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Voltage Stability Improvement by Optimal Allocation of STATCOM

Shubham Sharma, Ajay Bhardwaj, Dr. Sarfaraz Nawaz
Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur
8949222980and sharmamani912@gmail.com, Sarfaraz@skit.ac.in

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Abstract

Need for reliability, precision and rapid response is growing everyday in the current deregulated structure of power system. Voltage instability is a threat to security and reliability of the electrical power network. Hence, Flexible AC Transmission System (FACTS) devices are used to restore and regulate voltage at weak buses. One of these devices, Static Synchronous Compensator (STATCOM) provides fast acting dynamic compensation in case of severe fault. In this paper, voltage stability improvement by minimization of voltage deviation of an IEEE-14 bus testing system is presented. For this purpose, Specific indices can be used to identify the system's weakest bus. Different indices like Simplified voltage stability index (SVSI), FVSI (Fast Voltage Stability Index) and L-Index are considered in this paper. PSCAD software has been used for simulation of the test system using STATCOM

Keywords: *Voltage Stability Index, STATCOM(Static Synchronous Compensator, SVSI(Simplified Voltage Stability Index), RED(Relative Electrical Distance)L-Index, FVSI(Fast Voltage Stability Index).*

I. INTRODUCTION

Voltage instability has become an universal phenomenon that causes the biggest blackouts of world [1]. From 1965 to 2005, twelve blackouts were observed which shows that voltage instability is significant phenomena in current situation [2]. The term voltage failure/collapse has come into picture since then. The cycle of voltage failure events gets losses in a essential part of the power network due to the sequence of voltage instability occurrenceThe causes of a voltage collapse are high load and reactive power losses. [3]. The collapse of voltage occurs on the maximum load level of the total system blackout [4]. In these conditions, reactive power reserves are required for safe operation of the power system [5]. In all contingencies, system must remain stable. The stability of voltage can be maintained via FACTS devices. FACTS devices are rectifying power compensator that can produce and absorb reactive power. These devices can adjust impedance, voltage range and phase angle, this will minimize the losses in heavy load condition, improve reliability and protection of power system in emergency situation [6]-[7]. SVC (Static Var Compensators) and STATCOM (Static Synchronous Compensators) can be used to improve the stability of voltage.

The IEEE Power Engineering Committee described the definition of voltage stability is as follows: a device has the capacity to retain voltage level under increased loading condition that will ensure the low voltage regulation [8].Voltage instability is being affected by reactive sources failure and failure of power lines to deliver the specific amount of reactive power which is needed in system [9].

We need to take some corrective measures for avoidance of voltage instability. Here are the main points. [10]:-

1. At the power system planning point we need to improve weak buses and lines by DG (distributed generation).
2. Switching of shunt capacitor and shedding of loads.
3. The voltage stability margin (VSM) of FACTS needs to be extended.
4. Blocking of tap changers.

The identification of weak transmission lines and buses in power systems is one the main applications of the voltage stability indices. [11-15]. The VSIs are used in this case in both online and offline mode, and the relevant data is extracted from the static analysis or PMUs. Therefore the line or bus nearest to the critical value is chosen as the weakest line and bus. Different VSI methods for DG positioning and size calculation, capacitor allocation and power planning are used in different situations. [16-20].

II. PROBLEM FORMULATION

Instability in voltage has a very untoward effect on reliability of electric power system. This paper's primary objective is to eliminate the problem of voltage deviation V_D in the system. The voltage difference is as small as possible in the load bus for voltage increment.The objective function of minimization of V_D at load bus is defined as:

$$V_D = \min \left(\sum_{1}^{n} |V_n - V_{refn}|\right)$$

Where

V_D is the voltage deviation
n is the number of buses
V_n is the voltage of nth bus
V_{refn} Reference voltage at nth Bus, basically it is set at 1

Voltage improvement at load buses is the primary objective, which can be established by optimal allocation of STATCOM at weak bus. The STATCOM Controlling System can be planned, calibrated and optimally configured for analysis under both stable and dynamic system environments.

