Voltage Instability and Possible Countermeasures

Sanjib Kumar Nandi[1], Abu Hena Md. Shatil[2]

Electrical & Electronic Engineering, American International University-Bangladesh
, Bangladesh

sanjib.eee.aiub@gmail.com

[1]Electrical & Electronic Engineering, American International University-Bangladesh
, Bangladesh

[2]Electrical & Electronic Engineering, American International University-Bangladesh
, Bangladesh

**American International University-Bangladesh, Dhaka, Bangladesh*
Email address: sanjib.eee.aiub@gmail.com, abu.shatil@aiub.edu

Abstract— **Voltage stability analysis is the major concern in order to operate any power system as secured. Voltage Stability of Electric Power Systems presents a clear description of voltage instability and collapse phenomena. Voltage instability refers to a system's inability to maintain steady operating condition. It proposes a uniform and coherent theoretical framework for analysis and covers state-of-the-art methods. In this context there are many research work has been carried out to improve the voltage stability. The paper describes practical methods that can be used for voltage security assessment and offers a variety of examples. This paper briefly described about the phenomenon of voltage instability and different types of voltage instability have been discussed as well. Voltage instability occurs for a number of reasons. The reasons as valuable parts of voltage instability analysis have focused here. The impact of the factors associated with voltage instability is another focal point on this research. The paper also presents the description of Static Var Compensator (SVC) against voltage instability and the investigation on enhancement of voltage stability and performed MATLAB analysis of a popular counter-measure which uses SVC were presented. MATLAB is used as the simulation tool in the venture. Then, this study is being compared and demonstrated with the use of Simulink and the latest Power System Analysis Toolbox (PSAT) package for network analysis of alternative means of improving existing power transmission system voltage stability. The proposed method explains how voltage stability can be improved with the continuation power flow methods in case of increasing loading of contingency. The propose methodology found advantages because it is simple, faster and very convenient to apply for voltage stability analysis**

Keywords— **Voltage instability, Load flow analysis, Countermeasure, Static var compensator (SVC), Voltage Stability margin**

I. INTRODUCTION

In recent years greater demands have placed on the transmission network, with this increased demands on transmission lines, hence it is the responsibility of the power suppliers to supply safe and economical electric power to customers with the existing transmission line efficiently. "Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance"[1]. In power system environment voltage instability plays major role, it is integral part of the power system stability. In general Voltage instability occurs more frequently in a heavily loaded system. The change in voltage is directly proportional to change in load and hence voltage stability is sometimes termed as load stability. Instability and collapse cannot be separated from the general problem of system stability. The reactive power compensation close to the load centres as well as at critical buses in the network is essential for overcoming voltage instability. The location, size and speed of control have to be selected properly to have maximum benefits. The SVC provides fast control and helps improve system stability.

II. VOLTAGE INSTABILITY PHENOMENON IN POWER SYSTEM

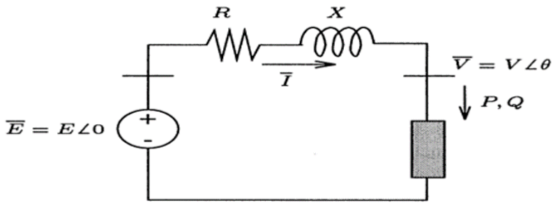

Fig. 1: Circuit representation of simple infinite BUS system [2]

One of the primary causes of power system instability is the transmission of (large amounts of) power over long electrical distances. In voltage stability, attention is paid to power transfers between generation and load centres. Let us first recall some fundamentals of the power transfer between a generator and a load. We use the simple model of Fig. 1, in which we consider for simplicity a purely reactive transmission impedance jX and we assume that the synchronous generator behaves as a constant voltage source of magnitude E .

