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Voltage Stability Analysis of Power System with Photovoltaic Power Plant

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A B S T R A C T

Photovoltaic power plants usually do not provide reactive power output; hence the application of large photovoltaics in power systems will decrease the voltage stability level of the power system. Capacitor banks can provide reactive power to compensate the photovoltaic plants; therefore, capacitor banks can overcome the reactive power deficiency of photovoltaic plants. However, the effect of capacitor bank installation on the system's voltage stability is unknown. Therefore, the research aims to investigate whether installing a capacitors bank can restore the level of system voltage stability. The study employs the method of Voltage Stability Margin and transient stability simulation to the IEEE 9 bus system. The IEEE 9 bus system is modified where one generator of the system is replaced with a photovoltaic plant, and a capacitor bank is also installed. The study results show that the modified system voltage stability level is lower than the original system. When the capacity of the capacitor bank is increased to the maximum allowable value, the voltage stability level rises. However, it is still unable to be restored to its original value.

INTRODUCTION

To combat global warming and climate change, the IPCC (Intergovernmental Panel on Climate Change), a body of the United Nations, has set a target for net zero CO_2 emissions in 2050 [1]. This implies that net zero carbon in the electricity sector will be critical to achieving this target. The Global Climate Summit, COP 26, urges all nations to end the utilisation of coal power plants [2]; since they contribute 30% of global CO_2 [3]. In the near future, utility companies must replace their coal power plants with carbon-free power plants.

Renewable energy power plants have grown significantly to realise the net zero target in the electricity sector. In 2021, generation from renewable energy increase by 7% or 522 TWh, where 90% of this growth comes from PV and wind power. Renewable energy has contributed 28.7% of global electricity generation [4], which will continue to increase. Therefore, utilities need to understand the effect of renewable generation on system operation.

Renewable energy plants such as photovoltaic and wind generation do not utilise synchronous generators for generating electricity as conventional power plants do [5]–[7]. Thus, conventional photovoltaic and wind generation usually do not produce reactive power. To provide reactive power in the power system, the utility company can install reactive power compensation such as capacitor banks, Static Var Compensator (SVC), Synchronous Condenser and Static Synchronous Compensator (STATCOM) [8], [9]. Literature has proposed voltage source inverters for photovoltaics that can generate reactive power [10]. However, this ability will significantly depend on solar irradiation. The reactive power output can fluctuate rapidly due to clouds. Also, the current applied standard, such as IEEE 1547, states that inverters are prohibited from actively regulating the voltage at the point of common coupling (PCC) [11]. Therefore, dedicated reactive compensations are needed.

The voltage stability of power systems is determined by reactive power adequacy for demand sides [12]. When fossil power plants that usually have synchronous generators are replaced by large photovoltaic power plants, the source of reactive power will be lost. The loss of reactive power sources may result in a decrease in system voltage stability.

Research about the voltage stability of grid-connected photovoltaics can be found in several literatures. However, their focuses are different from this study. In [13], the study analysed the system voltage stability before and after photovoltaic installation; however, the photovoltaic is not a replacement for the existing synchronous generator but an additional power generation. In [14]–[18], voltage stability analysis is conducted for a system with a photovoltaic inverter that generates reactive power, which does not follow standards, such as IEEE 1547, that prohibits actively regulating the voltage at the point of common coupling (PCC) [11]. Therefore, this study aims to examine whether installing a capacitor bank to compensate the reactive power, after a synchronous

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generator replacement with photovoltaic, can restore voltage stability level.

In this research, the power system voltage stability is quantified using static analysis, i.e. Voltage Stability Margin (VSM) technique. VSM represents the distance between the current power system operation to the critical loading point [19]. A critical loading point is a boundary between the system's stable and unstable state. The smaller VSM means the worse the system stability condition. The study also conducts dynamic voltage stability analysis using transient simulation since several literatures considered the static analysis alone does not capture the system condition sufficiently[13], [20] [21].

METHODOLOGY

The test system IEEE 9 bus is employed to examine the system voltage stability condition. The system consists of three synchronous generators, three bus loads and six transmission lines rated 230 kV [22]. The single-line diagram of the IEEE 9 bus system is shown in Figure 1. The system in Figure 1 is called the original system, which will be used as the benchmark in this study.