III. VOLTAGE STABILITY INDICES (VSI)

In order to estimate the stability limit, indices of voltage stability are implemented. These are essential instruments to calculate closeness of a certain voltage instability operating stage. The voltage breakdown has been seen under crucial load demand in various industrial areas of the distribution network. Real occurrence of these phenomena was reported in [21], this is only occurs in that device where voltages collapsed periodically, and a reactive compensation of rapid reaction was needed to avoid the repetition of voltage collapse [22]. The primary purpose of voltage stability indices is to calculate, how much steady state stability margin is near with particular point. The indices of voltage stability are used to maximize the prevention of voltage collapse possibilities [23]. Elements like reactive power-generation systems, tap-changing transformers are modified optimally at each stage by which, the voltage stability index as well as the global voltage stability indices of each bus will minimize. By minimization of Index of Voltage stability power system will be perform in a stable stage.

This strategy used an index of voltage stability, dependent on the power flow equation solution [24]. Assumptions are made in this approach based on the model of thevenin as shown in figure 1.

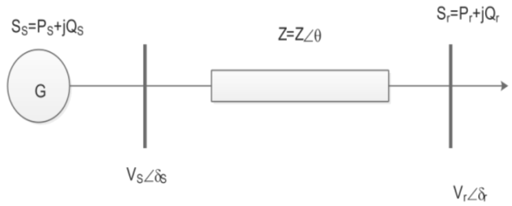

Figure 1.Power system presentation by thevenin equivalent

The amplitude of the load bus voltage is the voltage decrease in the impedance of thevenin (Z). (a) The separation to a generator is the total sum of the absolute voltage drop for each line across the small range from node to generator; (B) When certain generators have exactly the same size; it is possible to take one of them as nearest as possible.

A matrix can be described by an iterative algorithm, which will help to figure out the nearest generator bus n. Drawbacks of this approach are as follows: (1) Due to large number of iterations, it has high computational cost (2) The tree matrix which has difficulties in the wide power system must be determined for any topological change in perspective of the range of the generator's limits.

A. *FAST VOLTAGE STABILITY INDEX (FVSI)*

Musirin et al proposed a line stability index name as FVSI, the main base of this index is single line power flow [25]. The mathematical formulations of FVSI are as follows:-

$$FVSI_{ij} = \frac{4Z_{ij}^2\ Q_j}{V_i^2 X_{ij}}$$

Where

Z = line Impedance
X_{ij} = Reactance of line
Q_j= Receiving end Reactive Power
V_i = Voltage of Sending End

The value of FVSI for a line is close to 1 that is tends towards its point of instability. When the FVSI reaches 1.00, one of the attached buses will unexpectedly experience a voltage drop that will lead to a system failure. The bus which takes smallest maximum load is the weakest bus [11].

These are the steps to improve the maximum load capacity to identify the weakest bus:-

Step 1: The base case power flow program is implemented using Newton Raphson iterative techniques.
Step 2: For every line in system, measure the value of FVSI.
Step 3: The reactive loading by 5MVar varies slowly in a certain charging bus until the flow power solution differ for the maximal FVSI estimation.

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Step 4: Choose the maximum stability index value.
Step 5: For a particular bus load, repeat steps three and four.
Step 6: Extract the highest reactive power loading for every load bus, for the higher value of FVSI..
Step 7: Arrange the maximal loadability achieved in ascending order in step 6. The bus is marked as the weakest bus which is ranked as a smallest maximum loadability at higher order.

B. SIMPLIFIED VOLTAGE STABILITY INDEX

Perez-Londono et al. suggested SVSI based on the definition for VSLBI. The SVSI (Simplified Voltage Stability Index) is an enhanced voltage stability index preferable for the evaluation of power system voltage stability. This index is explained by the relative electrical distance (RED), this is why, it is include to identifying the generator which is closest to a particular load bus and also for the variation in electrical variables, in order to improve its output.

1. *RELATIVE ELECTRICAL DISTANCE(RED)*

The RED principle is based on the relative distances theory of the generator from the load bus in a network. It is also preferable that the next generator mostly follows a load but holds all limitations as far as possible.

