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Voltage Stability Analysis based on Power Voltage (P-V) and Reactive Voltage (Q-V) Curves in Transmission Lines Using Static Var Compensator (SVC) with the Power Factory Program

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Voltage Stability Analysis based on Power Voltage (P-V) and Reactive Voltage (Q-V) Curves in Transmission Lines Using Static Var Compensator (SVC) with the Power Factory Program

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Abstract. Due to the great demand for energy, electrical power systems, when subjected to voltage stress, present voltage instability, generating blackouts in the system with economic losses and in the components. Through a static approach, the P-V and Q-V curves are widely used in operation studies, planning that allow us to detect the weakest bus in the system to obtain the exact location in which to connect the SVC to compensate with reactive power in order to have system voltage stability. Through this article, we evaluate a voltage stability study on the IEEE-9 bus with the Dig-Silent Power Factory 2020 program in order to compensate the system with reactive power.

1. Introduction

Due to modernization and industrialization, the demand for electricity is increasing. This has resulted in most power systems operating under stressful conditions [1]. Currently, interest in integrating renewable energy sources (RES) into energy systems in countries around the world is increasing rapidly due to significant shortages and / or rising prices of fossil fuels and the need to avoid damage from the effects of global climate change [2]. Renewable energy generation and grid integration have gained significant local and global attention [3]. One of the main limitations to increasing the integration of renewable energies in the electricity grid is voltage stability [4]. In a survey, carried out by the International Council of Large Electrical Networks (CIGRE), among the system operators it was found that limited technical studies were carried out to evaluate the changing behavior of the electrical system [5].

Voltage instability occurs when a power system cannot maintain the voltage across all buses in the system, subjecting it to a disturbance [6]. The potential for voltage instability and collapse also increasingly depends on the limits of network topology, system operation, and the nature of electrical system components [7].

The priority of the power system network is to transmit power from the sending side to the receiving side with minimal losses [8]. The electrical power system (SEP) must operate under a stable regime. Voltage stability is the ability of a power system to keep the voltage across all buses in the system unchanged [9]. The voltage breakdown is usually related to the reactive power demand of the load that has not been satisfied due to the lack of production and transmission of reactive power. [10]. Voltage collapse should be prioritized as much as possible as it leads to cascading blackouts throughout the network. By voltage stability indices, it is possible to determine the stability point for the transmission and distribution system, so that the weakest bus in the system can be determined [11]. In [1] we show

that there are two types of approaches (dynamic and static) for the study of voltage stability, for static approaches we can use P-V and Q-V curves. For dynamic approaches, an evaluation and monitoring of the stability of the line voltage is performed based on data from synchro phasors [12].
Voltage Stability Margin (VSM) and Load Power Margin (LPM) play a very important role in the analysis of voltage instability. Both VSM and LPM are obtained from the P-V and Q-V curves [13]. Strategies based on software and dedicated control equipment are recent categories of promising technological advances, so it is very useful since it takes as a starting point the assistance to the operator and to the network as such [14]. Flexible Alternating Current Transmission System (FACTS) such as Static Synchronous Compensators (STATCOM) and Static Variation Compensators (SVC) have been used as reactive power offsets to improve voltage stability [15]. STATCOM compensation is studied under different contingencies with constant power load [16]. The P-V and Q-V analysis is the best method to find the weakest bus in the system that is close to the voltage collapse [17].
This analysis aims to find the weakest bus of the SEP and avoid voltage collapses through the P-V and Q-V curves. We will have the optimal location for the SVC device to improve the safety, reliability and voltage stability of the IEEE-9 bus system in the Power Factory software 2020.

2. Methodology

2.1 P-V Curve
The P-V analysis of a SEP is another static analysis tool. They represent the characteristic of the voltage behavior as a function of the active power when the system load is modified [18].

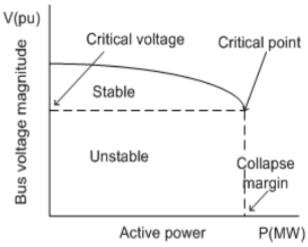


Figure 1. P–V curve [17].

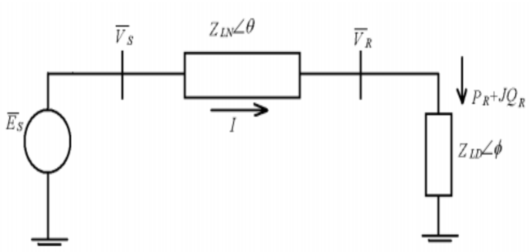


Figure 2. Radial system for stress stability analysis [19].

