

## Location of static var compensator in a multi-bus power system using unique network equivalent

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**Abstract.** This paper presents a new approach to identify the suitable location for static var compensator in a multi-bus power system for voltage stability enhancement using a unique two-bus  $\pi$ -network equivalent derived with optimal power flow solution of the actual system at different operating conditions. An index named equivalent network based index (ENBI), derived from the parameters of two-bus equivalent of the multi-bus power system is used for positioning the static var compensator. The proposed approach has been tested under simulated condition on a practical power system (203-bus Indian Eastern Grid) for illustration purpose. Simulation results obtained with the proposed approach are compared with the results of well-established  $L$ -index method. Improvement in voltage stability margin using static var compensator is also investigated for the test system considered.

**Keywords:** two-bus  $\pi$ -network equivalent; optimal power flow; static var compensator;  $L$ -index; equivalent network based index; global voltage stability indicator

### 1. Introduction

Modern power system operations are exposed to highly stressed conditions due to increased system complexity, changes in network topology and continued growth of load demand with limited transmission and/or generation enhancement. This makes the system vulnerable to stability and security problems. Voltage stability problem is the main issue with stressed power systems and is the major concern for researchers and power system engineers over the past few decades because of several events of the voltage collapse occurred all over the globe (Kundur 1994, Van Custer 1991, Mala De and Goswami 2011, Nourizadeh *et al.* 2012). The main factor for causing voltage instability is the reactive power mismatch in the power system and it is the cause for system collapse in which the system voltage decays to a level from which it is unable to recover. So, a power system needs to be sufficient reactive power capability to remain voltage secured even under highly stressed conditions (Yamashita *et al.* 2008, Ritwik Majumder 2014, Mala De and Goswami 2014, Chebbo *et al.* 1992, Juan *et al.* 2011).

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Several reports have shown that the flexible AC transmission system (FACTS) controllers are a good choice to compensate reactive power and to improve the voltage stability in power system. Power systems have seen a new era of technology with the development of FACTS devices (Hingorani and Gyugyi 1999, Xiao-Ping *et al.* 2006). They offer a versatile alternative to conventional methods with potential advantages of increased flexibility, lower operation and maintenance costs with less environmental impacts. FACTS devices responds quickly enough to changing network conditions to provide real-time power flow control, which is essential when large number of power transactions occur in a fully deregulated electric industry. Their application in improving the performance of the power system in terms of voltage stability is discussed in (Sode-Yome and Mithulanathan 2004, Thukaram and Lomi 2000, Sharma *et al.* 2003, Zhang *et al.* 2007, Singh and David 2001, Sode-Yome *et al.* 2007). However to achieve the better performance of the FACTS controllers, proper placement in the power system is very much needed.

The best location for reactive power compensation for the improvement of system voltage stability is the weakest bus of the power system (Hingorani and Gyugyi 1999, Xiao-Ping *et al.* 2006). The weakest bus is defined as the bus nearest to experiencing a voltage collapse. There are several methods/indices available in the literature for finding the location of FACTS controllers from voltage stability point of view. These indices provide reliable information about the proximity of voltage collapse and the weakest bus/area of the system. The indices derived for voltage stability analysis are either referred to a line or bus. Line stability indices can be used to determine the weakest line of the system and to evaluate the voltage stability condition, where as the bus stability indices can be used to identify the weakest bus or area of the system. For practical power systems, different buses are differently sensitive to the overall power system voltage stability. Some buses are more, and some are less. To a large extent, proper allocation of FACTS controllers can make great enhancement to voltage stability. Therefore, it is an actual and important subject to appropriately select the suitable place for FACTS controller installation at the view point of voltage stability improvement (Thukaram and Lomi 2000, Sharma *et al.* 2003, Zhang *et al.* 2007).

In this paper, an index named equivalent network based index (ENBI) is proposed for the identification of weakest bus and hence the placement of FACTS device, static var compensator (SVC) for the effective improvement of the voltage stability and so the overall performance of the system. The index is developed based on a two-bus  $\pi$ -network equivalent of the multi-bus power system (Nagendra *et al.* 2011a, Nagendra 2011b). Required data to evaluate the equivalent system are obtained from the results of optimal power flow solution of the original system. The concept of deriving single line two-bus equivalent network of any multi-bus power system is very attractive due to its simplicity and less computational effort. The occurrence of voltage collapse on the basis of single line equivalent can be studied easily and it is not necessary to consider every line or bus of the system separately (Jasmon and Lee 1991, Jasmon and Lee 1991, Nagendra *et al.* 2010, Juan *et al.* 2014). All the parameters required to develop the single line equivalent model of the actual system could be evaluated if the total generation, load, losses and voltages are available. In real time operation of power systems, the power control centers would be fed the various system state measurements. Such information is similar to the result summary provided by the load flow or optimal power flow study. So the equivalent system can easily be evaluated and employed to assess the behavior of the system as a whole i.e., in global mode without computation of Jacobian or Hessian matrix. Therefore, the representation of any multi-bus power system in an equivalent domain enables the fast assessment of voltage stability and so useful for the practical on-line

monitoring of power systems.