For a certain method, as shown in the admittance matrix, the relation of a generator bus (G) to a load bus (L) between a complex current (I) and voltage vectors (V) is as described:

$$\begin{bmatrix} I_G \\ \mathrm{I_L} \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} \mathrm{V_G} \\ \mathrm{V_L} \end{bmatrix} \quad (1)$$

Where

I_G = the current injected of generator Buses
I_L = the current injected of Load Buses
V_G = complex bus voltages of generator
V_L= complex bus voltage of Load

$[Y_{GG}]$,$[Y_{GL}]$,$[Y_{LG}]$, $[Y_{LL}]$ = Are related elements of the Y-bus matrix network. Rearranging equation (1) , (2) can be given as:

$$\begin{bmatrix} V_L \\ \mathrm{I_G} \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} \mathrm{I_L} \\ \mathrm{V_G} \end{bmatrix} \quad (2)$$

In this matrix, F_{LG}= -$[\mathrm{Y_{LL}}]^{-1}$ $[Y_{LG}]$, which provides relation between load and source bus voltage, it is a complex matrix. The Relative electric distance theory says that the F_{LG} matrix give the relative location of load buses in respect to generator buses, is proposed by given by equation (3).

$$R_{LG} = [\mathrm{A}]\text{-abs}[F_{LG}]=[\mathrm{A}]\text{-abs}([\mathrm{Y_{LL}}]^{-1}[Y_{LG}]) \quad (3)$$

Where [A] is the (n-g)*g size matrix, n is total number of buses in the system, g is the total number of generator buses. Matrix [A] is the unity matrix. The electrical distance between load and generator buses rather than direction algorithms can be obtained by the [R_{LG}] matrix.

The concept of the SVSI is as follows:

$$SVSI_r = \frac{\Delta V_r}{\beta V_r} \quad (4)$$

Where β is the factor of correction which can be determined by equation (5).

$$\beta = 1\text{-}[\max(|V_m|\text{-}|V_l|)]^2 \quad (5)$$

The voltage decrease on the thevenin impedance is expressed through ΔVr, it can be calculated by

$$\Delta V_r \cong |\ V_g\text{-}V_r\ | \quad (6)$$

Here V_r and V_g are the voltage phasor, which is calculated between t, the loading bus and the generator respectively. This can be determined by the relative electrical distance (RED) theory. When the value of the SVSI is nearest to 1 for a particular bus, that bus is the critical bus and this will be the bus of allocation of FACTS.

C. *L-INDEX*

Kessel et al. [24] introduced an index of voltage stability based on the equations of power flow. The L-index is a formulation for estimating the distance to the stability limit from the actual system state. The L index defines the stability of the entire system and provides the following information:

$$\mathrm{L} = \max_{j\in\alpha_L}\{L_j\} = \max_{j\in\alpha_L}\left|1 - \frac{\sum_{j\in\alpha_G} F_{ji}V_i}{V_j}\right| \quad (7)$$

Here, α_G is the generator buses sets, V_j and V_i are the j and bus i voltage phasor, F_{ij} is the j-Row and i column element, whose elements are generated in the admissions matrix as in the j-th column .The admittance matrix F is as follows:

$$F_{LG}= -[\mathrm{Y_{LL}}]^{-1}\ [Y_{LG}] \quad (8)$$

And

$$\begin{bmatrix} I_G \\ \mathrm{I_L} \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} \mathrm{V_G} \\ \mathrm{V_L} \end{bmatrix} \quad (9)$$

The L-index will have values, zero for no load condition and one for voltage collapse so that, it has same definition as VCPI (Voltage Collapse prediction Index) [24]. So according to VSIs definition the highest value can be 1 is the voltage instability so that bus having index value nearest to 1 is the system's weakest bus.

IV. STATIC SYNCHRONOUS CONDENSER (STATCOM)

In order to enhance the operation and control of power systems, the implementation of high-power electronic equipments are necessary. These equipments are name as flexible AC transmission systems (FACTS) like STATCOM and SVC; these are the best example of FACTS [26]. In this paper, we are using STATCOM for enhancement of voltage profile. It is a reactive power compensating device which can generate and absorb reactive power and the connection of STATCOM is

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always connected in shunt way. The STATCOM can vary its output voltage to regulate specific parameter of an electric power network. In STATCOM, the voltage source inverter (VSI) is plays important role because it can work easily with the higher switching frequencies. It can improve transmission and distribution systems.The basic structure of STATCOM is shown by figure 2.

