Optimal Placement for FACTS to Improve Static Voltage Stability

Min-Yan Gu* and Young-Sik Baek†

Abstract - FACTS devices, such as the Thyristor Controlled Series Compensator (TCSC) and Static Var Compensators (SVC), can help increase system load margin to improve static voltage stability. In power systems, because of the high cost and the effect value, the optimal placement for FACTS devices must be determined. This paper investigates the use of the series device (SVC) and the parallel device (TCSC) from the point of load margin to increase voltage stability. It considers the sensitivity of load margin to the line reactance and eigenvector of the collapse. The study has been carried out on the IEEE 14 Bus Test System to verify the validity and efficiency of the method. It reveals that incorporation of FACTS devices significantly enhance load margin as well as system stability.

Keywords: FACTS, load margin, optimal placement, static voltage stability.

1. Introduction

The problem of voltage collapse in power systems is now becoming one of the most important predicaments to resolve, as several major blackouts throughout the world have been directly associated to this phenomenon. Moreover, because of the blackout that occurred in America and Canada in 2003, people are attempting to discover alternative methods of improving voltage stability. In fact, power flow is very difficult to control because mechanical devices are too slow to switch alternating current cycle by cycle. Some fast acting hardware is needed that can work with existing lines to enhance their capabilities. FACTS devices meet this need.

The conception of FACTS as a total network control philosophy was first introduced by Dr. N. G. Hingorani from the Electric Power Research Institute (EPRI) in the USA in 1988, although the power electronic controlled devices had been used in the transmission network for many years before that.

Thyristor Controlled Series Compensators (TCSC) and Static Var Compensators (SVC) are the most popular devices of the FACTS. When TCSC is used in the network, it can control the transmission line impedance to improve the line transfer capability as well as regulate the receive bus voltage. For SVC it is often used to stabilize the bus voltage or keep it within certain limitations. It is indicated that the effectiveness of the controls for different purposes mainly depends on the location of the control device [1]. Furthermore it is impossible to perform the simulation on every bus in a large power system. Because of that, it is useful and essential to select one method to determine optimal placement. There are studies that allocate FACTS devices for damping inter-area oscillations and stability enhancement by employing eigenvalue analysis [2, 3]. References [4, 5] introduce a model analysis of the voltage stability. It is based on the participation parameter to decide the placement. Ref. [6] proposes a voltage stability index that is line load divided by the maximum load. This index points out the optimal location when it obtains the biggest value. In [7], a sensitivity approach based on line loss has been proposed for placement of series capacitors. In [8, 9], the optimal locations of FACTS devices are obtained by solving the economic dispatch problem plus the cost of these devices making the assumption that all lines, initially, have these devices. This paper is based on the sensitivity of load margin with respect to the system parameter [10] to allocate the TCSC device. For the SVC that is a parallel device, this paper just considers the eigenvector to the zero eigenvalue in the collapse point.

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2. Methodology

For a particular operating point, increasing load in a specific pattern that would cause voltage collapse is called the load margin. Now load margin is considered as one of the main indices to reflect voltage stability, so it is important and useful for us to find it from the practical power system and increase it to enhance system stability.

In paper [10], there is discussion surrounding the method used to acquire the sensitivity of load margin with respect to the system parameters or controls, for example, system load, reactive power support, wheeling and line susceptance. This paper will continue to study the sensitivity of load margin to the line reactance to decide the placement of TCSC.

First we can write the equation of the power system like this:

$$f(y,\lambda,p)=0 \tag{1}$$

where y represents the vector of state variables, λ corresponds to the vector of real and reactive load powers and p means any parameter of the system. In any steady state of the system this equation is satisfied. That means at the beginning point of the operating (y_0,λ_0,p_0) and saddle node bifurcation point (y_*,λ_*,p_*) there are two equations:

$$f(y_0,\lambda_0,p_0)=0 \tag{2}$$

$$f(y_*,\lambda_*,p_*)=0 \tag{3}$$

Here there is a relationship between λ_0 indicating the real and reactive powers at the beginning point of operating and λ_* indicating the saddle node bifurcation point. If we specify a pattern of load increase with a unit vector n it can be written like this:

$$\lambda_* = \lambda_0 + nL \tag{4}$$

where L is the load margin. Since n is a unit vector, it also follows that:

$$L=|\lambda_* - \lambda_0| \tag{5}$$

At the saddle node bifurcation point, the jacobian matrix $f_y|_*$ is singular. Here we use the left eigenvector $\omega(x_*,\lambda_*,p_*)$ (a row vector) corresponding to the zero eigenvalue of $f_y|_*$ such that:

$$\omega(y_*,\lambda_*,p_*)f_y|_* = 0 \tag{6}$$

The points (y, λ ,p) satisfying (1) and (6) corresponding to bifurcations and a curve of such points can be obtained by varying p in relation to its nominal value p_* . Linearization of this curve in relation to the bifurcation (y_*,λ_*,p_*) yields:

$$\begin{aligned} f(y_*,\lambda_*,p_*) &= f(y_0,\lambda_0,p_0)+f_y|_*\Delta y+f_\lambda|_*\Delta\lambda+f_p|_*\Delta p \\ &= 0+f_y|_*\Delta y+f_\lambda|_*\Delta\lambda+f_p|_*\Delta p=0 \end{aligned} \tag{7}$$

where f_y is the derivative of f with respect to the state variables y, f_λ is the derivative of f with respect to the load powers λ, and f_p is the derivative of f with respect to the parameter p. And the '$|_*$' means evaluated at (y_*,λ_*,p_*). Multiplication (7) by $\omega(y_*,\lambda_*,p_*)$ yields:

$$\begin{aligned} &\omega(y_*,\lambda_*,p_*)f_y|_*\Delta x+\omega(y_*,\lambda_*,p_*)f_\lambda|_*\Delta\lambda \\ &+\omega(y_*,\lambda_*,p_*)f_p|_*\Delta p=0 \end{aligned} \tag{8}$$

since (6) implies that $\omega(y_*,\lambda_*,p_*)f_y|_*=0$, we can get:

$$\omega(y_*,\lambda_*,p_*)f_\lambda|_*\Delta\lambda+\omega(y_*,\lambda_*,p_*)f_p|_*\Delta p=0 \tag{9}$$

using the parameterization of λ by L from (2) yields $\Delta\lambda = n\Delta L$ and substitution in (9) gives:

$$L_p\Big|_* = \frac{\Delta L}{\Delta p} = \frac{\Delta\lambda}{\Delta pn} = \frac{-\omega(y_*,\lambda_*,p_*)f_p|_*}{\omega(y_*,\lambda_*,p_*)f_\lambda|_* n} \tag{10}$$

here $L_p|_*$ means the sensitivity of the load margin to the change in parameter. If we consider parameter p as line reactance, then

$$L_x\Big|_* = \frac{\Delta L}{\Delta x} = \frac{\Delta\lambda}{\Delta pn} = \frac{-\omega(y_*,\lambda_*,p_*)f_x|_*}{\omega(y_*,\lambda_*,p_*)f_\lambda|_* n} \tag{11}$$

Because the denominator is not a vector, neglecting it allows us to at last obtain effectiveness of line reactance to the load margin:

$$L=\omega(y_*,\lambda_*,p_*)f_x|_* \tag{12}$$

3. The optimal placement of TCSC and SVC

If we use TCSC in a power system to improve the static voltage stability, where it is placed will change the line reactance. From (12) we find the most optimal position to put the TCSC is where L gets its biggest value. The reason is that L reflects the effect degree of line reactance to load margin, and TCSC is put in the line in series, so TCSC should be used to change the line reactance and to control load margin. Then we can improve the static voltage stability.

If SVC is used in the system, we only consider the left and right eigenvector to the zero eigenvalue in the collapse point, that is ω and $_T$. Because SVC is located in the system by parallel connection, it will affect the system through one node, and the eigenvector is corresponded to the node. If we can discover the eigenvector, we can decide the effect of SVC to the system, and then the position is found. When we use TCSC in the system, we should consider the equation (12). Because TCSC is located in the system in series, it will affect the system through the two nodes. We must find the relationship of the two nodes. Equation (12) does just this.

From equation (12) we can find that the load margin sensitivity only depends on quantities at the nominal bifurcation point. Once the nominal bifurcation point is computed, the sensitivity requires computation of the left eigenvector ω and the derivative $f_x|_*$ of the power system equation with respect to the line reactance. In many cases $f_p|_*$ has only one or two nonzero entries. Here $f_x|_*$ has four nonzero entries. If TCSC is supposed to be put in the branch j and the buses are k and m, in this case we can find that:

$$f_{X(2k-1),j}=\frac{V_kV_m\sin\theta_{km}}{R_{km}^2+X_{km}^2}-\frac{2X_{km}}{(R_{km}^2+X_{km}^2)^2}\bullet[R_{km}(V_k^2-V_kV_m\cos\theta_{km})+X_{km}V_kV_m\sin\theta_{km}]$$
$$f_{X(2k),j}=\frac{V_k^2-V_kV_m\cos\theta_{km}}{R_{km}^2+X_{km}^2}-\frac{2X_{km}}{(R_{km}^2+X_{km}^2)^2}\bullet[X_{km}(V_k^2-V_kV_m\cos\theta_{km})-R_{km}V_kV_m\sin\theta_{km}]$$
$$f_{X(2m-1),j}=-\frac{V_kV_m\sin\theta_{km}}{R_{km}^2+X_{km}^2}-\frac{2X_{km}}{(R_{km}^2+X_{km}^2)^2}\bullet[R_{km}(V_m^2-V_kV_m\cos\theta_{km})-X_{km}V_kV_m\sin\theta_{km}]$$
$$f_{X(2m),j}=\frac{V_m^2-V_kV_m\cos\theta_{km}}{R_{km}^2+X_{km}^2}-\frac{2X_{km}}{(R_{km}^2+X_{km}^2)^2}\bullet[X_{km}(V_m^2-V_kV_m\cos\theta_{km})+R_{km}V_kV_m\sin\theta_{km}]$$

and the other element of f_{Xj} is zero. Here V_k and V_m represent the voltage magnitude of nodes k and m, respectively. $\theta_{km}=\theta_k-\theta_m$ indicates the voltage angle difference of k and m. R_{km} and X_{km} signifies the resistance and reactance of line j.

Based on the bifurcation theory, two basic tools have been developed and applied to the computation of the collapse point, direct and continuation methods. Direct method concludes the point of collapse (POC) method [11], [12] and a pair of multiple load flow solutions (PMLFS) [13] with Lagrange polynomial interpolation. Based on the conventional power flow equations, the jacobian matrix used in these methods may become singular and, consequently, show numerical difficulties. [4] points out a new direct method. It uses the equations:

$$\begin{cases} f(y_*,\lambda_0+nL)=0 \\ \omega * f_y|(y_*,\lambda_*)=0 \\ \omega * C-1=0 \end{cases}$$

The continuation methods [15-17] are presented to use a prediction/correction scheme to find a solution path for a set of power flow equations that has been reformulated to include a load parameter. The vertical and horizontal iteration technique may be employed [15] and the critical PQ bus may be treated as a 'PV like' bus [17]. These techniques permit the power flow equations to remain well conditioned so that divergence due to a singular jacobian will not be encountered. When we use the continuation method to perform computations, the pattern of load increase should be decided. Here we see that it increases proportionally from the base case loading and keeps the power factor constant. It is possible to compute load margin to voltage collapse and their sensitivity using static equations. Dobson [18] proves that there is no loss accuracy in using static models in place of underlying dynamic models when computing load margins and their sensitivity.

4. Simulation results

Both TCSC and SVC are separately tested on the IEEE 14 Bus Test System in Fig. 1 and useful results are observed. Before the insertion of the FACTS devices, the system was pushed to its collapsing point by increasing both active and reactive load discretely using continuation load flow. This allowed the load margin of every bus and the system to be obtained without the use of FACTS.

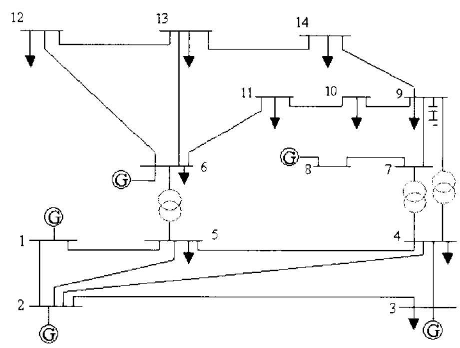

Fig. 1 IEEE 14-bus system diagram

When using the continuation load flow, the load increase direction is as shown in Table 1.

Table 1 Original load and the direction of load change

Bus number	Original load		Direction of load change	
	P	Q	P	Q
2	21.7	12.7	21.7	0.0
3	94.2	19.0	94.2	0.0
4	47.8	-3.9	47.8	-3.9
5	7.6	1.6	7.6	1.6
6	11.2	7.5	11.2	0.0
9	29.5	16.6	29.5	16.6
10	9.0	5.8	9.0	5.8
11	3.5	1.8	3.5	1.8
12	6.1	1.6	6.1	1.6
13	13.5	5.8	13.5	5.8
14	14.9	5.0	14.9	5.0

4.1 TCSC

For this IEEE 14 bus system, according to equation (12), we can obtain the value of L that is found in Fig. 2. It shows in lines 2-3 that the quantity of L reaches the greatest value. That means when the reactance of this branch is changed it will have the largest affect on the system load margin. Therefore, lines 2-3 should be selected first for TCSC. Lines 2-4 will also change the system greatly. Lines 12-13 and 13-14 will provide small contribution to the load margin.

