OPTIMUM LOCATION OF STATCOM USING Q-V CURVE ANALYSIS FOR POWER SYSTEM SECURITY

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Abstract:

Due to slit between the power supply and load, conditions like congestion or contingency arises. During congestion or contingency situations, power devices are connected in the network for enhancing power transfer capacity and thus for securing the power network. As due to economic contemplation, FACTS power devices cannot be connected randomly. This study reports the importance of Q-V curve analysis to verdict the optimum location of STATCOM FACTS power device. Additionally, to validate the result the weak bus or optimum location of STATCOM is identified through the power system analysis toolbox of MATLAB. Standard WSCC 9 bus network is considered as test case in power world simulator software and MATLAB power system analysis toolbox.

1 Introduction

The optimal location of FACTS power device is very significant issue in the power network since the weakest bus bar and/or transmission lines need to be identified to improve the security of the electricity network. Reduced real power loss on a specific line, reduced overall system real power loss, reduced total system reactive power loss, and maximum relief from system congestion are some of the goals of FACTS power device placement. [1].Various different techniques are already used for obtaining optimal location. Main Techniques are characterized as Sensitivity Analysis, Analytical Method, Heuristic search methods. Sensitivity analysis techniques are like loss sensitivity index, voltage loss sensitivity index and voltage sensitivity index and many more are used. In Heuristic search methods, algorithm like harmony search algorithm, Differential evolution, Particle Swarm Optimization, Genetic Algorithm, Ant Colony optimization and many more are used. In Analytical method, P-V and Q-V curve analysis are done. Various contributions of researchers are noted here. In [2] voltage stability analysis is carried out with conventional P-V and Q-V curve method for identifying strong and weak bus. IEEE 14 bus network has taken and validate in power world simulator software. Technical comparison of SVC and STATCOM parallel controller has done with V-I and V-Q curves, the response time, the physical size, the cost and behavior in steady-state and transient stability [3]. Voltage stability enhancement has been carried by P-V and Q-V curves taking 57 bus Patiala Rajpura Circle of India [4]. Optimal location of STATCOM has been carried out with two stage algorithm in 1st stage Sensitivity Analysis has been carried out for optimal location of STATCOM and in 2nd stage Optimum parameter carried out by N-R method using 14 bus network as test case in MATLAB [5]. In [6] measurement-based Q-V curve technique has proposed, which uses a particular compensation method and some configurable parameters (such as AVR settings) to conduct the measurement operation, may measure a portion of the Q-V curve in real time around the operating point.

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The study on Voltage Collapse Mitigation utilizing Voltage Collapse Indices and Q-V Curves is presented in [7]. The primary contribution of paper [8] is the identification of weak power system buses using static voltage stability analysis methods, as well as the selection of the appropriate STATCOM size and location for voltage stability enhancement. In [9] five buses and a real Brazilian system has been used to see the effect of Q-V curves in dynamic behavior of power system. The best location and size for a FACTS STATCOM device has been carried out by increasing the transmission system's static voltage stability margin [10]. The major goal of this work reported [11] here to improve voltage stability and load ability using the Quantum behaved Particle Swarm Optimization (QPSO) technique at the STATCOM location. With a change in scale on the voltage axis, this study reported in [12] will show that for some simple load models, the energy-based security measure is identical to the region contained by the well-known Q-V curve. Using the Kenyan Power Network as an example, this [13] provides a method for assessing the static voltage stability analysis. Power voltage curves, sensitivity analysis (VQ), and reactive power and voltage modal analysis are all part of this particular approach. In [14] coherent groups of load buses are compared using the Reactive Reserve Margin (RRB) from V-Q curve analysis and a brand-new generator sensitivity-based STATCOM placement approach. The best position for shunt FACTS devices in transmission lines to provide the greatest benefit under typical conditions has been examined in [15] article. For the inquiry, three distinct line models are taken into consideration. In [16] allocation of UPFC has been done by sensitivity analysis. In [17] optimal location by sensitivity analysis has been done for series FACTS device. In [18] contingency analysis has been carried out with STATCOM and SVC. In [19] optimal location of TCSC has been done for improving power system security by sensitivity analysis method. Congestion management and other issues are addressed in this [20] research by comparing TCSC and SSSC in both regular and emergency scenarios. Optimal Power transfer capability and voltage profile are both improved by optimally placing these devices, which eliminates congestion under normal and contingency problems using a modified 14-bus test network with the help of the power world simulator programme.