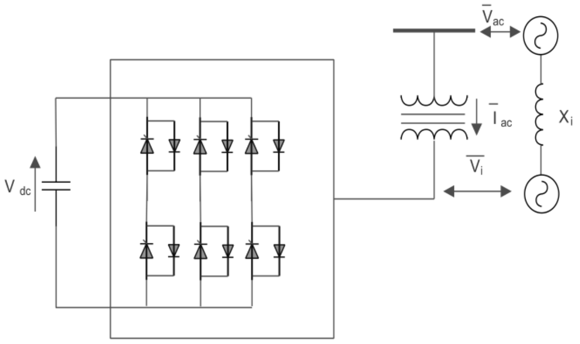

Figure 2. Basic Structure of STATCOM

The STATCOM is the power quality devices (PQ), it may be either in series or parallel connection with transmission line that will be maintained by the digital monitoring controller [27]. The reactive power for nonlinear loads can be proposed by the STATCOM [28].The recently used technique for the reactive power compensation is STATCOM. It is an inverter based FACTS device. It is most recent device used for voltage stability enhancement.

The STATCOM can be divided in two ways first one is current bridge circuit other one is voltage bridge circuit. The current bridge circuit having less rating then the voltage bridge circuit so that voltage bridge circuit is the preferable application of STATCOM. Figure (3) is the configurations of the STATCOM.

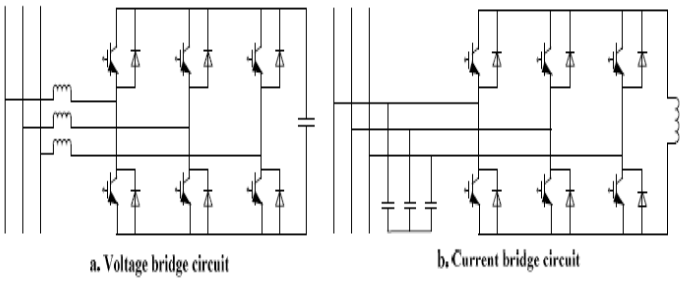

Figure 3. Basic circuit diagram of STATCOM

In this paper, we are using STATCOM for the optimum allocation for voltage stability enhancement. There are many meta-heuristic optimization algorithm are developed in last few years. Such algorithms can be defined by their nature inspired nature inspiration, Where the algorithm can be built from the evolutionary phenomena, creature corporate behavior (Swarm Techniques), physical laws, principles related to human beings [29].There have been many research works on the optimal allocation of STATCOM are used by various optimization - based approaches in transmission systems such as PSO and genetic algorithm (GA)[30].

V. Simulation Results and Comparisons

The 14 Bus system of IEEE in PSCAD software is used for the simulation results of the proposed FVSI, SVSI and L-Index voltage stability indices. Figure (5) shows single line diagram of 14 bus system of IEEE, that is having three synchronous condensers, 17 transmission lines and bus number 1 is named as slack bus having voltage "1" in every condition. The Base case voltages of 14 Bus system is as follows by table number 1.

Table 1: Base Voltage of IEEE 14 Bus System

Bus Number	Bus Voltage
1	1
2	1.001
3	0.9999
4	0.971
5	0.9702
6	1.008
7	0.993
8	1.005
9	0.988
10	0.9835
11	0.991
12	0.991
13	0.9862
14	0.968