Under balanced three-phase, steady-state sinusoidal conditions, system operation is described by the power flow or load flow equation

$$P = -\frac{EV}{X}\sin\theta \qquad (1)$$

$$Q = -\frac{V^2}{X} + \frac{EV}{X}\cos\theta \qquad (2)$$

where P (respectively Q) is the active (respectively reactive) power consumed by the load, V the load bus voltage magnitude, and d the phase angle difference between the load and the generator buses (see Fig. l). Solving (l), (2) with respect to V yields

$$V = \sqrt{\{\frac{E^2}{2} - QX \pm \sqrt{(\frac{E^4}{4} - X^2P^2 - XE^2Q)\}}}$$

Fig. 2 shows how the terminal voltage V changes with the load powers P, Q (dimensionless variables are used in the figure). In "normal" conditions, the operating point lies on the upper part of the surface (corresponding to the solution with the plus sign in (3), with I close to E . Permanent operation on the lower surface, characterized by a lower voltage and higher current, is unacceptable. The figure also confirms the existence of a maximum load power, well-known from circuit theory . More precisely, the figure shows a set of maximum load power points, located on the "equator" of the surface (where the two solutions in (3) coalesce, i.e., the inner square root vanishes). The projection of this limit curve onto the (P, V) plane is the parabola shown in Fig. 2. in the (P, V) load power space, this parabola bounds the region where operation is feasible.

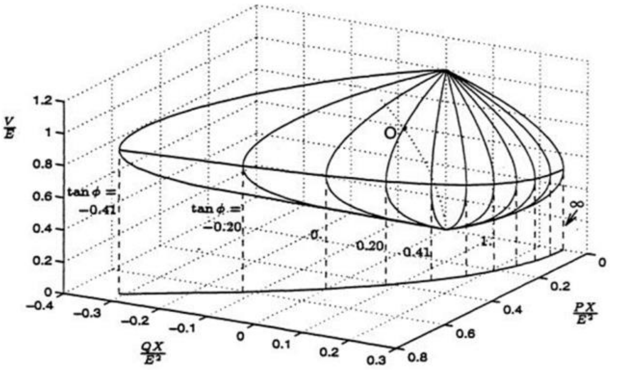

Fig. 2: Voltage as a function of load active and reactive powers [2]

In many reasoning (and industry practice) it is common to consider the curves which relate voltage to (active or re-active) power. Such curves, referred to as PV (or QV) curves or nose curves are shown in Fig. 3, for our simple system. The curves depend on how Q varies with P; in Fig. 3, a constant power factor, i.e., $Q = \tan \varnothing P$, has been assumed for each curve. This also corresponds to the solid lines in Fig. 2. Similarly, one may consider PV curves under constant Q, or QV curves under either constant power factor or constant P. Simply stated, voltage instability results from the attempt to operate beyond maximum load power. This may result from a severe load increase or, more realistically, from a large disturbance that increases X and/or decreases .E to the ex-tent that the pre-disturbance load demand can no longer be satisfied.

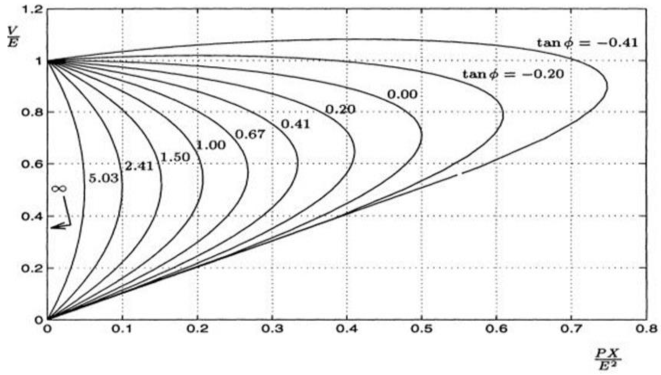

Fig. 3: Normalized PV-curves for different power factor [2]

III. LOAD FLOW ANALYSIS AND TEST RESULTS OF VOLTAGE INSTABILITY

A. IEEE 14 BUS system

For the purpose of the thesis, an IEEE-14 bus system is used. A single line diagram of the IEEE 14-bus standard system is shown in Figure 4. It consists of five synchronous machines with IEEE type-1 exciters, three of which are synchronous compensators used only for reactive power support. There are 11 loads in the system totalling 259 MW and 81.3 MVar.