This [21] study uses the active power flow performance index to determine the best location for the thyristor controlled phase angle regulator in the 5 bus system using MATLAB. The PWS 12.0 programme is used to validate the MATLAB results. To enhance the security of power systems, this article [22] suggests a way to find out where the Thyristor Controlled Series Compensator and Static Synchronous Series Compensator should be placed. A line outage distribution factor and the actual power flow performance index sensitivity constitute the basis of the method. A modified 30 bus system is used to assess the effectiveness of the proposed controller using Power World Simulator Software Version 12.0. In order to improve system security, this [23] study proposes an optimization strategy that takes into account the best placement of the Unified Power Flow Controller. Using the sensitivity power flow index and the Genetic Algorithm (GA), the ideal placement during congestion has been identified. In [24] and sizing and optimal location of UPFC is carried through hybrid version of Genetic Algorithm and Firefly Algorithm. In [25] total system loss sensitivity indices and simulation results of power world simulator and power system analysis toolbox of MATLAB are used to identify the optimum location of STATCOM in 57 bus IEEE system after congestion. Many research were carried out for optimal location of FACTS device with numerous algorithms or methods. Mostly, Q-V curve analysis has been carried out for stability purpose. But, in this article, for finding optimal location of STATCOM, Q-V curve analysis in power world simulator software (PWS) is done. For validation of results, weak bus is identified through power system analysis toolbox (PSAT) of MATLAB. Western System Coordinating Council (WSCC) is taken as the test case. The system is modelled in Power World Simulator software (PWS) and Power System Analysis Toolbox (PSAT). To show the justification, contingency condition is created by one of the line outage in the system. As due to contingency, the network goes into over-loading condition and with this condition optimal location and weak bus has been traced with the proposed analysis.

2 Q-V Curve Analysis

An investigation of the relationship between reactive power injection and voltage at a bus is shown by a Q-V analysis. The reactive power injection may be tracked together with other system characteristics. The system's essential buses and the reactive power injections required at those buses to maintain voltage security are identified using Q-V curves. Most often, the Q-V curve approach is employed. It has several advantages over the P-V curve method, is less prone to convergence issues, and has a direct connection to shunt reactive compensation [6]. Q-V curve tool of Power World Simulator software is used for the analysis. A fictional generator (synchronous condenser) is installed at the bus under investigation in order to produce a Q-V curve. This generator's voltage set-point is adjustable, and its variable output can be any value as long as it achieves the voltage set-point. A Q-V curve shows the output of the fictional generator in MVAR on its vertical axis (y-axis). Under these circumstances, the corresponding voltage is shown horizontally (on the x-axis). An illustration of the system's baseline operating point is the x-intercept of the curve. The fictional generator is at 0 reactive power output at this stage, which represents the basic scenario. Moving from higher to lower voltage set-points causes the hypothetical generator's reactive power output to decline, which represents an increase in reactive load. The curve thus represents the voltage that would result from a rise in MVAR load. The bottom of the curve will eventually be reached when the generator's MVAR value stops lowering. The maximum load MVAR that may be added to this bus before voltage collapse occurs is shown by this point. An example of a typical QV curve is shown below in Figure 1. Despite being referred to as the QV curve, the graphic is actually a VQ curve.

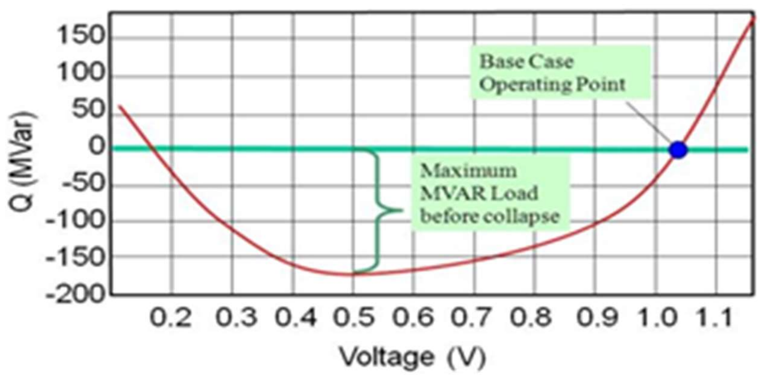


Figure 1. Q-V Curve.