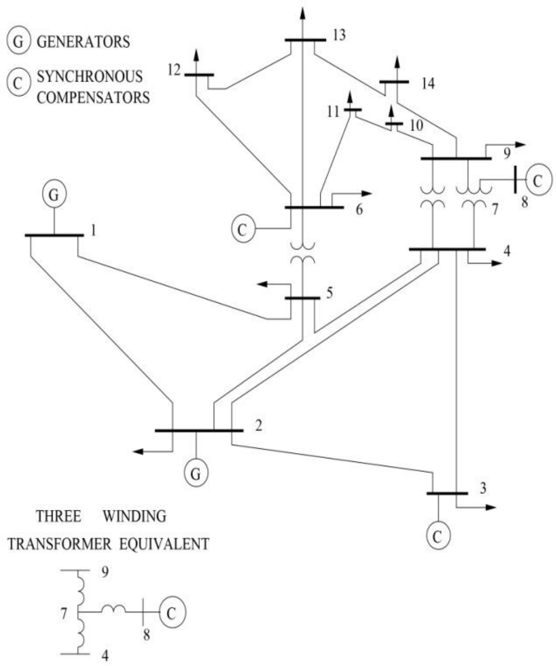

Figure: 4 Single line diagram of 14 Bus system

A. SIMPLIFIED VOLTAGE STABILITY INDEX

In this case, by calculating the SVSI, the optimal location of the STATCOM can be identifies. SVSI Needs all the bus voltage levels from the PSCAD model, as shown in table 1. Now, for all load buses the SVSI is calculated and shown in table 2.

Table 2: SVSI For load Buses

Bus No.	Voltage
4	0.0309
5	0.0317
7	0.0221
9	0.0172
10	0.0249
11	0.0163
12	0.0163
13	0.0221
14	0.043

Bus 14 has SVSI's highest value, so bus number 14 is the weakest bus of the system. Therefore, location of STATCOM is bus number 14. The profile of voltage for all buses has been enhanced after connection of the STATCOM as shown in the table 3.

Table 3: Voltage with and without STATCOM

Bus No	Voltage (with -out STATCOM)	Voltage (with STATCOM)
1	1	1
2	1.001	1.002
3	0.9999	1.001
4	0.971	0.9735
5	0.9702	0.9722
6	1.008	1.012
7	0.993	0.9994
8	1.005	1.006
9	0.988	0.9996
10	0.9835	0.9938
11	0.991	0.9989
12	0.991	0.9985
13	0.9862	0.9856
14	0.968	0.9986

After STATCOM installation the voltage profile of each bus is enhanced. Now voltage deviation is measured as:

Condition	Without STATCOM	With STATCOM
Voltage Deviation	0.1441	0.0489

B. L-INDEX

In this case the optimum position of the STATCOM can be defined by measuring the L-Index and this index also includes all of the PSCAD model bus voltage levels, as shown in table 1. The L-Index is calculated and shown in Table 4 for all load buses.

Table 4: L-Index For Load Buses

Bus No.	Voltage
4	0.2389
5	0.0967
7	0.1083
9	0.3198
10	0.1498
11	0.0926
12	0.1265
13	0.3969
14	0.3287

Bus number 13 has the lowest value of L-Index, so the bus number 13 is the weakest bus in the system. Hence STATCOM's best location is bus number 13. The profile of voltage for all buses are being enhanced after STATCOM attachment, as is shown in Table 5.

Table 5:Voltage With and without STATCOM

Bus No	Voltage (with -out STATCOM)	Voltage (with STATCOM)
1	1	1
2	1.001	1.007
3	0.9999	1.006
4	0.971	0.9988
5	0.9702	0.9893
6	1.008	1.013
7	0.993	1.007
8	1.005	1.008
9	0.988	1.003
10	0.9835	0.9963
11	0.991	1.001
12	0.991	0.9975
13	0.9862	0.9927
14	0.968	0.9794

So, after installation of STATCOM the profile of voltage for each bus will improved. Therefor, the voltage deviation is:

Condition	Without STATCOM	With STATCOM
Voltage Deviation	0.1441	0.1003

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C. FAST VOLTAGE STABILITY INDEX

In this case, measurement of the FVSI will determine the optimum position of the STATCOM and this index also includes all PSCAD model bus voltage levels, as shown in table 1.FVSI is the line stability index, it is focused on a single line principle of power. But, this stability index can also be helpful for determination of the weakest bus of system.From the values of FVSI for the line, first bus from that line is the system's weakest bus[32].Now for all lines the FVSI will determined which is shown in table 6 and Maximum loading parameters are given by table no. 7.

