capacitor', the 'Controller' and the 'Active Power Reduction' represents the PV inverter in which its operation meet the German Grid Code. The 'AC Voltage' block produces an output voltage for the LV bus whereas the 'Phase Measurement' block contains a built-in

PLL device from the library of the DIGSILENT PowerFactory. All the operation blocks are finally connected to the 'Static Generator' which is then integrated to the grid.

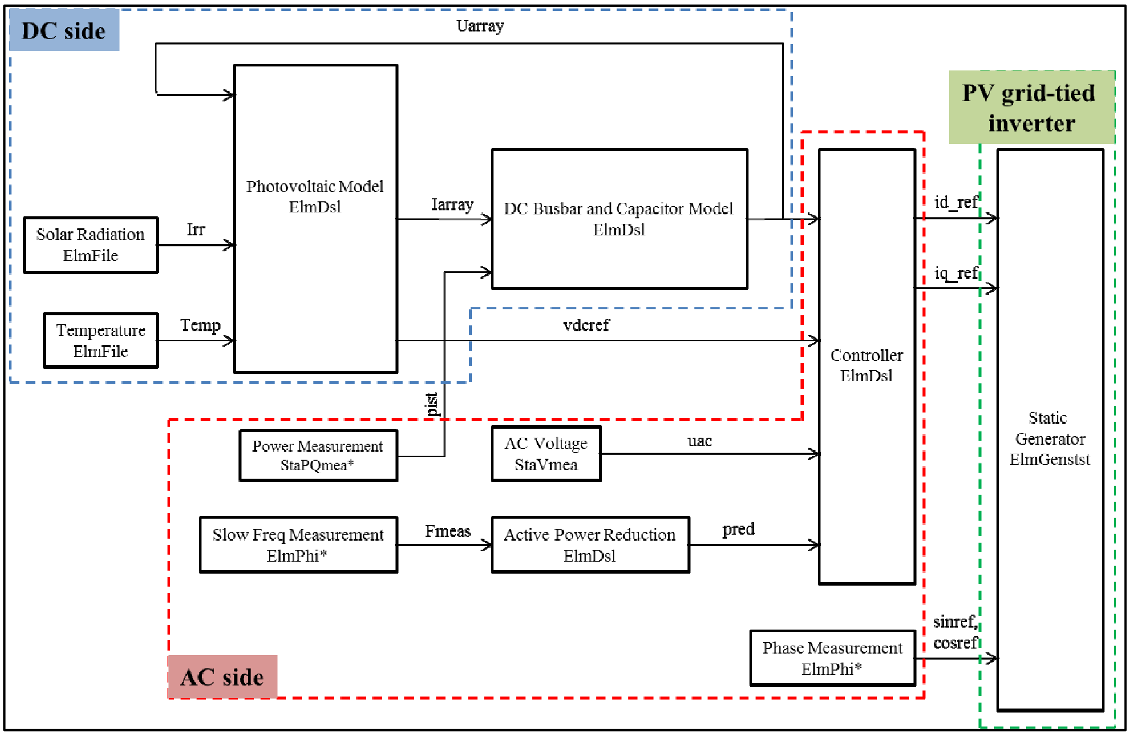

Figure 3: Grid-connected PV system simulation model 0.48 kV/0.5 MVA

4. Test Case Study

To simulate dynamic aspects of voltage stability, time domain simulation technique is applied to produce the system time response in sequence to the discrete events. In this study, input solar radiation and temperature are recorded within 24 hours. However, for simulation purposes, the time range is shortened and input data are simulated within 30 seconds to avoid computer complexity and longer simulation times. In the case study, first the impact of PV penetration level on the system voltage is investigated and then higher PV penetration level that a system can tolerate is determined. At maximum PV penetration level, the test system is forced to operate at higher load and its effect on system voltage stability is investigated. All calculations were made in the time domain simulation which is closely related to power flow simulation. The simulation process stopped when the power flow stop converging.

4.1. Test system

The IEEE 13 unbalanced node test feeder shown in Figure 4 was constructed using the DIGSILENT PowerFactory. The network is rated at 4.16 kV with highly unbalanced and distributed loads. The system is modified for dynamic analysis. Hot weather is assumed by considering the following conditions; hot and cloudy day, solar radiation of 1000 W/m^2, and an ambient temperature of 35 °C. The system is expected to operate under heavy load in these weather conditions. As such, the load has been modified to demonstrate that the system is under heavy load conditions. The PV system and a complex load are installed at Busbar 634.