3 Test Case

Western System Coordinating Council 9 bus network is considered here for the analysis which is shown in Figure 2. It consists of nine busses, three generators, three transformers, three busses and six lines.

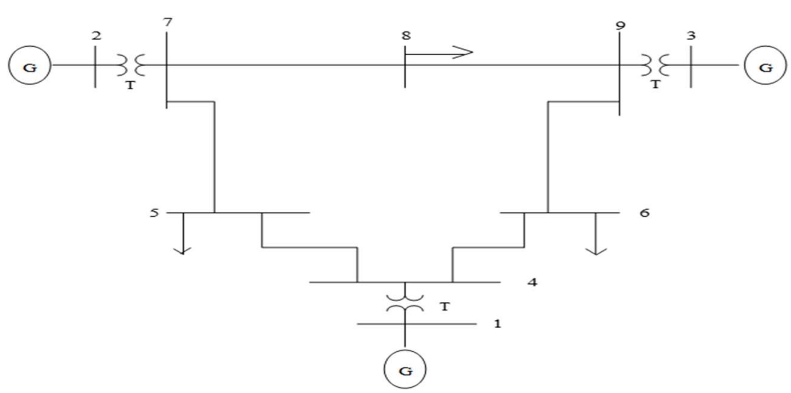


Figure 2. WSCC Test Network.

WSCC is modelled in power world simulator software and power system analysis toolbox of MATLAB as per standard referred data tabulated in Table 1 and 2.

Table 1. Bus, Load and Generator Data.

		Bus		Load		Generator	
Bus	Type of Bus	Voltage (pu)	Angle	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	Slack	1.040	0	-	-	-	-
2	PQ	1.025	0	-	-	163	-
3	PQ	1.025	0	-	-	85	-
4	PQ	1.000	0	-	-	-	-
5	PQ	1.000	0	125	50	-	-
6	PV	1.000	0	-	30	-	-
7	PQ	1.000	0	-	-	-	-
8	PV	1.000	0	100	35	-	-
9	PQ	1.000	0	-	-	-	-

Table 2. Line Data.

Bus No	Bus No	R (pu)	X (pu)	½ B (pu)	Transformer Tap
1	4	0	0.057	0	1
2	7	0	0.0625	0	1
3	9	0	0.0586	0	1
4	5	0.0100	0.0850	0.1760	1
4	6	0.0170	0.0120	0.1580	1
5	7	0.0320	0.1610	0.3060	1
6	9	0.0390	0.1700	0.3580	1
7	8	0.0085	0.0720	0.1490	1
8	9	0.0119	0.1008	0.2090	1

The base KV levels are 13.8 kV, 16.5 kV, 18 kV, and 230 kV. The line complex powers are around hundreds of MVA each. Figure 3 and 4 shows the modelled WSCC network of PWS and PSAT software.

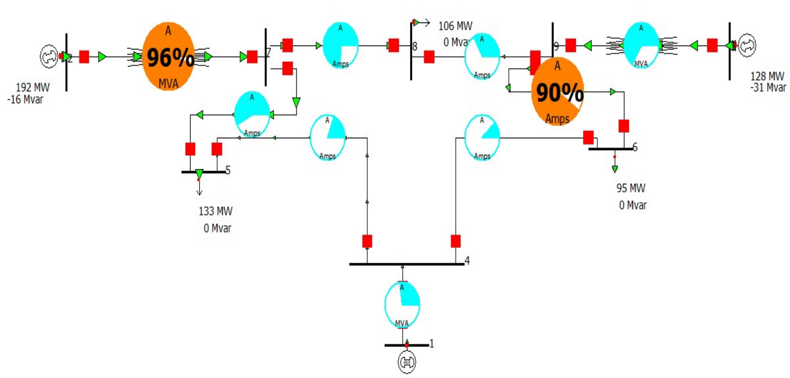


Figure 3. WSCC Network in PWS.