The proposed method can be applied for accurate position of the SVC in the system at which the reactive power compensation is required. To demonstrate the effectiveness of the method, a practical 203-bus system has been used. Simulation results are compared with the results obtained by *L*-index methodology (Kessel and Glavitsch 1986) for the identification of location of SVC. Voltage stability margin augmentation with the application of SVC at the weakest bus is also compared with the system having no compensation. The rest of the paper is organized as follows: In section 2, the *L*-index is overviewed and the relative equations are given. Steady state model of SVC and its inclusion in the optimal power flow formulation is discussed in section 3. In section 4, equivalent two-bus pi-network model and the ENBI for positioning SVC are presented. In section 5, computational algorithm for the proposed work is presented. Simulation results are given in section 6 to demonstrate the feasibility and effectiveness of the proposed approach, followed by concluded remarks of the present work in section 7

## 2. The *L*-index

Using the power flow results, the *L*-index proposed by Kessel and Glavitsch (1986) is

$$L_j = \left| 1 - \sum_{i=1}^g F_{ji} \frac{V_i}{V_j} \right| \quad (1)$$

where  $j=1,2,3, \dots, n$ ;  $n$  is the total number of buses with  $1,2,\dots, g$  generator buses,  $g+1, g+2, \dots, n$ , the load buses. All the terms within the sigma on the right hand side of (1) are complex quantities. The values of  $F_{ji}$  are obtained from the *Y* bus matrix as follows

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

where  $V_G, V_L, I_G, I_L$  represent the voltages and currents at the generator buses and load buses. Rearranging the Eq. (2)

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (3)$$

where  $F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]$  are required values i.e.,  $F_{ji}$  are the complex elements of  $[F_{LG}]$  matrix.

The value of *L*-index lies between 0 and 1. An *L*-index value less than 1 and close to 0 indicates an improved voltage stability margin. The *L*-indices for a given load condition are computed for all load buses. The higher values for *L*-indices are indicative of most vulnerable buses and thus maximum of *L*-indices is an indicator of proximity of the system to voltage collapse and also indicator of most critical bus.

## 3. Static VAR compensator

Static var compensator, an important FACTS controller, is a shunt connected device used to provide the controlled reactive power or voltage support mostly wherever needed. SVC consists of

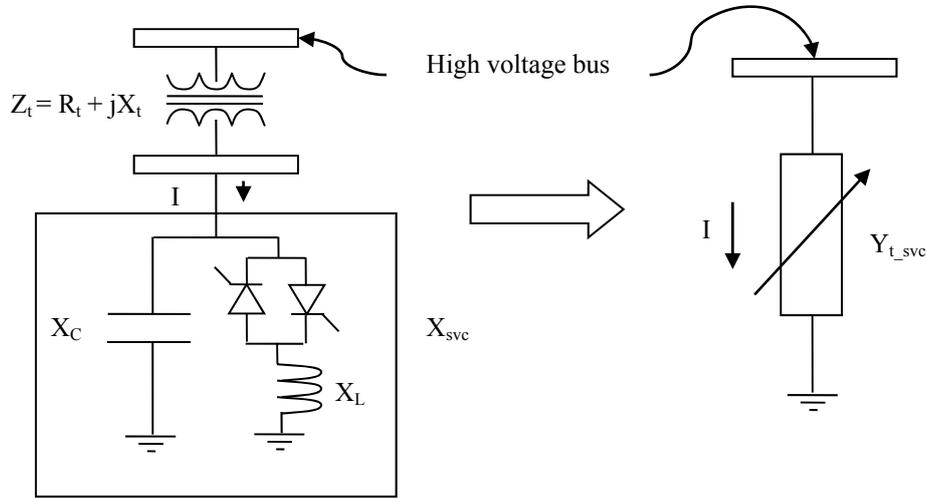


Fig. 1 SVC connected to the transmission network via a step-down transformer

a group of shunt connected capacitors and reactor banks with fast control action by means of thyristor-based switching elements (Hingorani and Gyugyi 1999, Xiao-Ping *et al.* 2006). The inclusion of SVC at any load bus makes that bus as voltage-controlled bus with zero active power output but having reactive generation and specified voltage magnitude at that bus along with operating limits of SVC. With suitable control, it allows appropriate voltage regulation by injecting reactive power into the system, so that the voltage magnitude of the bus connected to SVC can be maintained constant. The steady state model of SVC has been used here to find the suitable location for its installation.