The current flowing through the line is given by the following equation:

$$I = \frac{V_S}{Z_{LN} + Z_{LD}} \tag{1}$$

Where VS = Voltage at the sending node. I = Current through the transmission line. θ = Angle of line impedance. φ = Angle of the impedance of the load. To find the magnitude of the circulating current, the impedance of the load and the line in their Cartesian components is added and the norm is taken to obtain the magnitudes [19].
The equation is as follows:

$$I = \frac{V_S}{\left[\left(Z_{LN}Cos(\theta) + Z_{LD}Cos(\emptyset)\right)^2 + \left(Z_{LN}Sen(\theta) + Z_{LD}Sen(\emptyset)\right)^2\right]^{1/2}} \tag{2}$$

To simplify the expression a bit, the impedance term can be expressed as a constant F.

$$I = \frac{V_S}{F^{\frac{1}{2}} \times Z_{LN}} \tag{3}$$

Where F equals:

$$F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right) + 2 \times \left(\frac{Z_{LD}}{Z_{LN}}\right) Cos(\theta - \emptyset) \tag{4}$$

The magnitude of voltage at the receiving node VR is equal to:

$$V_R = Z_{LD} \times I \tag{5}$$

Replacing current by the expression of equation (1).

$$V_R = \frac{1}{F^{1/2}}\left(\frac{Z_{LD}}{Z_{LN}}\right) \times V_S \tag{6}$$

The power delivered to the receiving node is equal to:

$$P_R = V_R \times I \times Cos(\emptyset) \tag{7}$$

Replacing equations (5) and (6) in equation (7) we have:

$$P_R = \frac{Z_{LD}}{F} \times \left(\frac{V_S}{Z_{LN}}\right)^2 \times Cos(\emptyset) \tag{8}$$

2.2 Q-V curve

The Q-V curve method shows MPR values and voltage profile of the bus under study, this allows us to know its robustness. This method must be applied to the weakest member of the system [20], [21].

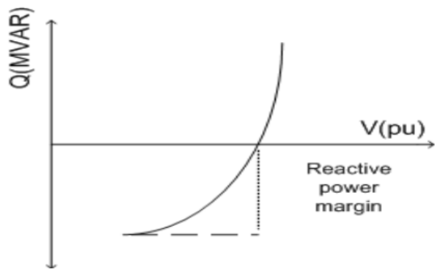


Figure 3. Q–V curve [17].

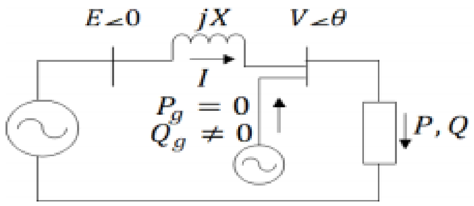


Figure 4. Connection of a compensation device in a basic circuit [20].

To obtain the Q-V curve it is necessary to connect a fictitious synchronous generator (Qg) in parallel to the load node, see the basic circuit of Figure 4 [22].

From Figure 4, it follows (9) and (10).

$$P = -\left(\frac{EV}{X}\right) \times Sen(\theta) \tag{9}$$

$$Q - Q_g = -\left(\frac{EV}{X}\right) \times Cos(\theta) - \frac{V^2}{X} \tag{10}$$

For the construction of the Q-V curve in the circuit of Figure 4, the constant power factor and active power are considered, and giving voltage values is obtained θ through (9) and Qg through (10) [22].

3. Simulation y resulted

The present study is carried out on IEEE-9 bus figure 5, that is composed of 9 buses, 3 generators, 3 loads, 6 transmission lines and 3 transformers [23]. The total load demand of the SEP is 319.63 MW. The case study is performed in Dig-Silent power factory software version 2020. By means of the P-V and Q-V curves we will obtain the critical bus and by means of an SVC we will compensate the reactive power.

In this system, we will obtain the voltages in p.u. of each bus. The buses are stable since they are above 0.99 p.u. and under normal conditions as shown in figure 6.