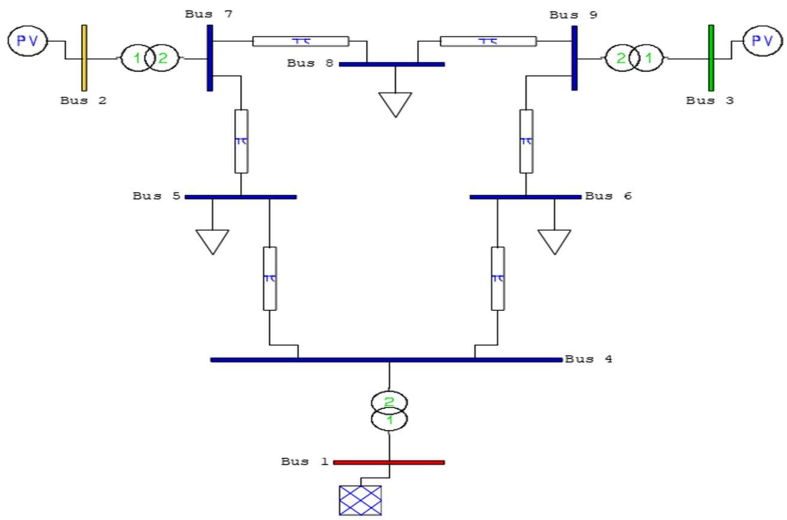


Figure 4. WSCC Network in PSAT.

4 Static Synchronous Compensator (STATCOM)

A Static synchronous compensator (STATCOM) can provide or take in reactive power more quickly than a spinning synchronous condenser since it doesn't have any moving parts. The STATCOM and similar systems can be modelled as a synchronous condenser with a rotating core. Given the following voltage source representation, the STATCOM power flow equations are given.

$$E_{vR} = V_{vR}\,(\cos\delta_{vR} + j\sin\delta_{vR}) \tag{1}$$

Based on shunt connection, apparent power can be represented as,

$$S_{vR} = V_{vR} I_{vR}^{*} \tag{2}$$

$$S_{vR} = V_{vR}\, Y_{vR}^{*}(V_{vR}^{*} - V_{k}^{*}) \tag{3}$$

STATCOM power equation are acquired for the converter are,

$$P_{vR} = V_{vR}^{2} G_{vR} + V_{vR} V_{k}\,[G_{vR}\,cos(\delta_{vR} - \theta_{k}) + B_{vR}\,sin(\delta_{vR} - \theta_{k})] \tag{4}$$

$$Q_{vR} = -V_{vR}^{2} B_{vR} + V_{vR} V_{k}\,[G_{vR}\,sin(\delta_{vR} - \theta_{k}) - B_{vR}\,cos(\delta_{vR} - \theta_{k})] \tag{5}$$

$$P_{k} = V_{k}^{2} G_{vR} + V_{k} V_{vR}\,[G_{vR}\cos(\theta_{k} - \delta_{vR}) + B_{vR}\sin(\theta_{k} - \delta_{vR})] \tag{6}$$

$$Q_{k} = -V_{k}^{2} B_{vR} + V_{k} V_{vR}\,[G_{vR}\sin(\theta_{k} - \delta_{vR}) - B_{vR}\cos(\theta_{k} - \delta_{vR})] \tag{7}$$

With above power equations, the linearized STATCOM can be modeled, where the voltage magnitude V_{vR} and phase angle δ_{vR} are taken to be the state variables.

5 Result and Discussions

Power World Simulator is an advanced power network simulation program software. In power world simulator software, contingency condition is created by opening line number 4-5 as an outage. As soon as there is an outage, the lines in the network become overloaded which shown in Figure 5 below.