SVC is considered as a continuous, shunt variable susceptance, which is adjusted in order to achieve a specified voltage magnitude while satisfying constraint conditions. The SVC is connected to the transmission network via a step-down transformer as shown in Fig. 1. Suitable control of the equivalent reactance is brought about by varying the current through the TCR by controlling the gate firing instant of thyristors and thus the equivalent susceptance  $B_{t\_svc}$  is a function of the firing angle  $\alpha$ . The SVC effective reactance  $X_{svc}$  is determined by the parallel combination of  $X_C$  and  $X_{tcr}$  and is given by

$$X_{svc} = \frac{X_C X_L}{\frac{X_C}{\pi} (2(\pi - \alpha) + \sin(2\alpha)) - X_L} \quad (4)$$

The partial derivatives required to calculate load flow Jacobian with respect to the SVC (connected at  $m^{\text{th}}$  bus) firing angle  $\alpha$  are

$$\frac{\partial P_m}{\partial \alpha} = \frac{\partial P_{t\_svc}}{\partial \alpha} = V_m^2 \frac{\partial G_{t\_svc}}{\partial \alpha}$$

$$\frac{\partial Q_m}{\partial \alpha} = \frac{\partial Q_{t\_svc}}{\partial \alpha} = -V_m^2 \frac{\partial B_{t\_svc}}{\partial \alpha}$$

where net active power injected at node  $m$  is given by

$$P_m = \text{activepower injected by lines connected to the node} + P_{t-svc},$$

and net reactive power injected at node  $m$  is given by

$$Q_m = \text{reactivepower injected by lines connected to the node} + Q_{t-svc},$$

$$\text{Here, } G_{t-svc} + jB_{t-svc} = 1 / (R_t + j(X_t + X_{svc}))$$

The Lagrangian function including the  $\alpha$  iteration model of SVC in OPF (David *et al.* 1984, Fuerte-Esquivel *et al.* 2000, Ambriz-Perez *et al.* 2000) is given below, where  $Q_m$  (SVC is connected to the  $m^{\text{th}}$  bus of the network) is a function of the thyristor firing angle  $\alpha$  as well as bus voltage magnitudes  $|V|$  and phase angles  $\delta$  (transformer resistance  $R_t$  and hence  $G_{t-svc}$  is assumed to be negligible).

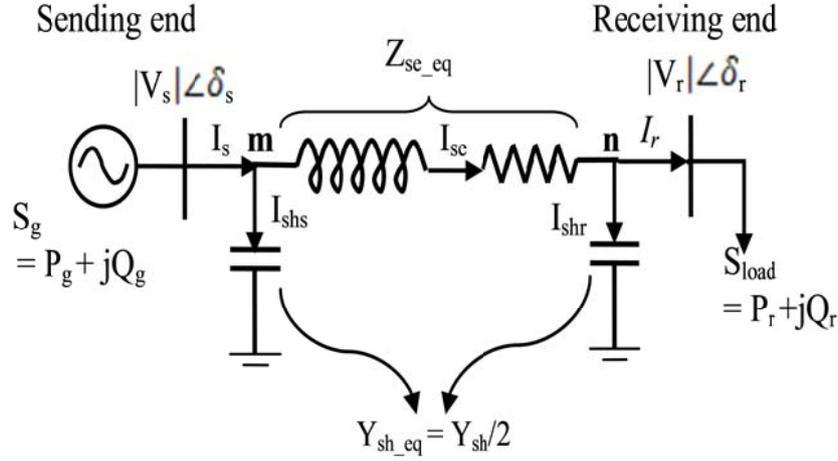
$$\begin{aligned} L(P_g, |V|, \delta) = & \sum_{i=1}^{NG} F_c(P_{g_i}) + \sum_{i=1}^N \lambda_{p_i} [P_i(|V|, \delta) - P_{g_i} - P_{load_i}] \\ & + \sum_{i=NG+1}^N \lambda_{q_i} [Q_i(|V|, \delta) - Q_{g_i} - Q_{load_i}] \\ & + \lambda_{q_m} [Q_m(|V|, \delta, \alpha) - Q_{g_m} - Q_{load_m}] \end{aligned} \quad (5)$$

Where  $P_{g_i}, Q_{g_i}$  are the real and reactive power generations at  $i^{\text{th}}$  generator bus;  $NG$ , the total number of generators;  $F_c$ , the cost of generation at  $i^{\text{th}}$  generator; where  $P_i, Q_i$  are the active and reactive power injections at  $i^{\text{th}}$  bus respectively;  $\lambda_{p_i}$  and  $\lambda_{q_i}$  are Lagrangian multipliers for active power and reactive power balance at the  $i^{\text{th}}$  bus respectively.

If  $\alpha$  is within limits ( $90^\circ \leq \alpha \leq 180^\circ$ ), the specified voltage magnitude at the  $m^{\text{th}}$  bus is attained and it remains a PV bus-type. However, if  $\alpha$  goes out of limits, it is fixed at the violated limit and the bus becomes a PQ type bus with fixed susceptance connected to it.