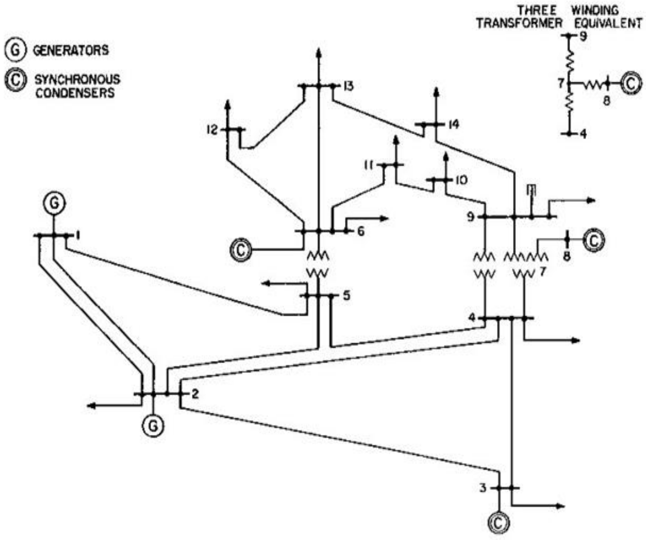

Fig. 4: IEEE 14 BUS system [3]

B. *Load flow results for IEEE 14 BUS using MATLAB*

TABLE 1
NEWTON RAPHSON LOAD FLOW ANALYSIS

Bus No.	V (pu)	Angle (Degree)	Injection		Generation		Load	
			MW	MVar	MW	MVar	MW	MVar
1	1.06	0.0	232	-15	232	-15.2	0.0	0.0
2	1.05	-4.9881	18.3	35.2	40.0	47.92	21.7	12.7
3	1.01	-12.749	-94.2	8.7	0.0	27.75	94.2	19.0
4	1.02	-10.242	-47.8	3.9	0.0	0.0	47.8	-3.9
5	1.02	-8.7601	-7.60	-1.6	0.0	0.0	7.6	1.6
6	1.07	-14.446	-11.2	15.5	0.0	23.0	11.2	7.5
7	1.05	-13.236	0.00	0.0	0.0	0.0	0.0	0.0
8	1.08	-13.236	0.00	21.0	0.0	21.0	0.0	0.0
9	1.03	-14.820	-29.5	-17	0.0	0.0	29.5	16.6
10	1.03	-15.036	-9.00	-5.8	0.0	0.0	9.0	5.8
11	1.05	-14.858	-3.50	-1.8	0.0	0.0	3.5	1.8
12	1.05	-15.297	-6.10	-1.6	0.0	0.0	6.1	1.6
13	1.05	-15.331	-13.5	-5.8	0.0	0.0	13.5	5.8
14	1.02	-16.071	-14.9	-5.0	0.0	0.0	14.9	5.0
Total			13.6	31.0	272	104.5	259	73.5

TABLE 2
LINE FLOW AND LOSSES

From Bus	To Bus	P MW	Q MVar	From Bus	To Bus	P MW	Q MVar	Line Loss MW	Line Loss MVar
1	2	157.08	-17	2	1	-153	30.7	4.3	13.2
1	5	75.5	8.0	5	1	-73	3.5	2.8	11.5
2	3	73.4	6.0	3	2	-71	3.9	2.3	9.8
2	4	55.9	3.0	4	2	-54	2.1	1.7	5.1
2	5	41.7	4.7	5	2	-41	-1.9	0.9	2.8
3	4	-23	7.7	4	3	24	-6.8	0.4	1.0
4	5	-60	12	5	4	60	-10	0.5	1.5
4	7	27.0	-15	7	4	-27	17	0.0	2.0
4	9	15.5	-2.6	9	4	-15	3.9	0.0	1.3
5	16	45.9	-21	16	5	-46	27	0.0	5.8
6	11	8.3	8.9	11	6	-8	-8.6	0.1	0.3
6	12	8.0	3.1	12	6	-8	-3.0	0.1	0.2
6	13	18.3	10	13	6	-18	-9.5	0.3	0.5
7	8	0.0	-20	8	7	0.0	21	0.0	0.7
7	9	27.0	15	9	7	-27	-14	0.0	1.0
9	10	4.4	-0.9	10	9	-4.4	0.9	0.01	0.01
9	14	8.6	0.3	14	9	-8.5	-0.1	0.08	0.2
10	11	-4.6	-6.7	11	10	4.7	6.9	0.1	0.1
12	13	1.9	1.4	13	12	-1.9	-1.4	0.01	0.01
13	14	6.5	5.1	14	13	-6.3	-4.9	0.10	0.22
Total Loss		13.593	56.91						

From the above data analysis we observe that every bus has its own load capability. When we increase the individual load of every bus by 0.1 MW then some bus shows real collapse phenomena. Only 3 buses showed some voltage decrease picture which we can observe by graphical representation using MATLAB.