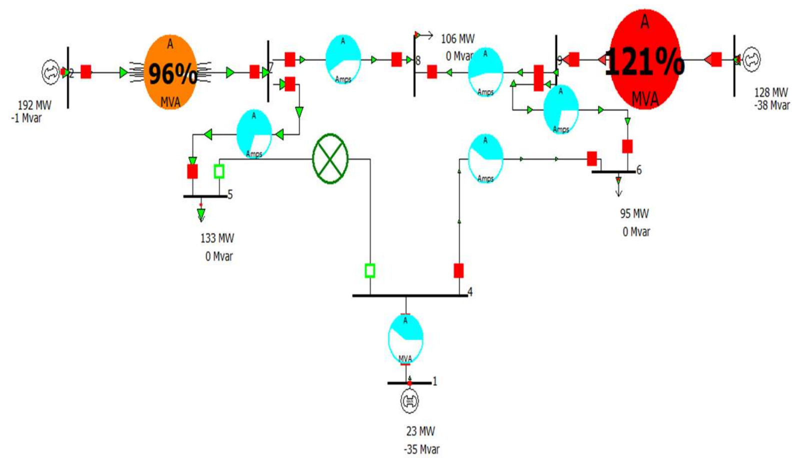
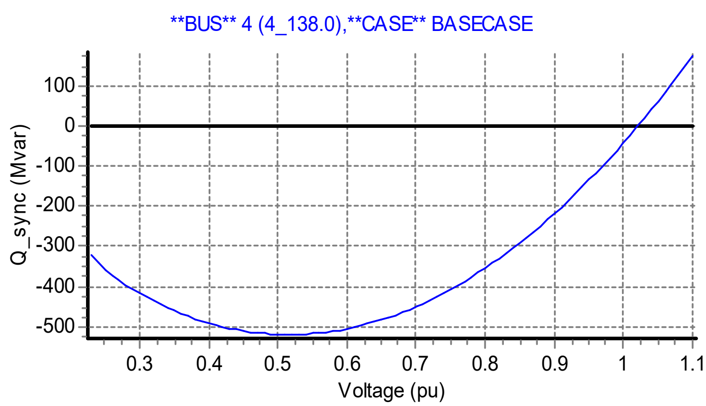
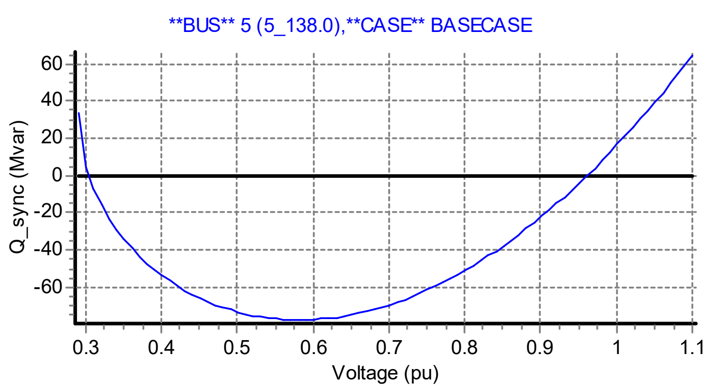


Figure 5. Line 4-5 Outage in WSCC network.

Q-V curves are plotted in the PWS software for bus number 4, 5, 6, 7, 8 and 9.