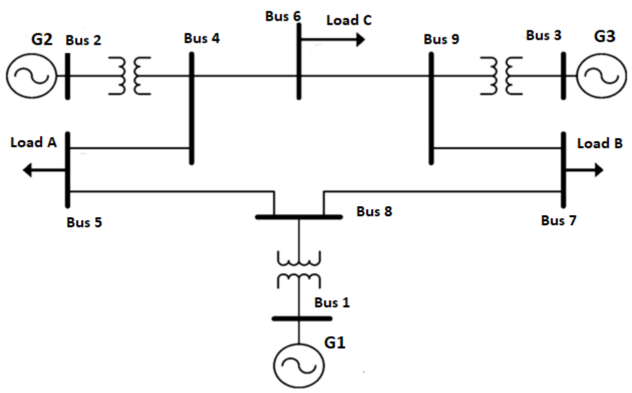

Figure 1. Test System: IEEE 9 Bus

The generator G2 in the original system is replaced with a photovoltaic power plant with the same rated active power (163 MW) to create the modified system. Four system scenarios were examined in the study, i.e.:

- Original system: IEEE 9 bus without modification
- Modified 1: IEEE 9 bus with G2 replaced with photovoltaic of the same rated
- Modified 2: modified 1 with capacitor bank 6.7 Mvar at bus 2
- Modified 3: modified 1 with capacitor bank 15 Mvar at bus 2

In the modified 2 system, the installed 6.7 Mvar capacitor bank is the same as the reactive power rating of the replaced generator G2. In the modified 3 system, the 15 Mvar capacitor bank is the maximum reactive compensation that can be installed on bus 2 without causing a violation of the maximum permitted voltage.

The VSMs of the four systems are compared using the methodology shown in the flowchart of Figure 2. Digsilent Powerfactory software [23] is used to simulate the systems in this study which consist of power flow simulation for VSM calculation (static analysis) and RMS simulation for transient simulation (dynamic analysis).

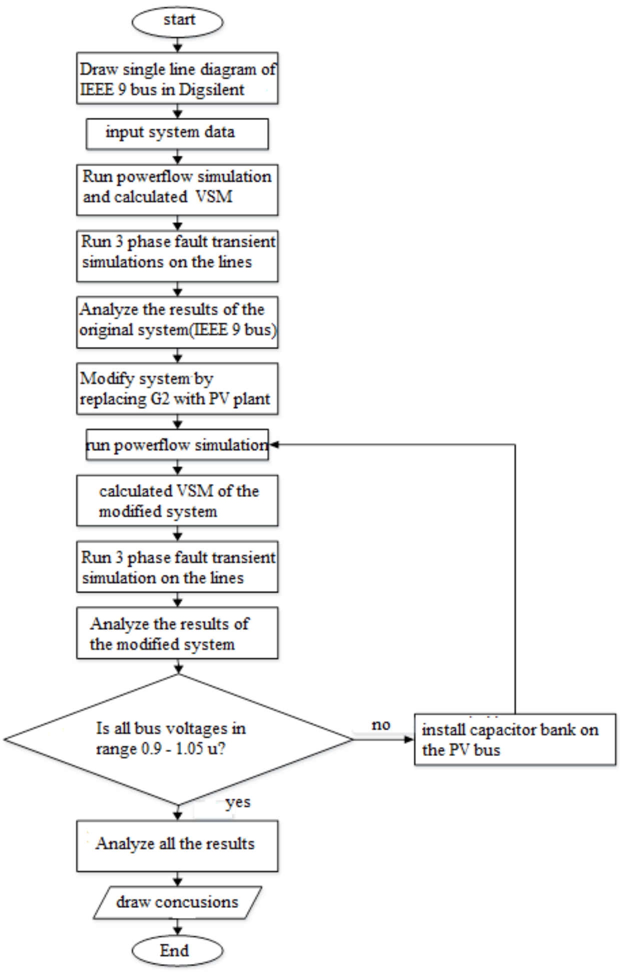

Figure 2. Flowchart of the research methodology

Quantification of the voltage stability level of a load bus is carried out using the Voltage Stability Margin (VSM). A VSM measures the distance between the operating point and the critical point of the P-V or Q-V curve. A critical point is the nose of a P-V or Q-V curve where the system starts to become unstable, also called as maximum loading limit. VSM from the P-V curve is called VSM P, whereas from the Q–V curve is called VSM Q. Methods for calculating both VSM are shown in Figures 3 and 4, respectively [24].