The Lagrangian function can be optimized using the following set of equations given in the matrix form

$$\begin{bmatrix} \frac{\partial^2 L}{\partial P_{g_i} \partial P_{g_k}} & 0 & \frac{\partial^2 L}{\partial P_{g_i} \partial \lambda_{p_k}} & 0 & 0 & 0 \\ 0 & \frac{\partial^2 L}{\partial \delta_i \partial \delta_k} & \frac{\partial^2 L}{\partial \delta_i \partial \lambda_{p_k}} & \frac{\partial^2 L}{\partial \delta_i \partial \lambda_{q_k}} & \frac{\partial^2 L}{\partial \delta_i \partial |V_k|} & 0 \\ \frac{\partial^2 L}{\partial \lambda_{p_i} \partial P_{g_k}} & \frac{\partial^2 L}{\partial \lambda_{p_i} \partial \delta_k} & 0 & 0 & \frac{\partial^2 L}{\partial \lambda_{p_i} \partial |V_k|} & 0 \\ 0 & \frac{\partial^2 L}{\partial |V_i| \partial \delta_k} & \frac{\partial^2 L}{\partial |V_i| \partial \lambda_{p_k}} & \frac{\partial^2 L}{\partial |V_i| \partial \lambda_{q_k}} & \frac{\partial^2 L}{\partial |V_i| \partial |V_k|} & 0 \\ 0 & \frac{\partial^2 L}{\partial \lambda_{q_i} \partial \delta_k} & 0 & 0 & \frac{\partial^2 L}{\partial \lambda_{q_i} \partial |V_k|} & \frac{\partial^2 L}{\partial \lambda_{q_i} \partial \alpha} \\ 0 & 0 & 0 & \frac{\partial^2 L}{\partial \alpha \partial \lambda_{q_k}} & 0 & \frac{\partial^2 L}{\partial \alpha^2} \end{bmatrix} \begin{bmatrix} \Delta P_{g_i} \\ \Delta \delta_i \\ \Delta \lambda_{p_i} \\ \Delta \lambda_{q_i} \\ \Delta |V_i| \\ \Delta \alpha \end{bmatrix} = \begin{bmatrix} -\frac{\partial L}{\partial P_{g_i}} \\ -\frac{\partial L}{\partial \delta_i} \\ -\frac{\partial L}{\partial \lambda_{p_i}} \\ -\frac{\partial L}{\partial \lambda_{q_i}} \\ -\frac{\partial L}{\partial |V_i|} \\ -\frac{\partial L}{\partial \alpha} \end{bmatrix} \quad (6)$$

Fig. 2 Equivalent two-bus  $\pi$ -network model

At the end of the  $i^{\text{th}}$  iteration, the variable firing angle  $\alpha$  is updated like other state variables as,  $\alpha^{i+1} = \alpha^i + \Delta\alpha^i$ .  $G_{l\_svc}$  and  $B_{l\_svc}$  are calculated for the new value of firing angle  $\alpha$  and hence the admittance matrix of the system is modified incorporating the change in diagonal term  $Y_{mm}$  of the admittance matrix. However, if the new angle  $\alpha$  violates any of the limits then it is fixed at the corresponding limit and  $\alpha$  no longer serves as a state variable, instead the voltage magnitude at bus  $m$  which was a specified variable now becomes a state variable.

#### 4. Equivalent network based index for SVC location

The equivalent network based index (ENBI) is developed using the parameters of the  $\pi$ -network equivalent obtained from the result summary of optimal power flow study of multi-bus power system. The development of  $\pi$ -network equivalent is explained in (Nagendra *et al.* 2011a, Nagendra 2011b) and briefly described in this section. Let us consider a two-bus system where sending end bus is assumed as a generator bus and receiving end bus a load bus along with the series and shunt admittances representing the equivalent of the entire multi-bus network as shown in Fig. 2.

The behavior of the proposed two-bus equivalent network should be the same as that of multi-bus network and it should reflect the common properties of original system and make possible the fast evaluation of voltage security. Therefore, the power balance equation for the two-bus equivalent network can be written as

$$S_g = P_g + jQ_g = \overline{V_s} \overline{I_s}^* = (S_{se} + S_{sh}) + S_{load} \quad (7)$$

where  $S_{se} = (\overline{V_s} - \overline{V_r}) \overline{I_{se}}^*$  and  $S_{sh} = \overline{V_s} \overline{I_{shs}}^* + \overline{V_r} \overline{I_{shr}}^*$  and at the same time  $S_{se}$  and  $S_{sh}$  are total complex series and shunt transmission line loss of the original multi-bus power network. Here  $V_s$ ,  $V_r$  and  $I_s$ ,  $I_r$  are the sending and receiving end voltages and currents;  $I_{se}$  is the current through series equivalent impedance;  $I_{shs}$ ,  $I_{shr}$  are the shunt branch currents at sending and receiving end sides

respectively.

Applying Kirchoff's current law at the two nodes ( $m$  and  $n$ ) simplification yields

$$S_g |\overline{V}_s|^2 \overline{V}_r + S_g |\overline{V}_r|^2 \overline{V}_s - S_{sh} |\overline{V}_s|^2 \overline{V}_r - S_{sh} |\overline{V}_r|^2 \overline{V}_s - S_{load} |\overline{V}_s|^2 \overline{V}_s - S_{load} |\overline{V}_r|^2 \overline{V}_s = 0 \quad (8)$$

From Fig. 2, the formulation of the index is as follows:

The equivalent series impedance,

$$Z_{se\_eq} = \frac{(\overline{V}_s - \overline{V}_r)}{I_{se}}$$

and equivalent shunt admittance,

$$Y_{sh\_eq} = \frac{Y_{sh}}{2} = \frac{I_{shr}}{\overline{V}_r} = \frac{I_{shs}}{\overline{V}_s} \quad (9)$$