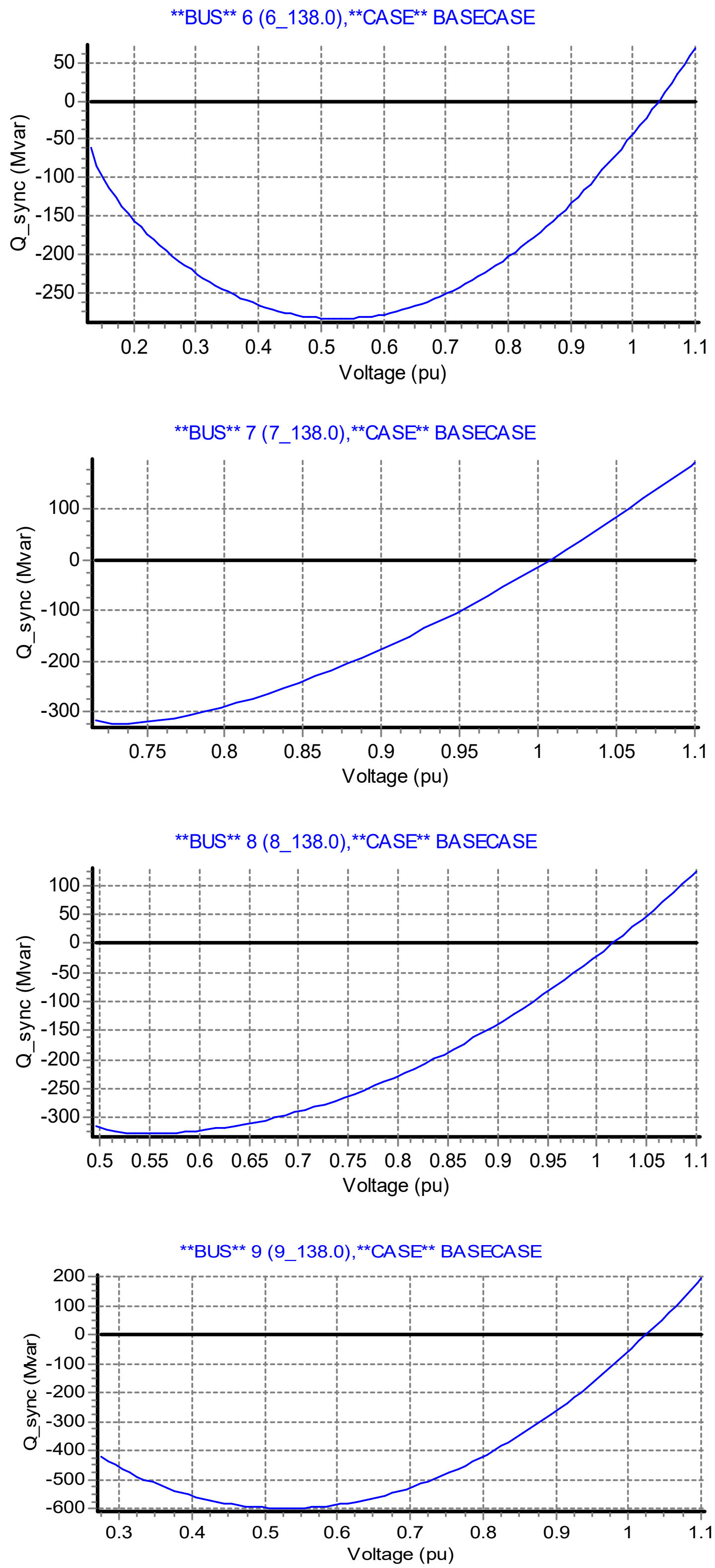


Figure 6. Q-V Curve without STATCOM.

This Q-V curve represents, reactive power (MVAR), critical voltage in per unit and base case voltage in per unit without STATCOM are noted in Table 3.

Table 3. Q-V Curve analysis without STATCOM.

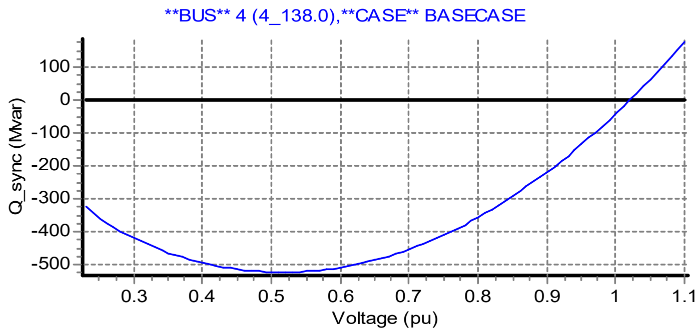
Bus	Qc (MVAR)	Vc (p.u)	V at Q_0 (p.u)
4	-520.96	0.5201	1.02
5	-77.57	0.5812	0.96
6	-283.65	0.5314	1.04
7	-323.61	0.7375	1.01
8	-327.29	0.5462	1.02
9	-599.65	0.5348	1.02