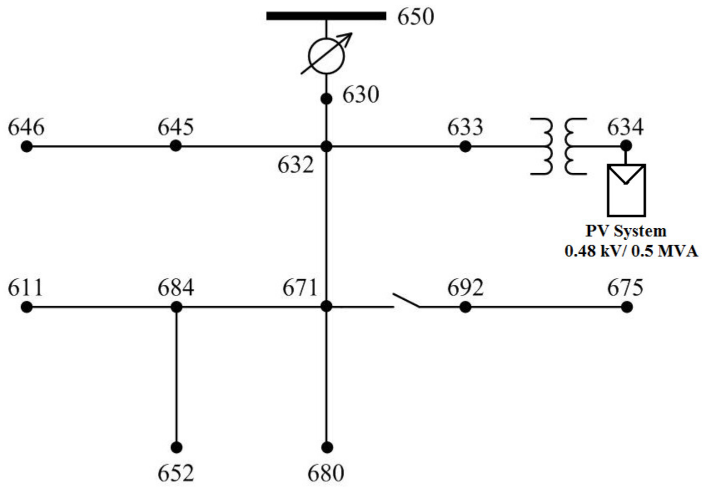

Figure 4: IEEE 13 node test feeder

4.2. Increase in PV penetration level

A PV system with solar intermittency and variation in solar temperature is installed at Busbar 634. The rated active power for the base case is 0.12 MW (10% PV penetration level). The PV penetration level is increased up to the maximum level the system can tolerate under constant load and without any disturbance. Solar PV penetration level is measured based on the ratio of the total PV power under STC (1000 W/m^2 sun radiation and 25 °C ambient temperature) to the total actual power of the load. The formula for solar PV penetration level is given as,

$$\%\ \text{PV penetration level} = \frac{Ppv}{Pload} \times 100 \tag{7}$$

4.3. Increase in load

The system load consists of unbalanced three-phase spot and distributed loads at Busbar 634. The load factor is increased by a certain percentage of its base value to determine the effect of loading on dynamic voltage stability. Only active power is increased for the three phases as shown in Table 3.

Table 3: Active power at Bus 634 based on loading factor

Load Factor (%)	Active Power at Bus 634 (MW)			Total (MW)
	Ph-1	Ph-2	Ph-3	
0	0.160	0.120	0.120	0.400
20	0.446	0.406	0.406	1.258
40	0.732	0.692	0.692	2.116
60	1.018	0.978	0.978	2.974
70	1.161	1.121	1.121	3.403
80	1.304	1.264	1.264	3.832

4.4. Line outage

Line outage is first simulated at line connecting busbar 632 to busbar 633 on the distribution network without the integrated PV system. Then, the same simulation is applied by increasing PV penetration level. Note that the load at Busbar 634 is kept at original loading throughout the simulation.

5. Results

5.1. Effect of PV penetration level

The active power of the PV system is increased to the level at which the increment affects the system voltage stability. In this simulation, solar radiation is recorded within 24 h but the time range is shortened and input data are simulated within 30 s to avoid computer complexity and long simulation times. The PV system is integrated at Bus 634 and the voltage profile at Bus 634 with various PV penetration levels is shown in Figure 5. The results show that increasing the PV penetration level increases the voltage profile at the particular busbar. The maximum PV penetration level that the system can tolerate is 60%. Although few sudden voltage drops occur during the simulation, the voltage remains within acceptable range of ± 10%. Thus, integrating a PV system into a distribution network does not disrupt the voltage operational limit even at high PV penetration levels.

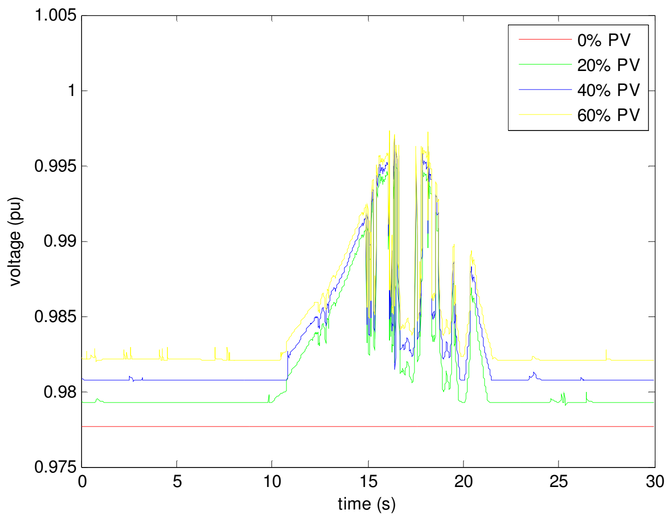

Figure 5: Voltage at Bus 634 with various PV penetration levels

5.2. Effect of increase in load

During a hot day, solar PV panels deliver high amount of active power to the grid because of intense sun irradiation. Yet, the PV power will rapidly decrease during cloud sweep. These conditions result in uncertainty output PV power and somehow will affect voltage stability of a power network especially during heavy load conditions. Dynamic load model considering induction motor is considered in the simulation. Here, the actual power of an induction motor load increases resulting in bus voltage decrease. Further voltage drop will increase reactive power consumption. Figure 6 shows the variation in voltage at Bus 634 as load is increased from 60% to 80% of its original value. The simulation results are summarized in Table 4. Without integrated PV system and at constant load, the distribution network operates under normal condition and that the voltage is within acceptable limit. However, at load factor of 40%, the voltage magnitude is ±10% below its operational limit. The voltage value kept decreasing following heavy load consumption. At load factor of 80%, the system operates at 0.79 pu which is the edge point of voltage operational limit. A bus system is considered voltage unstable when it experiences progressive voltage drop in response to the critical loading power. Moreover, unbalance in the active and reactive power supply also contributes to voltage instability because the PV system only provides additional active power while the reactive power is limited by the conventional generators. Any further increase in load will result in voltage collapse, which is represented by non-convergence in power flow and hence terminate the time domain simulation.