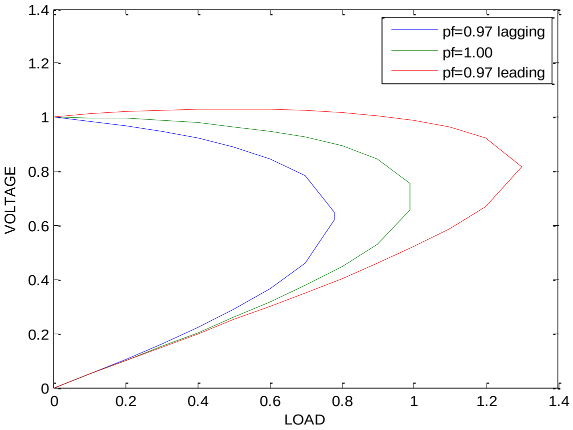

Fig. 5: Load vs. Voltage Curve

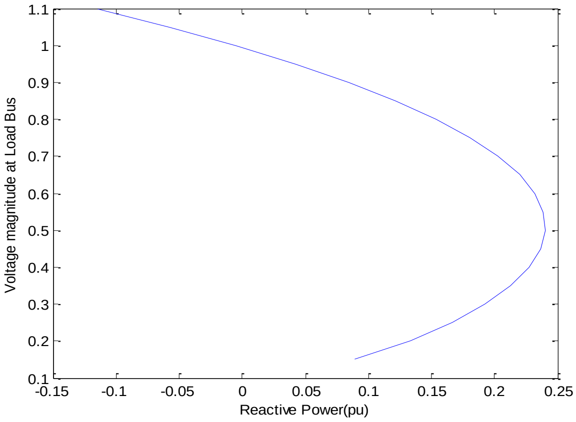

Fig. 6: Reactive Power versus Load Curve

C. *The power loss in the transmission line*

To deliver electric power to the user, a transmission line is needed. The power loss is due to the resistor from the transmission line. The Power of the transmission line is, P=IV It can be re-write as $P=I_R*(I_RR)$ $=I^2_RR$, Or, $P=IV=(V_R/R)*V_R=V^2_R/R$

However, we need to use the voltage across the resistor V_R or the current flow through the resistor I_R. For calculating the power loss of the transmission line with, then the voltage should be the voltage from the transmission line (not the total voltage). It is not the same as the voltage from the power plant. When, the source voltage is V, the resistor of the transmission line is r, and the resistor of the transformer is R. So the voltage on the transmission line is,

$$V_t= V*(r/(r+R))$$

For the transmission line, the resistor from the transformer will change according to voltage ratio between transformers. It is not a constant so a simulation was created to help for a better understanding of it. The power loss can be calculated from $P_{loss}=I_rV_r=I^2_r*r$ and the power delivered $P=I_rV$. So, power loss in the transmission line,

$$P_{loss}=I^2_r*r=(P/V)^2*r=(P^2/V^2)*r$$

And the percentage of power loss can be calculated as,

$P_{loss}/P=(P/V^2)*r$, which is inverse proportional to V^2

IV. SOLUTION OF VOLTAGE INSTABILITY USING SVC

The Static VAR Compensator (SVC) is composed of the capacitor banks/filter banks and air-core reactors connected in parallel. The air-core reactors are series connected to thyristor. The current of air-core reactors can be controlled by adjusting the fire angle of thyristor. [4] The SVC can be considered as a dynamic reactive power source. It can supply capacitive reactive power to the grid or consume the spare inductive reactive power from the grid. Normally, the system can absorb the reactive power from a capacitor bank, and the spare part can be consumed by an air-core shunt reactor. [4]

As mentioned, the current in the air-core reactor is controlled by a thyristor valve. The valve controls the fundamental current by changing the fire angle, ensuring the voltage can be limited to an acceptable range at the injected node(for power system VAR compensation), or the sum of reactive power at the injected node is zero which means the power factor is equal to 1. Current harmonics are inevitable during the operation of thyristor controlled rectifiers, thus it is essential to have filters in a SVC system to eliminate the harmonics. The filter banks can not only absorb the risk harmonics, but also produce the capacitive reactive power. The SVC uses closed loop control system to regulate bus bar voltage, reactive power exchange, power factor and three phase voltage balance.