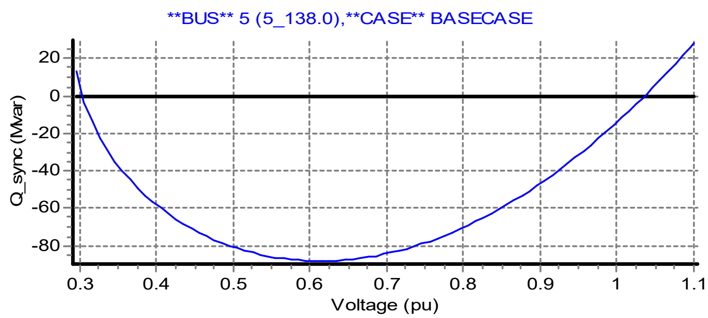
Qc is the maximum reactive MVAR reserve before the voltage collapse. From the Q-V analysis, the bus 5 having minimum Qc reserve, hence it is more prone to voltage collapse as compared to other in contingency condition, hence can be consider as weak bus. Thereof, the STATCOM is connected to the load bus number 5 in WSCC network in PWS software. STATCOM is a network-connected shunt FACTS device that regulates the amount of reactive power input and output to the power grid. Based on the results of the Q-V curve 5.
But for validation, the weak bus or optimum bus is identified through Power system Analysis toolbox (PSAT) software when line 4-5 is disconnected. Voltage magnitude of each bus after line outage of line 4-5 is shown in Table 4.

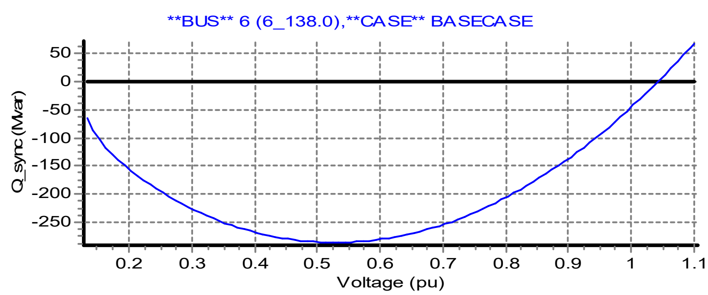
Table 4. Voltage magnitude after line outage (4-5) Without STATCOM.

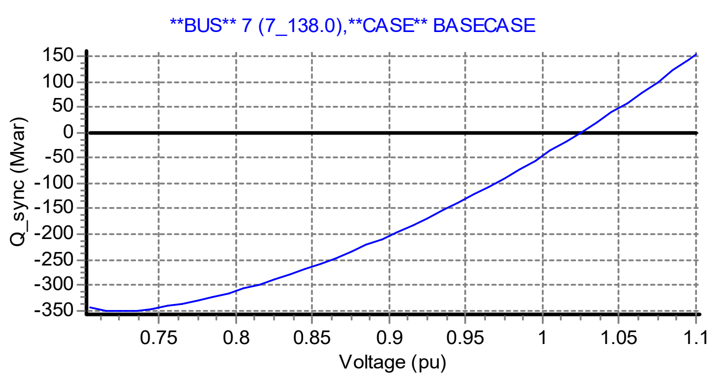
Bus	Voltage Magnitude
1	1.04
2	1.025
3	1.025
4	1.030
5	0.584
6	0.998
7	0.915
8	0.929
9	1.001

From Table 4, it is noticed that after outage of 4 to 5 line, bus 5 has the lowest voltage magnitude, which is more prone to voltage collapse. Hence bus 5 of 9 bus system can be considered as weak bus. In order to create a Q-V curve, a fictitious generator (STATCOM) is placed at the bus which is being analysed in power world simulator. Thereof, the STATCOM is connected to the load bus number 5 in WSCC network in power world simulator software. The Q-V curve are plotted for STATCOM connected network, shown in Figure 7.


BUS 4 (4_138.0),**CASE** BASECASE
Q_sync (Mvar)
100
0
-100
-200
-300
-400
-500
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage (pu)


BUS 5 (5_138.0),**CASE** BASECASE
Q_sync (Mvar)
20
0
-20
-40
-60
-80
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage (pu)


BUS 6 (6_138.0),**CASE** BASECASE
Q_sync (Mvar)
50
0
-50
-100
-150
-200
-250
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage (pu)


BUS 7 (7_138.0),**CASE** BASECASE
Q_sync (Mvar)
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
Voltage (pu)