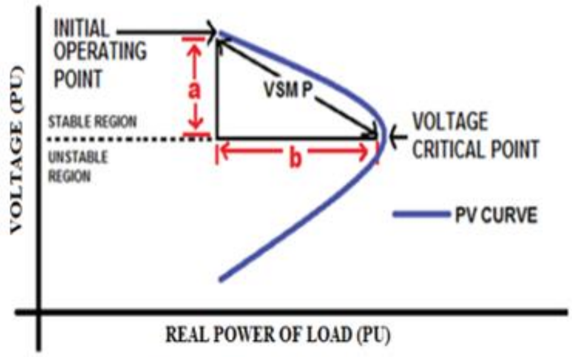

Figure 3. P-V curve and its VSM P

VSM P is calculated as:

$$VSM\ \mathrm{P} = \sqrt{a^2 + b^2} \tag{1}$$

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Where a and b are the distance between the critical point and the operating point in term of voltage and real power, respectively, as shown in Figure 3.

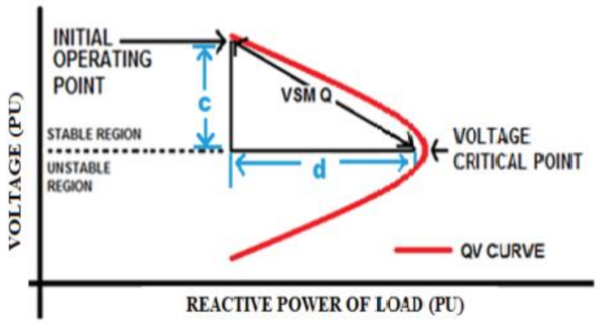

Figure 4. Q – V curve and its VSM Q

VSM Q is calculated as:

$$VSM\ Q = \sqrt{c^2 + d^2} \tag{2}$$

Where c and d are the distance between critical point to operating point in term of voltage and reactive power, respectively, as shown in Figure 4. The a, b, c and d are in per unit quantities.

The P-V and Q-V curve are obtained through repeated power flow solutions by increasing the load demand (P or Q individually) until the solution does not converge [25]. The point where the power flow does not converge is the critical point of the curve.

The VSMs of each system (original and modified) are compared and analysed. It is expected that VSM of the modified system can be the same as VSM of the original system when the given reactive power compensation is the same as reactive power capacity of the replaced generator.

Transient simulation of three-phase faults and their clearance using circuit breakers are also carried out to assess the system's voltage stability level. The load busses' steady state post disturbances voltages are used to measure the voltage stability level. Higher steady-state voltage values indicate a more stable system [20], [26].

RESULTS AND DISCUSSION

VSM P of each load bus in original system and modified 1 are shown in Figure 5. The figure shows that the VSM P of the modified 1 system is less than the original system.

VSM Q of each load bus in original system and modified 1 are shown in Figure 6. Similarly, the VSM Q of the modified 1 system is also less than the original system.

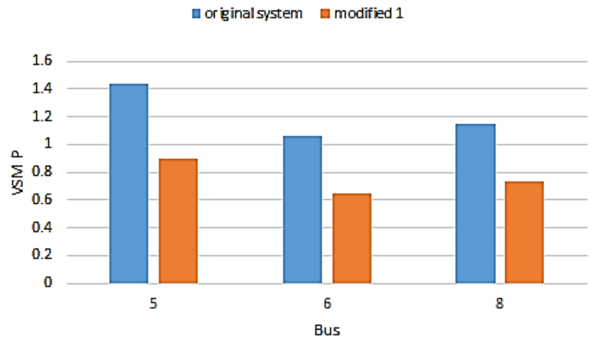

Figure 5. VSM P of original and modified 1 systems

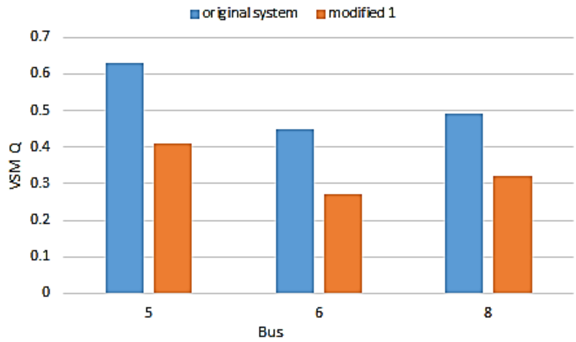

Figure 6. VSM Q of original and modified 1 systems

In Figure 5 and 6 can be seen that both VSM P and VSM Q of the modified 1 system are lower than the original system. This less VSM conforms with the theory that a system with a less reactive power supply will be more unstable than a system with a more reactive power supply.