Thus, it can be concluded that a power network operates close to its stability limit during higher load demand. Even with integrated PV system, the power network still experience voltage instability problem.

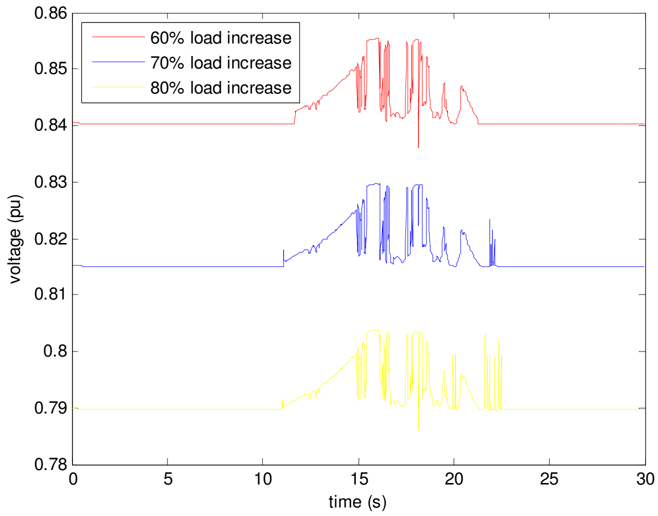

Figure 6: Load voltage at Bus 634 with load variation

Table 4: Summary of effect of increase in load

Load at Bus 634		**Voltage at Bus 634**			**Voltage Status**
Factor (%)	**Total P (MW)**	**t = 0 s**	**t = 15 s**	**t = 20 s**	
0	0.400	0.9822	0.9921	0.9823	Stable
20	1.258	0.9379	0.9477	0.9377	Stable
40	2.116	0.8900	0.9001	0.8901	Stable
60	2.974	0.8407	0.8504	0.8404	Stable
70	3.403	0.8151	0.8252	0.8151	Stable
80	3.832	0.7901	0.7999	0.7903	Unstable

5.3. Effect of line outage

Line outage is applied to Line 632 and 633. The line connects the PV busbar (Busbar 634) to the main network through a step-up transformer. Four different simulations have been performed; (i) line outage at base case, (ii) line outage with 20% PV penetration level, (iii) line outage with 40% PV penetration level and (iv) line outage with 60% PV penetration level. The voltage simulation result at Bus 634 with various PV penetration level is shown in Figure 7. Voltage at Bus 634 becomes unstable when the voltage drops below 0.8 pu at t = 5 s and does not improve even with the integrated PV system at high penetration levels. This is because, during line outage, Busbar 634 is disconnected from the main network, thus resulting in islanding condition. At this time, Busbar 634 only receives active power supply from the PV system and no reactive power is provided, thus resulting in voltage collapse condition.

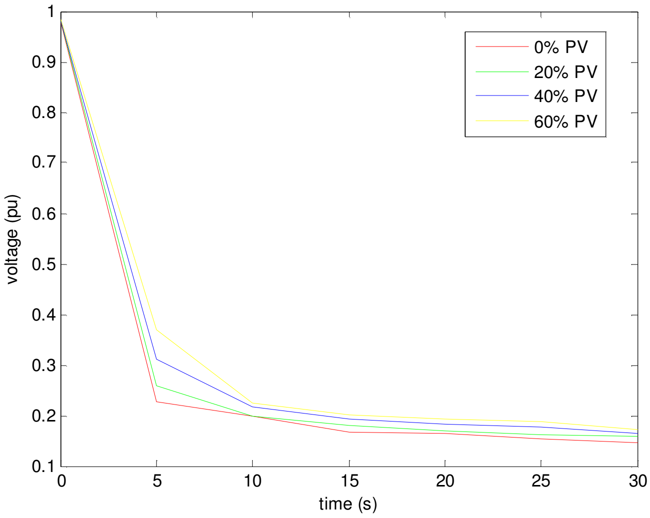

Figure 7: Voltages at Bus 634

5. Conclusion

The effect of a grid-connected PV generator on dynamic voltage stability of a distribution system has been studied by taking into account solar intermittency, PV penetration level, load increase, and line tripping. Dynamic voltage stability simulations were carried out using the DIGSILENT Power Factory software. Simulation results show that increasing the PV penetration level improves system voltage stability. However, in cases when load is increased by 80%, the system encounters voltage instability even at maximum PV penetration level. When line outage is applied, the system undergoes voltage collapse; because the PV generator is disconnected from the system and that the voltage at the PV connected busbar drops below its voltage operating limit.

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