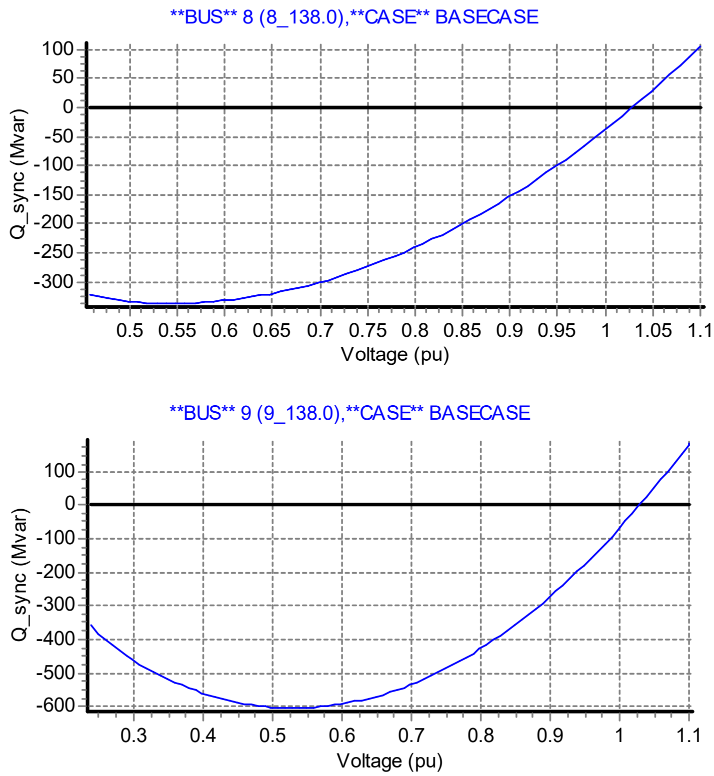


Figure 7. Q-V Curve with STATCOM.

Based on the Q-V curve of buses with STACOM, MVAR, critical voltage in per unit and base case voltage in per unit with STATCOM are noted.

Table 5. Q-V Curve analysis with STATCOM.

Bus	Qc (MVAR)	Vc (p.u)	V at Q0 (p.u)
4	-521.78	0.5209	1.02
5	-88.29	0.6155	1.04
6	-284.8	0.5335	1.04
7	-350.77	0.7251	1.03
8	-337.28	0.5483	1.03
9	-604.63	0.5289	1.03

From above table 5, it is observed that voltage profile is improved at Q0 with STATCOM at bus number 5. The implementation of a STATCOM at Bus 5 in the WSCC 9-bus system significantly enhances both reactive power support (Qc) and voltage stability, particularly under contingency scenarios. Before STATCOM installation, the Q-V curve analysis indicated that Bus 5 suffers from reactive power deficiency, with a steep negative slope in the Q-V characteristic near the operating point signifying proximity to voltage collapse. The reactive power demand at this bus could not be adequately met by nearby generators or the network itself, leading to a depressed voltage level. Upon placement of the STATCOM, simulation results show a marked improvement in reactive power support. The STATCOM injects reactive power dynamically as the bus voltage drops, effectively shifting the Q-V curve upwards. This leads to a flatter slope at the operating point, indicating improved voltage stability margin. The reactive power injected by the STATCOM (Qc) varies proportionally to system demand, showcasing its adaptive behavior and its ability to stabilize the local voltage in real time.
Voltage magnitudes across all buses were monitored with and without the STATCOM under both normal and contingency conditions. The voltage at Bus 5, which initially dropped below acceptable limits during

contingency, improved significantly with the STATCOM in place maintaining levels close to 1.0 p.u. This stabilization is due to the STATCOM's capability to inject or absorb reactive power based on real-time voltage deviations. In particular, during line outage scenarios, the STATCOM mitigates voltage dips at Bus 5 by supplying the required Qc, which reduces the stress on nearby generators and prevents further deterioration of the voltage and thus improves security of the network.

6 Conclusion

A Q-V curve analysis method is proposed here for finding optimal location of STATCOM in WSCC network for power network security. From Q-V curve the weak bus can be determined, whose voltage profile is poor and deficient in reactive power. The load bus with poor voltage profile is selected as the optimal location of STATCOM. This results are again validated with the help of weak bus identification in PSAT Software after contingency. From both verification, bus 5 is coming out to be weak bus for WSCC 9 bus system, and which is ideal for STATCOM location. With STATCOM at bus 5, it is seen that the voltage profile has enhanced significantly and thus maintain the security of the network during contingency condition.

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