Once the global two-bus pi-network equivalent of the multi-bus power system is obtained, then the global voltage stability indicator could be formulated in a straight forward manner from the parameters of the global network as follows (Nagendra *et al.* 2011a, Nagendra 2011b):

ABCD parameters of the two-bus  $\pi$ -equivalent system are given by

$$A = D = 1 + \frac{YZ}{2}; \quad B = Z; \quad C = Y \left( 1 + \frac{YZ}{4} \right) \quad [\text{assuming } Z_{se\_eq} = Z \text{ and } Y_{sh\_eq} = \frac{Y}{2}]$$

also assuming

$$A = |A| \angle \alpha; \quad B = |B| \angle \beta; \quad \overline{V}_s = |\overline{V}_s| \angle \theta; \quad \overline{V}_r = |\overline{V}_r| \angle \delta; \quad \delta < \theta$$

Sending end voltage being constant ( $1 \angle 0^\circ$  p.u.), the active and reactive power at receiving end are given by

$$P_r = \frac{|\overline{V}_r|}{|B|} \cos(\beta + \delta) - \frac{|A| |\overline{V}_r|^2}{|B|} \cos(\beta - \alpha)$$

$$Q_r = \frac{|\overline{V}_r|}{|B|} \sin(\beta + \delta) - \frac{|A| |\overline{V}_r|^2}{|B|} \sin(\beta - \alpha)$$

Jacobian matrix of above power flow equation is given by

$$J = \frac{1}{|B|} \begin{bmatrix} -|\overline{V}_r| \sin(\beta + \delta) & \cos(\beta + \delta) - 2|A| |\overline{V}_r| \cos(\beta - \alpha) \\ |\overline{V}_r| \cos(\beta + \delta) & \sin(\beta + \delta) - 2|A| |\overline{V}_r| \sin(\beta - \alpha) \end{bmatrix}$$

Then, at critical point of voltage stability the determinant of Jacobian matrix,  $\Delta[J]=0$

$$\therefore |\overline{V}_r| = V_{cr} = \frac{1}{2|A| \cos(\delta + \alpha)} \quad (10)$$

where  $V_{cr}$  is the critical value of receiving voltage at voltage stability limit. Lower value of  $V_{cr}$

indicates the system will have better voltage profile along with higher load catering capability and therefore better voltage stability.

To maintain global voltage stability,  $\Delta[J]>0$ ; i.e., global voltage stability margin can be defined as  $GVSM=\Delta[J]$ . It indicates how far the present operating condition is from the global system voltage collapse i.e.,  $GVSM$  points on the global voltage security status of the present operating condition.

Now let us consider an SVC connected at any load bus of the multi-bus power system which is represented by its equivalent  $\pi$ -network model as considered above. The combined equivalent admittance of the SVC and step-down transformer is given by

$$Y_{t\_svc} = G_{t\_svc} + jB_{t\_svc} \quad (11)$$

Here 
$$G_{t\_svc} = \frac{R_t}{R_t^2 + X_{eq}^2}; \quad B_{t\_svc} = \frac{-X_{eq}}{R_t^2 + X_{eq}^2}$$

and 
$$R_t + jX_{eq} = R_t + j(X_t + X_{svc})$$

where  $R_t+jX_t$  is the impedance of the step-down transformer and  $X_{svc}$  is the SVC effective reactance.

This equivalent admittance varies with the variation of the SVC firing angle. If firing angle is within limits, the specified voltage magnitude is attained and the bus remains as voltage controlled bus. However, if firing angle violates the limits, then it is fixed at the violated limit and the bus becomes load bus again.

Using the above parameters, the equivalent network based index, ENBI is expressed as follows

$$ENBI = \frac{Y_{sh\_eq} - Y_{t\_svc}}{Y_{sh\_eq}} \quad (12)$$

The value of ENBI is different for different load buses at different operating conditions. The ENBI provides the information about the weak location of the system i.e. suitable position of the SVC. Higher value of ENBI indicates the higher weakness of load buses. So, the maximum value of the index gives the suitable location of the SVC.

## 5. Algorithm

The necessary algorithm of the proposed method for identifying the location of SVC in the system is given below:

- Step 1. Solve the optimal power flow problem incorporating the SVC at a chosen load bus with gradual increase of load at constant power factor. Go to step 6 if OPF iterative process does not converge.
- Step 2. Calculate total generation, load and transmission line loss. Calculate the equivalent shunt admittance ( $Y_{sh\_eq}$ ) of the two-bus  $\pi$ -network equivalent.
- Step 3. Calculate the equivalent admittance ( $Y_{t\_svc}$ ) of the SVC
- Step 4. Evaluate the equivalent network based index (ENBI)
- Step 5. Choose another load bus and repeat steps 1-4.

Step 6. Stop.