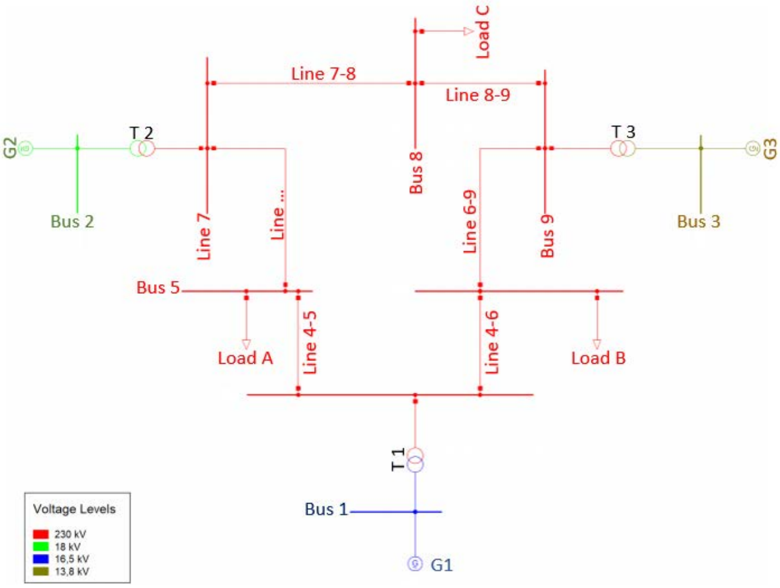


Figure 5. IEEE 9 bus system [23].

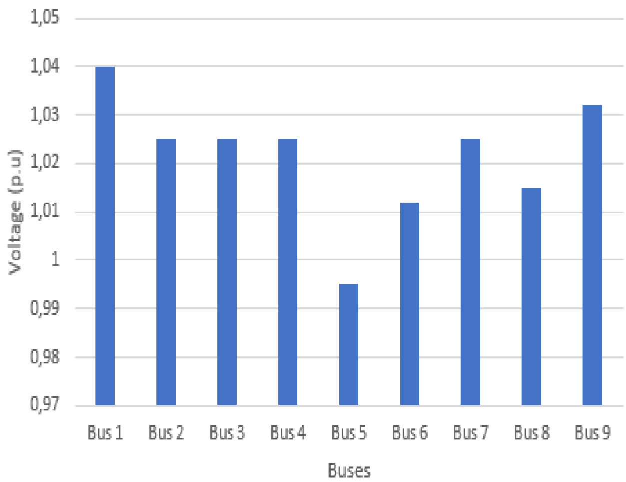
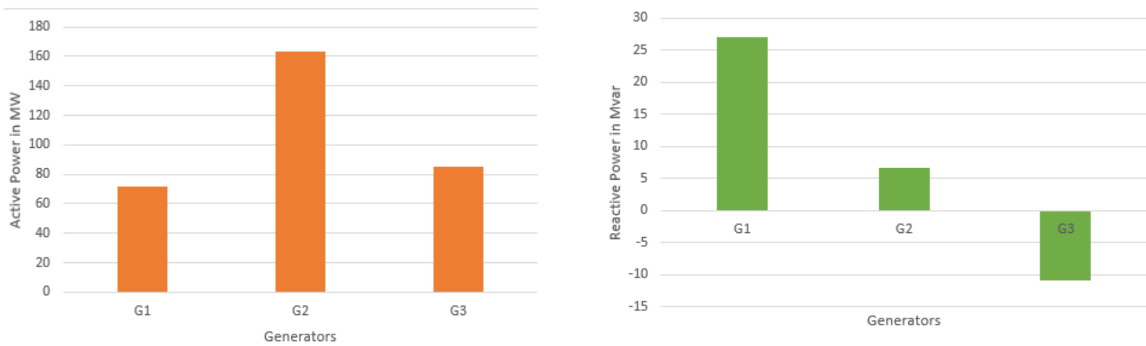


Figure 6. Bus voltages in p.u.

We obtain the active and reactive power supplied by our generators in figure 7 (a) and (b).