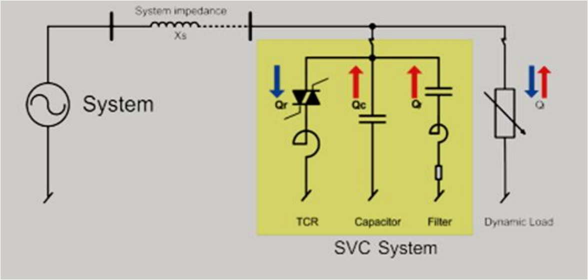

Fig. 7: SVC connected system [5]

V. SIMULATION AND RESULTS

A. *Voltage stability margin using SVC in math lab:*

SVC is used as a sample countermeasure against voltage instability. The scenario of different buses connected with SVC is given below at unstable condition: To deliver electric power to the user, a transmission line is needed. The power loss is due to the resistor from the transmission line.

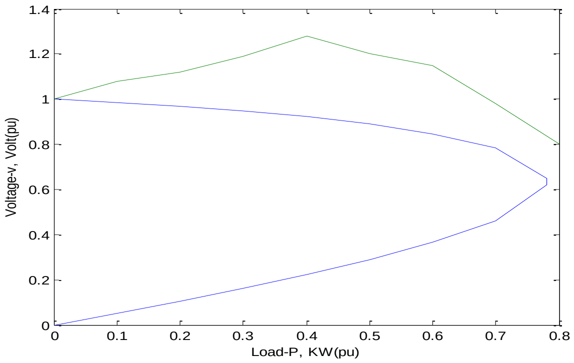

Fig. 8: Voltage stability margin increase using SVC at Bus 3

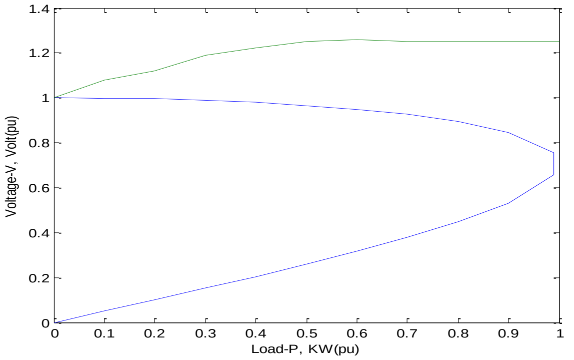

Fig. 9: Voltage stability margin increase using SVC at Bus 5

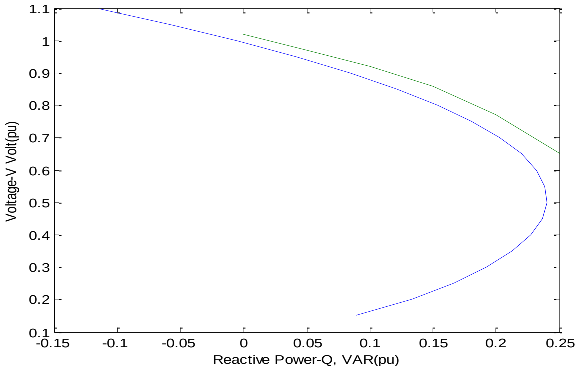

Fig. 10: Voltage stability margin increase using SVC at Bus 7

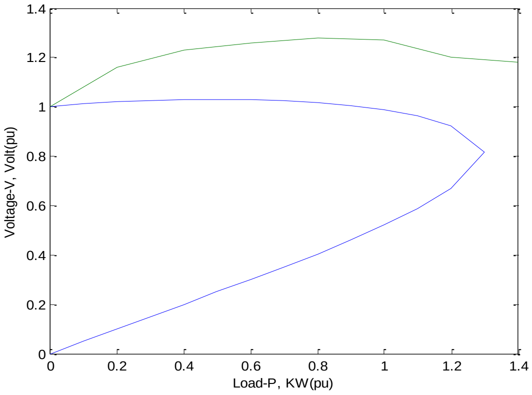

Fig. 11: Voltage stability margin increase using SVC at Bus 8

B. *With Simulink & PSAT toolbox:*

Voltage stability assessment on standard IEEE-14 bus system has been simulated to test the effectiveness of increasing load ability. This section illustrates PSAT features for steady state analysis by means of IEEE-6 bus test system. Fig. 11 depicts the model of the IEEE 14-bus network built using the PSAT Simulink library. Once defined in the Simulink model, one can load the network in PSAT and solve the power flow. PSAT also allows displaying bus voltages and power flows in Simulink library for different load levels within Simulink model loaded into the system.