### 6. Simulation results and discussion

The proposed algorithm has been tested on a robust practical West Bengal State Electricity Board (WBSEB) 203-bus Indian Eastern Grid system, which has a base load of 8887.48 MVA with 24 generators, 35 three-winding transformers, 37 two-winding transformers and 108 load buses which are interconnected by 267 transmission lines. Single line diagram of the test system is given in (Nagendra *et al.* 2011a). A computer software programme has been developed in the MATLAB environment to perform the optimal power flow analysis including the steady state model of SVC. Optimal power flow with the inclusion of SVC at any load bus is successively solved for uniformly increasing load conditions (at an increment of 20% of base value keeping the load power factor constant) until the OPF algorithm fails to converge. For each case, the required parameters (i.e.,  $Y_{sh\_eq}$  and  $Y_{L\_svc}$ ) have been calculated and have been used to determine the equivalent network based index. Same SVC has been used here at different load buses for calculating the value of ENBI. The parameters adopted for SVC are given in appendix. Simulation results obtained are compared with those found through the existing  $L$ -index method and found that the proposed method can provide reasonably good results with little computational requirement. The profiles shown below validate this fact.

In Fig. 3, the value of ENBI is plotted against different load buses of the WBSEB grid system. The bus under the simulation is equipped with SVC and then the value of ENBI is calculated. Similar procedure is applied for all other load buses. In the figure, it is observed that the value of ENBI is maximum for bus no. 172. Hence this is the weakest bus of the system and is the suitable location for positioning SVC for reactive power compensation.