(a) **(b)**

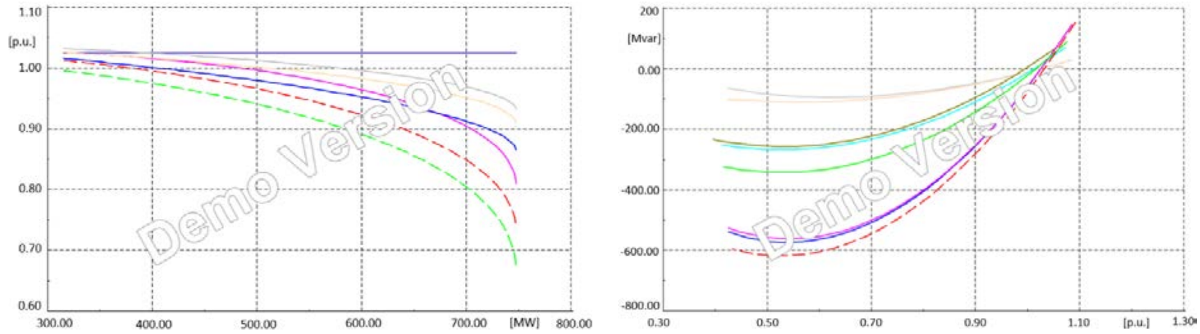
Figure 7. Active(a) and reactive (b) power of generators.

After the load flow, data analysis is performed on the P-V curve and the Q-V curve. In the analysis of the P-V curve data, bus 5 with 0.670 p.u., bus 6 with 0.737 p.u. and bus 8 with 0.865 p.u. are the most unstable, these three buses will be analyzed because they are connected to a load with the exception of bus 4 as shown in figure 5. In the Q-V curve, bus 9 is the most unstable 0.432 p.u. in table 1 but it is compensating with -617.76 MVar in table 2, so the bus 6 with 0.690 p.u. and bus 5 with 0.837 p.u. in table 1 are the ones that we will analyze to establish the best location of the SVC.

Table 1. Voltage data in p.u.

Bus name	Voltage (p.u.)	Voltage P-V (p.u.)	Voltage Q-V (p.u.)
Bus 1	1.040	1.040	1.040
Bus 2	1.025	1.025	1.025
Bus 3	1.025	1.025	1.025
Bus 4	1.025	0.810	0.892
Bus 5	0.990	0.671	0.837
Bus 6	1.012	0.737	0.690
Bus 7	1.025	0.909	0.856
Bus 8	1.015	0.865	0.650
Bus 9	1.030	0.933	0.432

In the P-V curve of Figure 8 (a), bus 5 is a weak bus with 0.67 p.u. shown in green and in lines. Buses 1, 2 and 3 remain stable, these buses are strong buses since they are close to the generators. In the Q-V curve of figure 8 (b), buses 2,3 will absorb reactive power from generators 2 and 3, compensating and stabilizing these buses. Bus 5 with a voltage of 0.671 p.u. in green and in lines, bus 6 with a voltage of 0.737 p.u. in red and in lines are those that require reactive compensation to stabilize the system.

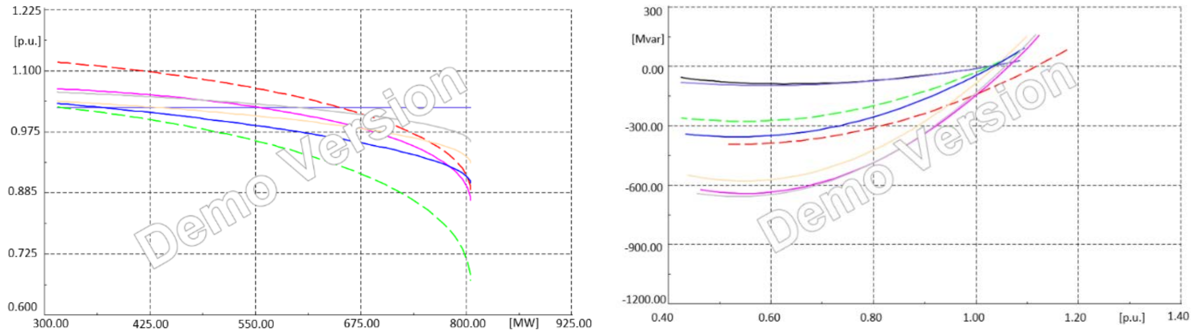


(a) **(b)**

Figure 8. P-V (a) and Q-V (b) curves.

In order to stabilize the system, we will connect SVCs in the weakest buses that we will analyze in two cases.