Table 6: FVSI for all the Lines

Line No.	From Bus	To Bus	FVSI
1	1	2	-0.04878
2	1	5	-0.01728
3	2	3	0.026135
4	2	4	-0.0473
5	2	5	-0.04558
6	3	4	-0.00869
7	4	5	-0.00689
8	6	11	-0.051855
9	6	12	-0.0436
10	6	13	-0.07458
11	7	9	-0.13322
12	9	10	0.073288
13	9	14	0.045722
14	10	11	0.464209
15	12	13	-0.03608
16	13	14	0.139804
17	4	7	-0.07649
18	4	9	0.063082
19	5	6	-0.11762
20	7	8	0

Table 7: Maximum Loading Parameters

From Bus	To Bus	Line outage	Maximum loading Parameter
1	2	1	1.27
1	5	2	1.5265
2	3	3	1.4251
2	4	4	1.3886
2	5	5	1.4216
3	4	6	1.4323
4	5	7	1.3626
6	11	8	1.31
6	12	9	1.3668
6	13	10	1.3632
7	9	11	1.3435
9	10	12	1.0154
9	14	13	1.3997
10	11	14	0.3324
12	13	15	1.346
13	14	16	1.3643

The line outage number 14 have highest value of FVSI, this line has two buses bus number 10 to bus number 11 and this line having smllest maximum loading parameter, so that bus number 10 is the weakest bus of the system.So that best location for STATCOM is the bus number 10. After connection of the STATCOM the voltage profile of all buses has been improved which is shown by table 8.

Table 8 : Voltage with and without STATCOM

Bus No	Voltage (with -out STATCOM)	Voltage (with STATCOM)
1	1	1
2	1.001	1.002
3	0.9999	1
4	0.971	0.9730
5	0.9702	0.9718
6	1.008	1.01
7	0.993	0.9983
8	1.005	1.006
9	0.988	0.9978
10	0.9835	0.999
11	0.991	1.001
12	0.991	0.9946
13	0.9862	0.9896
14	0.968	0.9751

So, after the connection of STATCOM the voltage profile of each bus will improved. Therefor, the voltage deviation is :

Condition	Without STATCOM	With STATCOM
Voltage Deviation	0.1441	0.0895

The table number 9 is the comparison of used Voltage Stability Indices techniques with the other techniques. This table shows that the SVSI is the best technique for voltage stability improvement or enhancement. The figure 5 shows the 14 Bus PSCAD Model with STATCOM for SVSI.

Table 9: Comparison of Voltage Deviation of Various Technique

Sr. No.	Name of Technique	Location of STATCOM	Voltage Deviation
1	**SVSI**	**14**	**0.0489**
2	**FVSI**	**10**	**0.0895**
3	**L-Index**	**13**	**0.1003**
4	**DA[2018][32]**	**9**	**0.3529**
5	**TLBO[2017][33]**	**5**	**0.4993**
6	**PSO[2013][34]**	**12**	**0.8952**