Based on this theory, to increase the system voltage stability, a capacitor bank is added to the bus where PV is installed, represented by the modified 2 and modified 3 systems. The VSM results of these systems and their comparison to the original system are shown in Figures 7 and 8.

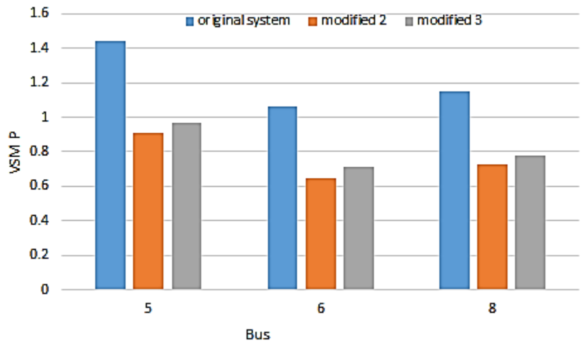

Figure 7. VSM P of original, modified 2 and modified 3 systems

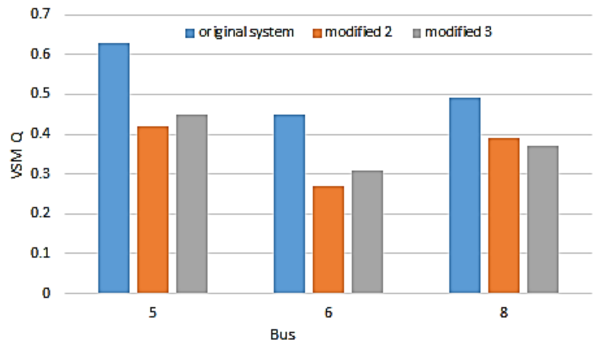

Figure 8. VSM Q of original, modified 2 and modified 3 systems

Figures 7 and 8 show that the same amount of reactive power supply as in the original cannot result in the same level of VSM. The modified 2 system still has less VSM than the original system, which means less stable in terms of voltage stability. Moreover, an additional reactive power supply in the modified 3 system can increase both VSM, but it does not result in the same level of VSM Q or VSM P as the original system. Also, from Figure 8, there is an anomaly of bus 8 VSM Q of the modified 3 system, where its value is slightly less than the modified 2 system. This condition may come due to the weakness of the V-Q method, as mentioned in [20].

To confirm this finding, dynamic analysis is carried out using transient simulation. Each transmission line is simulated for a three-phase fault in the middle of the line. Then, the fault is cleared by the operation of the circuit breakers on each end of the line at 0.2 seconds after the occurrence of the fault. The transient simulation results for the fault on line 4-5 of the original and modified 3 systems are shown in Figure 9 and 10, respectively.

It can be compared that the steady state post-fault voltage in the original system (figure 9) is greater than the modified 3 system (figure 10). In the original system, the lowest voltage is 0.901 pu, whereas in modified 3 is 0.858 pu. The highest steady state voltage in figure 9 is 1.021 pu, whereas in figure 10 is 1.016 pu.

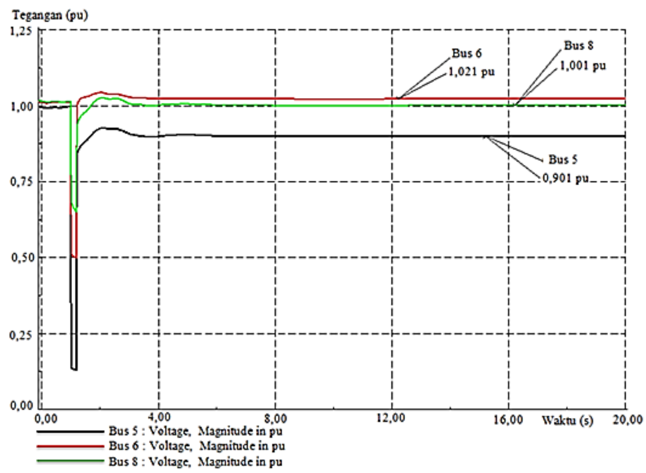

Figure 9. Voltage plot of transient simulation result for a fault on line 4-5 of the original system