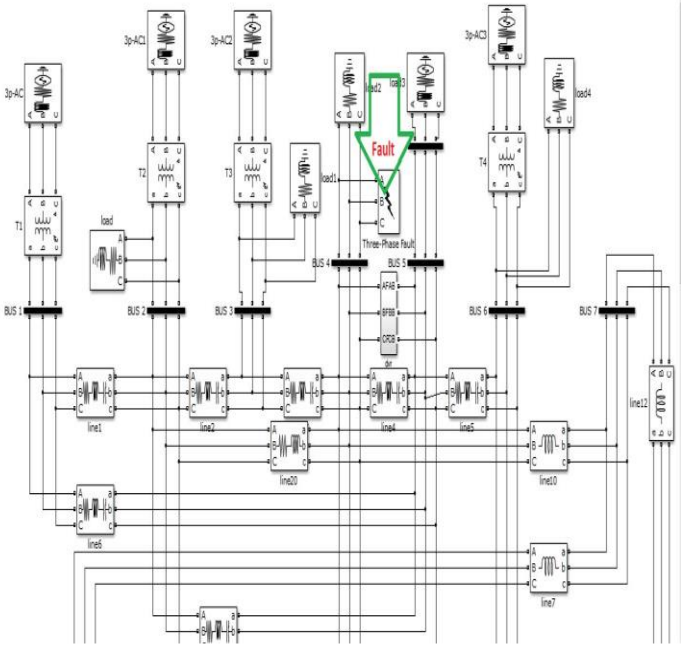

Fig. 12: IEEE 14 bus with fault

System Details

IEEE- 6 Bus System Data
MVA Base=100 MVA
System Frequency = 50 Hz
Bus Nominal Voltage =11KV
Bus Maximum Voltage = 11.5 KV
Bus Minimum Voltage = 10.4 KV

TABLE III
LINE DATA

Line	**Bus**	**Positive Sequence**	**Positive Sequence**
No.	**Code**	**Resistance, p.u**	**Reactance, p.u**
1	**p-q**	0.05	0.20
2	1-2	0.10	0.50
3	2-3	0.20	0.80
4	3-4	0.10	0.30
5	4-5	0.20	0.40
6	5-6	0.10	0.15
7	6-1	0.20	0.50

TABLE IV
BUS VOLTAGE MAGNITUDE

Bus No.	Bus voltages(p.u)				Phase angles (rad)			
	Load level(p.u)				Load level(p.u)			
	0.6	0.8	1	1.2	0.6	0.8	1	1.2
1	1	1	1	1	0	0	0	0
2	1.04	1.04	1.04	1.04	-0.034	-.058	-.063	-.063
3	1.02	1.02	1.02	1.02	-.003	-.025	-.038	-.038
4	1.07	1.07	1.07	1.07	-.059	-.091	-.108	-.108
5	1.02	.998	.991	.991	-.073	-.106	-.123	-.123
6	0.981	0.969	0.963	0.963	-.036	-.053	-.058	-.058

A simple method for identifying the weak bus and also optimal value of reactive power support was established. A comparative study between the base case and SVC with the help of Simulink and PSAT toolbox is presented to demonstrate the effectiveness of SVC. The faults at different Bus and the removal of the fault after using SVC were shown in the simulation results below:

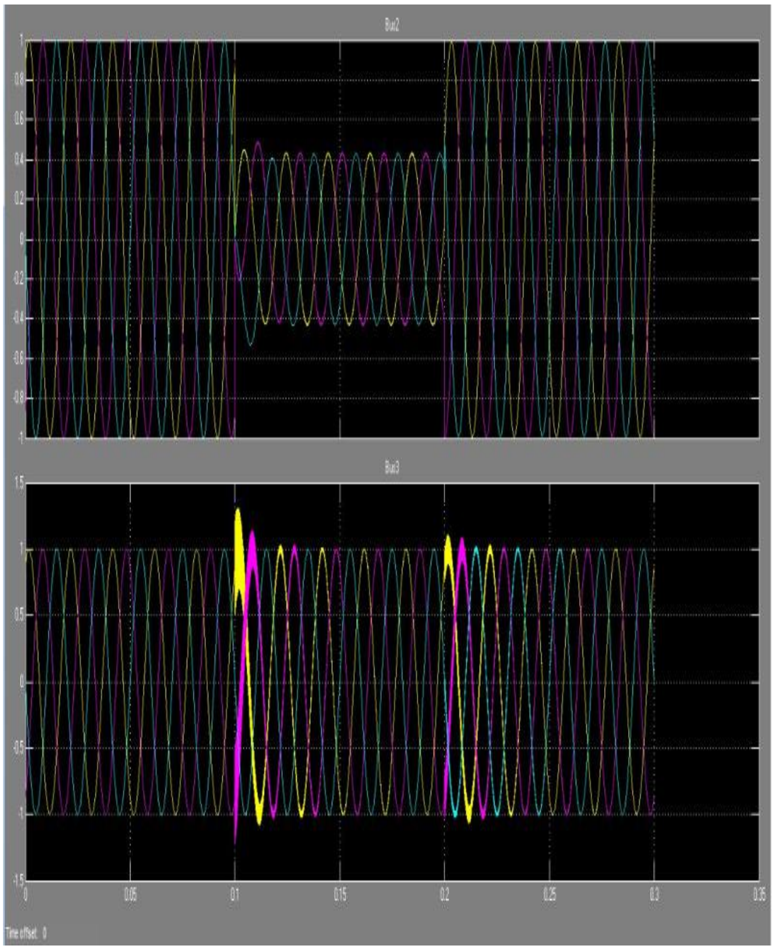

Fig. 13: Faults at bus 2 and after using SVC at bus 3, fault has removed

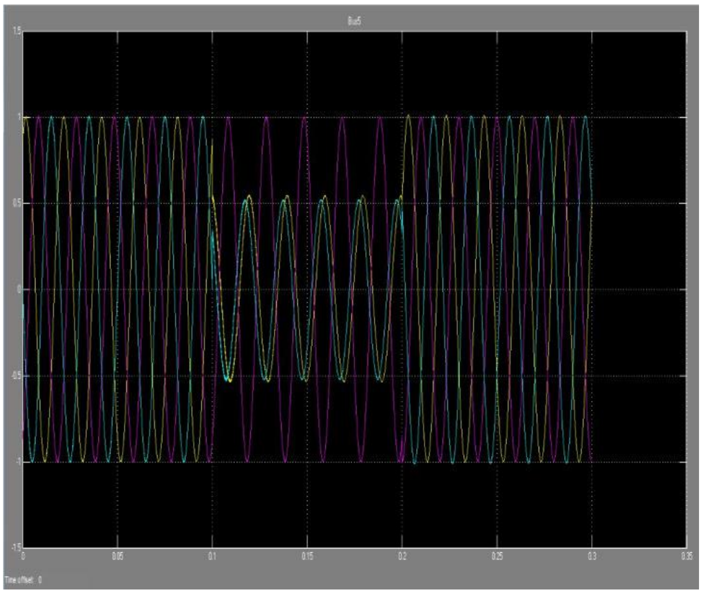

Fig. 14: Fault at bus 5

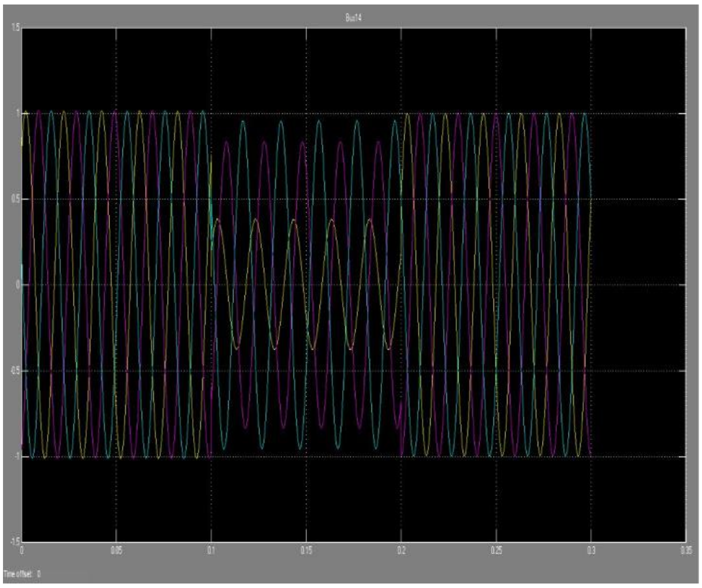

Fig. 15: Fault at bus 14, so the waveform changed

VI. CONCLUSION & FUTURE WORK

The scope of work in this field is so vast that the attempt to analyse and counter the phenomenon of voltage instability is quite incomplete. Because of voltage fluctuation, we will have instability in both areas like transmission and distribution. A huge amount of time and funding is required for further work on this matter. Still, there are a few things that beg attention from this study. Math lab is used exclusively for the working purposes and then with the help of Simulink and the PSAT toolbox a comparative study between the base case and SVC has been illustrated. There are few others simulation software that deal with voltage instability like Power world Simulator, Multisim etc. Given more time, the same simulations can be run through different software to see what has done here. The similarities and the differences (if any) between the simulation of different software could be noted. All the work is on IEEE-14 bus system. It's a great system for beginner analysis but given more time a system with more bus number would be great fit to analyse. The difference between different bus systems can be the highlight. It has been tried to prevent voltage collapse by using Static VAR Compensator. But it's not the only way to solve it. Different counter-measures can be applied to see their results and then they can be compared to see which ones are the most effective. Short-term voltage instability/fast voltage collapse or unacceptability slow voltage recovery is a growing industry problem. The problem is described in detail and performed load flow analysis for IEEE-14 bus. Based on the simulations, it can safely say that using Static VAR Compensator (SVC) is a good countermeasure against voltage instability. Other counter-measures have been discussed as well.

REFERENCES

[1] Prabha Kundur, " Power System Stability and Control ", McGraw- Hill