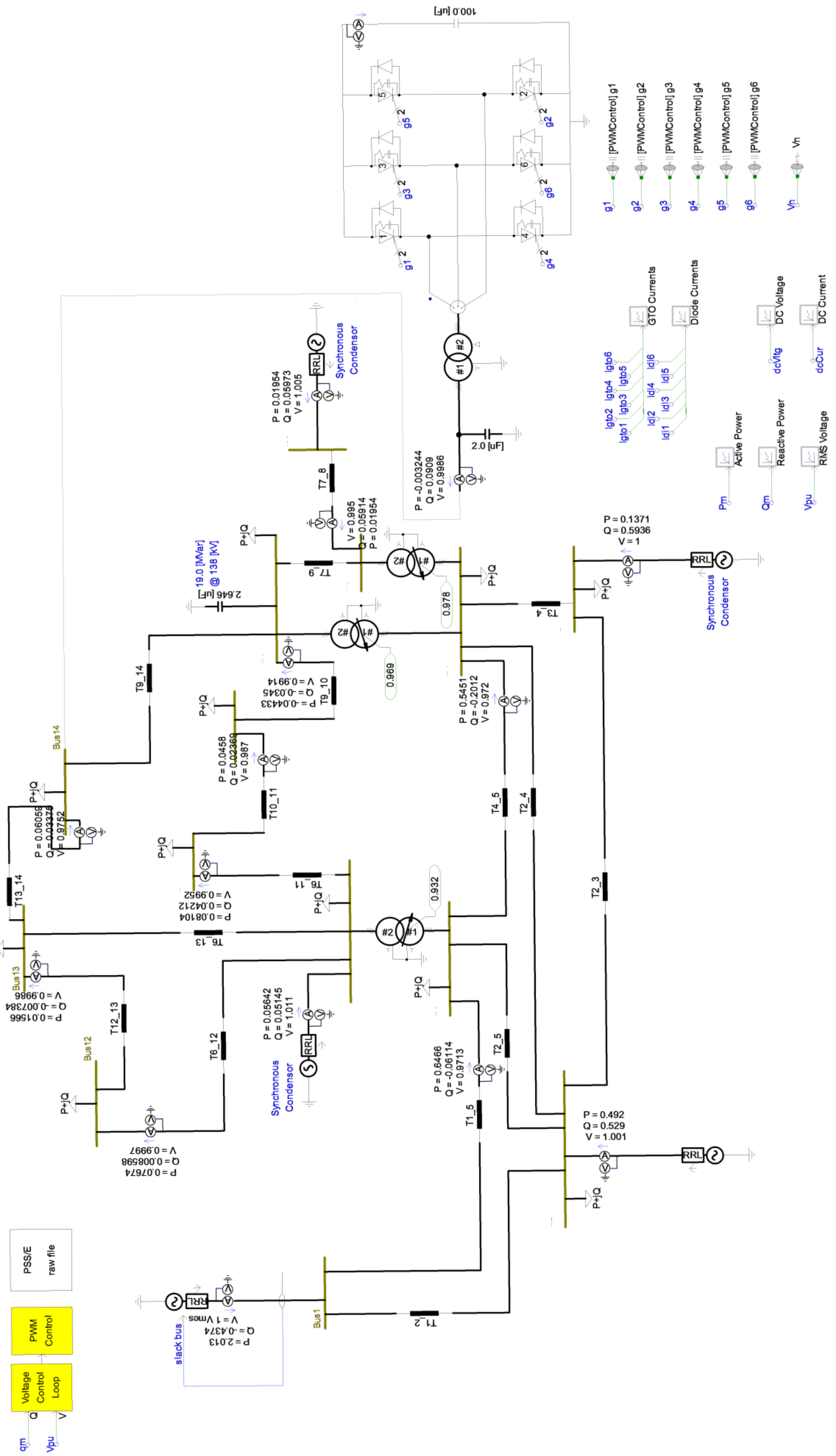

Figure 5: With STATCOM 14 Bus PSCAD Model for SVSI

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VI. CONCLUSION

In this paper, various indices like SVSI (Simplified Voltage Stability Index), FVSI (Fast voltage stability Index) and L-Index have been presented to determine the most critical node for allocation of FACTS devices. The main objective of this work is to enhance the voltage profile of transmission network and minimize the voltage deviation.STATCOM is used here for automatic reactive power compensation. The effectiveness of used indices has been evaluated on IEEE 14 bus test system. To check the efficacy of used indices, we have compared them with other techniques. SVSI gives minimized voltage deviation as compared to other techniques. Moreover, SVSI is simple and requires less computational effort.This work is useful to examine static voltage stability. In addition , this study can also be performed for dynamic voltage stability. For higher bus systems, the SVSI can be easily implemented. Results from several cases show that the critical bus location (as obtained from SVSI) is the best place for allocation of STATCOM.

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SHUBHAM SHARMA received B.Tech. degree in Electrical Engineering from Maharishi Arvind college of Engineering and Research Centre, Jaipur, India and Pursuing M.Tech. Degree from Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur , India affiliated to RTU, Kota. His research interest includes power system stability and enhancement of Voltage stability.

Mr. Ajay Bhardwaj received B.Tech. degree in Electrical Engineering from Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, India and M.Tech. degree from Yagyavalkya Institute of Technology, Jaipur, India affiliated to RTU, Kota. His research interest includes power system restructuring, electricity economics, power trading and power system optimization

Dr. Sarfaraz Nawaz was born in Jaipur, Rajasthan, India. He received the B.E. degree from the Rajasthan University, Jaipur, in 2005 and M.Tech. degree from MNIT, Jaipur, in 2010 and Ph.D. in 2017. He is currently working as associate professor in department of electrical engineering, SKIT Jaipur. His research areas include applications of power distribution automation problems, Distributed Generation problems, stability problem etc.