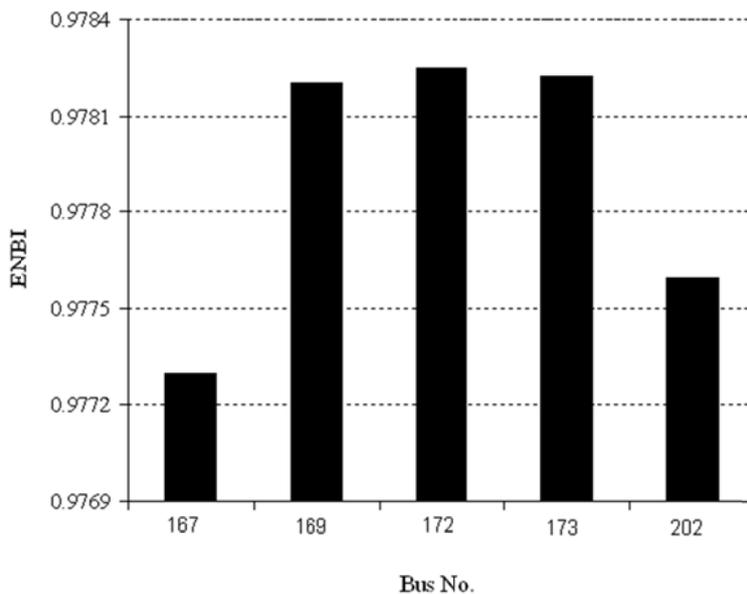


Fig. 3 ENBI for different buses for WBSEB grid system

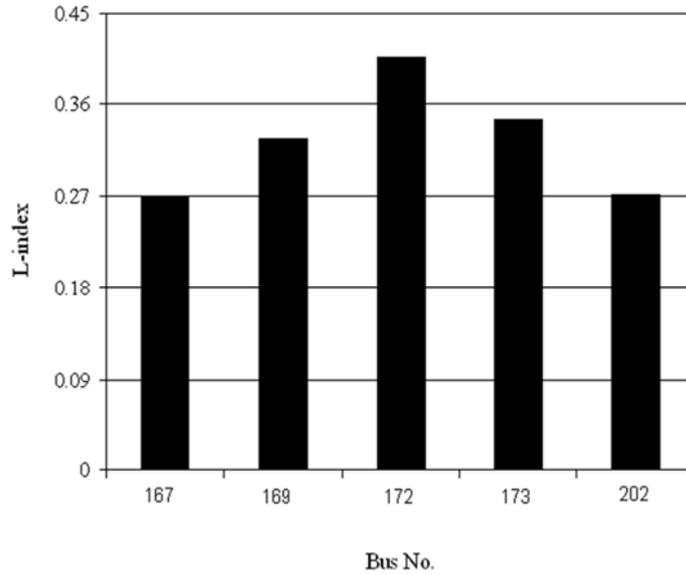


Fig. 4 *L*-index for different buses for WBSEB grid system

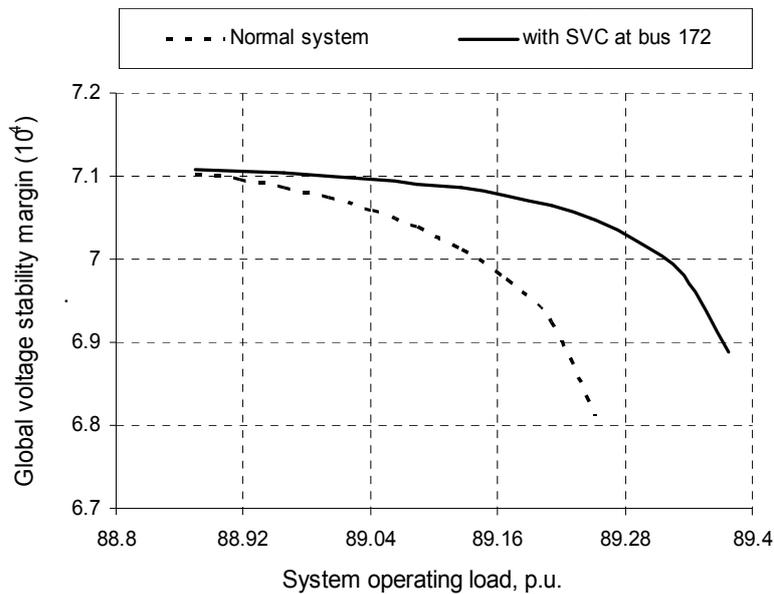


Fig. 5 Profile of global voltage stability margin with the variation of system operating load

To compare the results of the proposed method, an *L*-index method is applied to find the weakest bus of the system. Fig. 4 shows the *L*-index for different load buses. It can be noticed from the figure that this method also showing the bus no. 172 as the weakest bus of the system and hence the suitable location for SVC placement which is same as obtained from the proposed method.

Once the suitable location for placing the SVC is found then its effect on the power system performance in terms of voltage stability in the equivalent domain can be studied. Fig. 5 exhibits the profile of global voltage stability margin (GVSM) for WBSEB grid system indicating that the system gradually moves towards voltage instability with increase in load. It is clear from the figure that with the incorporation of SVC at suitable location i.e., at weakest bus (no. 172) of the system, the GVSM has been improved with better loading catering capability.

It should be clear here that the parameters of the two-bus  $\pi$ -network equivalent system vary with variation of system operating condition. At maximum loading point the value of GVSM becomes zero indicating that the system reaches voltage stability limit. A set of pre-calculated values of the GVSM corresponding to different operating condition may be useful for the real time operation where only the total line loss, total generation and total load of the entire system will be sufficient for calculating the present indicator value from the measured system data which if compared with the already pre-calculated GVSM data may reveal whether system is at the verge of voltage collapse or not, almost instantly. Thus this approach may be beneficial due to its simplicity associated with high speed of decision making.

The profile of global critical voltage ( $V_{cr}$ ) obtained for two-bus  $\pi$ -equivalent model with variation in system operating load at the weakest bus of the system is shown in Fig. 6. Here,  $V_{cr}$  increases with increase in load indicating more threatened operating condition since voltage collapse occurs even at higher voltage magnitude and it is also clear from figure that with the application of SVC, the profile goes downward which ensures the more stable system. The incorporation of the SVC enables the system to be stable even at much higher loading.

Table 1 shows the variation of weak bus voltage with system operating load. It is seen here that the voltage corresponding to weakest bus gradually decreasing and thereby it approaches voltage instability for increase in system loading. A flatter voltage profile is possible when SVC is connected at the weakest bus of the system with better load handling capacity. The bus voltage

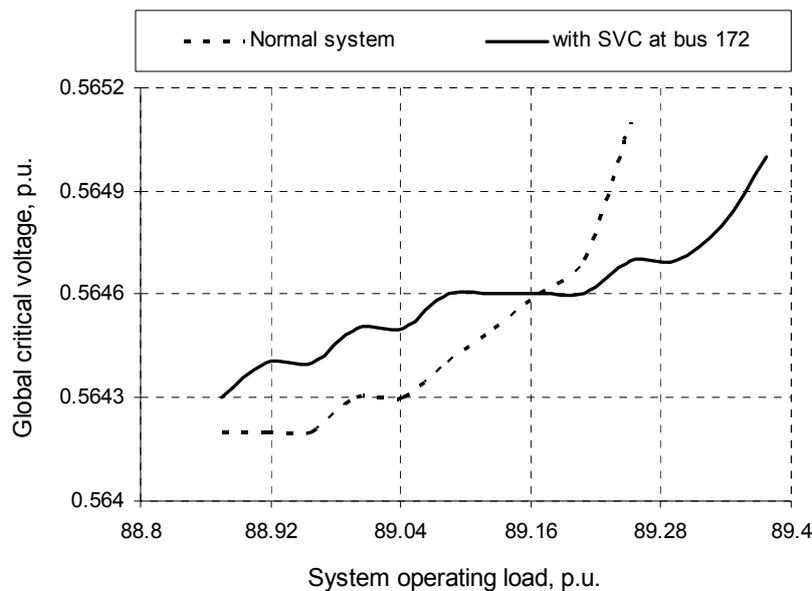


Fig. 6 Profile of global critical voltage with the variation of system operating load

Table 1 Variation of weak bus voltage with system operating load

System operating load (p.u.)	Weak bus voltage, $V_g$ (p.u.)	
	Normal system	System with SVC
88.8748	0.8978	1.0000
88.9167	0.8804	1.0000
88.9586	0.8616	1.0000
89.0005	0.8410	1.0000
89.0423	0.8182	1.0000
89.0842	0.7925	1.0000
89.1261	0.7627	0.9903
89.1679	0.7268	0.9646
89.2098	0.6791	0.9357
89.2517	0.5860	0.9024
89.2936		0.8622
89.3354		0.8090
89.3773		0.7041