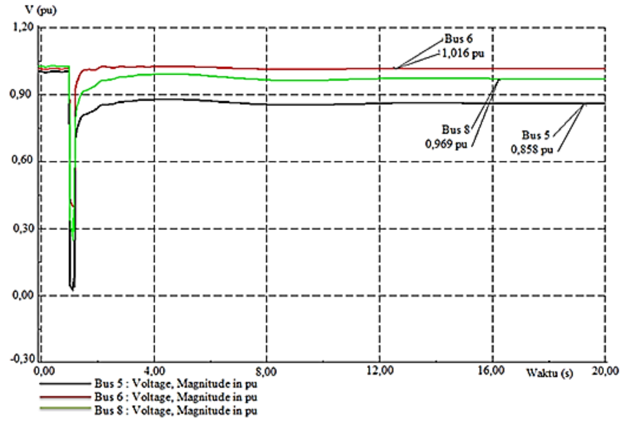

Figure 10. Voltage plot of transient simulation result for a fault on line 4-5 of modified 3 system

The steady state post fault voltages are compared between the original system and the modified 1,2 and 3 systems. The steady state bus 5 voltages of each system after clearance of different fault location are shown Table 1.

Table 1. Steady State Voltage (pu) on Bus 5 After Three Phase Fault Clearance

Faulted line	System			
	original	modified 1	modified 2	modified 3
4-5	0,901	0,820	0,837	0,858
5-7	0,955	0,946	0,948	0,950
7-8	0,988	0,950	0,963	0,981
8-9	0,992	0,948	0,960	0,975
6-9	0,979	0,953	0,959	0,968
4-6	1,001	0,990	0,996	1,003

Table 1 shows that the highest steady state voltages of bus 5 for each faulted line are provided by the original system and the lowest voltages are provided by the modified 1 system. The modified 2 and modified 3 voltages are higher than the modified 1 voltages however they are lower that the original voltages. Similar condition is also found for the other two load buses (bus 6 and 8). These transient simulation results match the result of the VSM method.

Based on the both methods i.e. VSM and transient simulation, the voltage stability level of the photovoltaic connected system always lower than the original system without photovoltaic. Installation of a capacitor bank to provide reactive power for the photovoltaic is not able to restore the voltage stability level to the original system level.

An explanation of the cause of the inability of the capacitor bank to restore the system's voltage stability level to that of the original system is as follows. During normal operations, the reactive power outputs of capacitor banks are always constant according to their rating, whereas reactive power outputs of synchronous generators vary in line with active power output. VSM P is obtained by increasing the amount of load on the examined bus. For the original system (with synchronous generator), the reactive power that supplied by the generator can be increased according system demand. However, for the modified 2 and 3 (with capacitor bank),

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the reactive power can be supplied is always constant, hence they result in lower critical point, and thus lower VSM P. During transient simulation, system voltages will lower than normal operation, this condition will cause output of capacitor bank also lower. The reactive power output of the capacitor bank is directly proportional to the square of the voltage. This difference is considered become the reason for the lower level of voltage stability of the modified 2 and 3 systems.

CONCLUSIONS AND FUTURE WORK

Replacement of a synchronous generator with a large photovoltaic plant cause reduction of system voltage stability level. Using method of Voltage Stability Margin and transient simulation has been found that installation of capacitor bank is able to increase the voltage stability level, however the stability level is still lower than the original system. Therefore, it can be concluded that capacitor bank cannot restore the voltage stability level into the original one.

A future study will apply different compensator which having ability to regulate reactive power output to the system. Therefore, it is expected the voltage stability level will be better.

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NOMENCLATURE

Meaning of symbols used in the equations and other symbols presented in your article must be presented in this section.

VSM Voltage Stability Margin

VSM P Voltage Stability Margin that measured from P-V curve

VSM Q Voltage Stability Margin that measured from Q-V curve

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