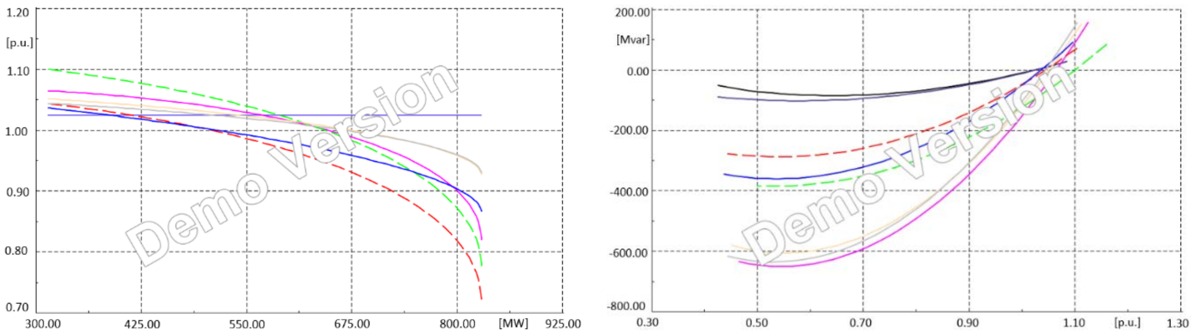
Case 1: Supply the system with reactive power through an SVC on bus 6 with -128 Mvar. In this case, the SVC with -128 Mvar is connected on bus 6 because it is one of the weakest buses and it will not reach up to the critical voltage if we add more reactive power. Analyzing the P-V curve in figure 9 (a), bus 6 improves the voltage from 0.737 p.u. to 0.857 p.u. and in other buses as shown in table 2. In the analysis of the Q-V curve in figure 9 (b), by supplying -128 Mvar with the SVC, the load margin increases from -266.70 Mvar to -394.61 Mvar, in turn improving the voltage from 0.690 p.u. to 0.834 p.u. and in other buses as shown in the table 2.



(a) **(b)**

Figure 9. P-V (a) and Q-V (b) curves with SVC on bus 6.

Case 2: Supply the system with reactive power through an SVC on bus 5 with -128 Mvar. For this case, the SVC with -128 Mvar is connected on bus 5 because it is one of the weakest buses and it will not reach up to the critical voltage if we add more reactive power. Analyzing the P-V curve in figure 10 (a), bus 5 improves the voltage from 0.671 p.u. to 0.778 p.u. and in other buses as shown in table 2. In the analysis of the Q-V curve in figure 10 (b), by supplying -128 Mvar with the SVC, the load margin increases from -256.80 Mvar to -384.73 Mvar, in turn improves the voltage from 0.837 p.u. to 0.961 p.u. and in other buses as shown in the table 2.



(a) **(b)**

Figure 10. P-V (a) and Q-V (b) curves with SVC on bus 5.

Table 2. Voltages (p.u.) without and with SVC.

	Without SVC				SVC in Bus 6			SVC in Bus 5		
Buses	**V (p.u.)**	**V P-V (p.u.)**	**V Q-V (p.u.)**	**Q (Mvar)**	**V P-V (p.u.)**	**V Q-V (p.u.)**	**Q (Mvar)**	**V P-V (p.u.)**	**V Q-V (p.u.)**	**Q (Mvar)**
Bus 2	1.025	1.025	1.025	-94.120	1.025	1.025	-88.670	1.025	1.025	-84.54
Bus 3	1.025	1.025	1.025	-109.54	1.025	1.025	-96.040	1.025	1.025	-101.99
Bus 4	1.025	0.810	0.892	-572.80	0.835	0.944	-642.67	0.821	0.939	-650.84
Bus 5	0.990	0.671	0.837	-256.80	0.671	0.880	-277.87	0.778	0.961	-384.73
Bus 6	1.012	0.737	0.690	-266.70	0.857	0.834	-394.61	0.719	0.729	-287.62
Bus 7	1.025	0.909	0.856	-561.72	0.912	0.871	-579.47	0.927	0.887	-605.96
Bus 8	1.015	0.865	0.650	-342.22	0.871	0.671	-356.65	0.867	0.675	-359.97
Bus 9	1.030	0.933	0.432	-617.76	0.955	0.456	-657.97	0.930	0.444	-635.46

4. Conclusions

In this article, an analysis of two cases is performed to improve the stability of the IEEE-9 bus system in the Dig-Silent 2020 software. To identify the weak bus zone in the system, it is performed using the P-V and Q-V curves to determine the best location for the SVC. To improve voltage stability in the system, the optimal location for SVC is connected to bus 5 with -128 Mvar each, since it not only improves stability on bus 5, but improves stability on all buses as shown. see in table 2. This optimal location of the SVC allows to improve the load margin, reduce energy losses and improve the power transmission capacity.

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