Table 2 Variation of global receiving voltage with system operating load

System operating load (p.u.)	Weak bus voltage, $V_g$ (p.u.)	
	Normal system	System with SVC
88.8748	0.8426	0.843
88.9167	0.8424	0.8429
88.9586	0.8422	0.8428
89.0005	0.842	0.8427
89.0423	0.8417	0.8427
89.0842	0.8414	0.8425
89.1261	0.8411	0.8424
89.1679	0.8406	0.8422
89.2098	0.84	0.8419
89.2517	0.8387	0.8416
89.2936		0.8412
89.3354		0.8406
89.3773		0.8395

starts drooping when SVC reaches its firing angle limit. It is observed here that the voltage level is significantly improved with the incorporation of SVC compared to the system with no compensation.

Table 2 gives the variation of global receiving end voltage ( $V_g$ ) with system operating load. It reveals that global receiving end voltage for the equivalent two-bus system is gradually decreasing with enhancement of load indicating the system is approaching towards local voltage collapse at equivalent receiving end. But with the application of SVC at suitable location, there is a sharp

improvement in voltage stability along with higher loading capability as it is observed from the table.

## 7. Conclusions

In this paper, an index called equivalent network based index (ENBI) is developed using the unique  $\pi$ -network equivalent derived with OPF solution of the actual system at different operating conditions, for identifying the suitable location for positioning SVC in the multi-bus system. Simulation results of the proposed method are compared with those found by the  $L$ -index method and found that the proposed method can be useful in identifying the location of SVC. Also the voltage stability margin augmentation with the application of SVC at the weakest bus is compared with the system having no compensation. Because of simplified approach and ability to calculate ENBI quickly, this new approach has the potential of being used in an on-line environment.

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## Appendix

SVC parameters adopted are:

- 1) Transformer reactance  $X_t=0.334$  p.u.,
- 2) Transformer resistance  $R_t=0$  p.u.,
- 3) Inductor reactance for the TCR,  $X_L=0.8741$  p.u. and
- 4) Capacitive reactance,  $X_C=3.2484$  p.u.

The maximum capacitive susceptance obtained is  $B_{SVC\_max} = 0.3431$  p.u. i.e., 34.31 MVar is the maximum reactive power that the SVC can inject at 1.00 p.u. terminal voltage. Fig. 7 depicts the variation in equivalent susceptance  $B_{t\_svc}$  and equivalent reactance  $X_{eq}$  with variation in firing angle  $\alpha$ . From the figure it is observed that resonance for the values adopted for the SVC model occurs at about  $128^\circ$ . Thus an initial value of  $140^\circ$  has been adopted for the firing angle  $\alpha$  and has been adopted for the test system considered.

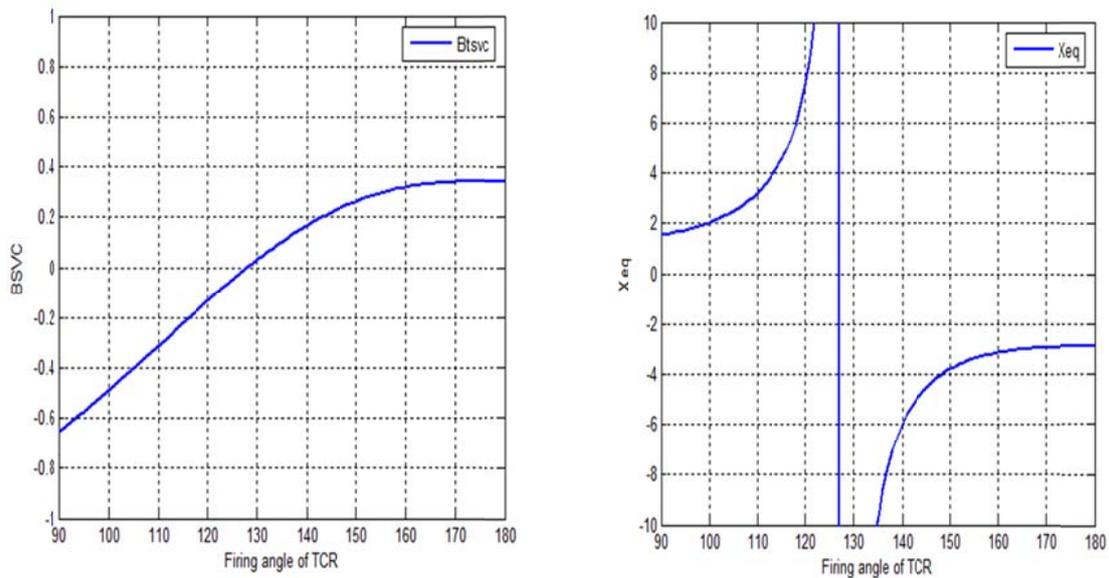


Fig. 7 Equivalent Susceptance ( $B_{t\_svc}$ ) & Total equivalent Reactance ( $X_{eq}$ ) of SVC