[2] T.Van Custem and C. Voumas, "Voltage Stability of Electric Power System".
[3] "Power system test case archive", available at: http://www.ee.washington.edu/research/pstca
[4] Edvard – Electrical engineer, programmer and founder of EEP, ' What is the Static Var Compensator (SVC)?' available at: http://electrical-engineering-portal.com/what-is-the-static-var-compensator-svc
[5] " SVC static var compensator: insurance for improved grid system stability and reliability " available at :http://www05.abb.com/global/scot/scot221.nsfverity display.pdf
[6] Leif Warland, "A voltage instability predictor using local area measurements VIP++ ''.
[7] R.J. Koessler, "Dynamic Simulation of SVC in Distribution Systems," IEEE Trans. On Power Systems, Vol. 7, No. 3, pp. 1285-1291, August, 1992.
[8] B. Gao, G.K. Morison and P. Kundur, "Towards the development of a systematic approach for voltage stability assessment of large-scale Power Systems," IEEE Trans. Power Syst., Vol. 11, No. 3, pp. 1314-1324, Aug. 1996
[9] T. Nagao, K. Tanaka and K. Takenaka, "Development of static and simulation programs for voltage stability studies of bulk power system," IEEE Trans. Power Syst., Vol. 12, No. 1, pp. 273-281, Feb. 1997.
[10] A. Sode-Yome, N. Mithulananthan, and Kwang Y. Lee, "A Maximum Loading Margin Method for Voltage Stability in Power Systems," IEEE Transaction on Power Systems, to be published.
[11] IEEE/PES Power System Stability Subcommittee, Voltage Stability Assessment: Concepts, Practices and Tools, special publication, final draft, Aug. 2003.
[12] IEEE Std 1031-2000 "IEEE Guide for the Functional Specification of Transmission Static Var Compensator.
[13] H. B. Nagesh and P. S. Puttaswamy, "POWER FLOW MODEL OF STATIC VAR COMPENSATOR AND ENHANCEMENT OF VOLTAGE STABILITY", International Journal of Advances in Engineering & Technology, May 2012.©IJAET ISSN: 2231-1963499 Vol. 3, Issue 2, pp. 499-507
[14] Bhakti Nitve, Rajani Naik, "Steady state analysis of IEEE-6 Bus System Using PSAT power toolbox" ISSN: 2319-5967, ISO 9001:2008 Certified International Journal of Engineering Science and Innovative Technology (IJESIT) Volume 3, Issue 3, May 2014