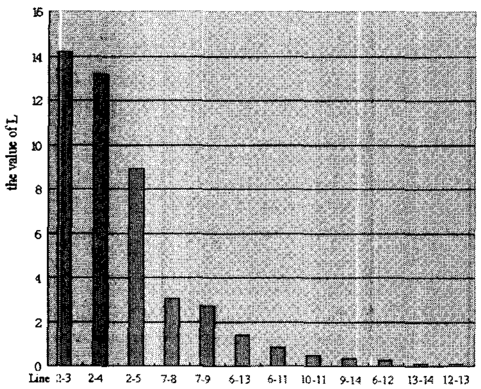

Fig. 2 The value of L

In fact when we put TCSC on a different line supposing the reactance is –j0.05, using the same continuation load flow we can get the load margin of the system. The numerical value of the load margin is identical between bus 14 and the system. Fig. 3 shows the load margin of bus 14 following installation of the TCSC on a different line as an example. In comparing Fig. 2 with Fig. 3 one conclusion achieved is that lines 2-3 show the most optimal placement for the TCSC. It also indicates that the sensitivity of load margin to the line reactance is a correct and useful method to direct the placement of the TCSC.

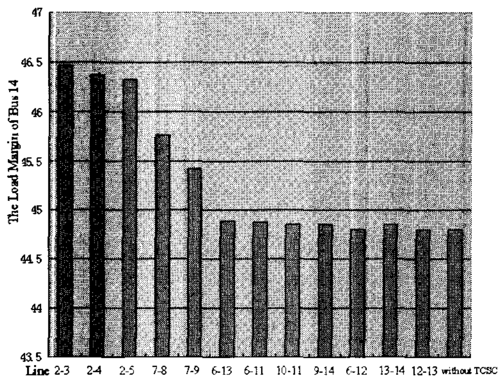

Fig. 3 Load margin of bus 14 after installing the TCSC on a different line

4.2 SVC

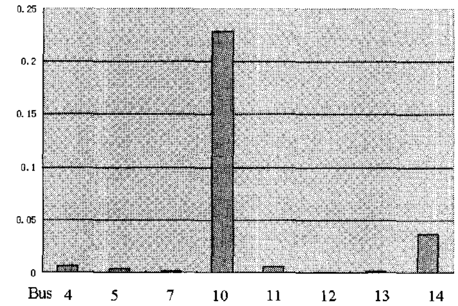

Fig. 4 The value of eigenvector

In this test system according to the eigenvector of the bifurcation point, upon comparing a different number we can find that bus 10 is the best placement point (Fig. 4). To affirm this theoretical result we suppose the SVC with susceptance 0.4 installed on a different bus. Fig. 5 shows its result with the load margin of bus 14. From these two figures, the identical result is received showing that bus 10 should be selected.

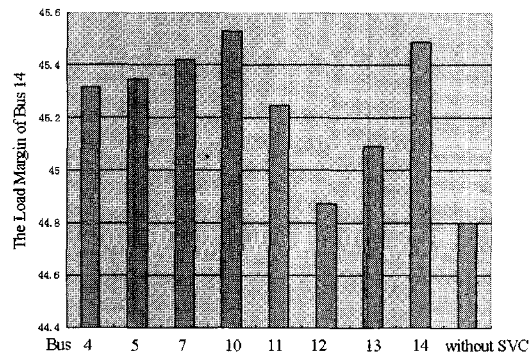

Fig. 5 Load margin of bus 14 after installing the SVC on a different bus

5. Conclusion

The method that is used to direct the placement of FACTS is a practical one. This paper employs the sensitivity analysis from the aspect of load margin with the outcome showing that it improved system stability. For the series devices, the two buses connecting the line must be considered. However, for the parallel devices, we simply use one correlative bus. As such, the series devices are more complex than the parallel devices. This theory is verified in the IEEE 14-bus system. However, in the large practical system, further studies are required in two respects. First, consideration should be given to the line stability limitation. Secondly, in some countries, when the voltage reaches the fixed lower limit, the auto-machines will decrease the load automation. These two factors will affect the system load margin.

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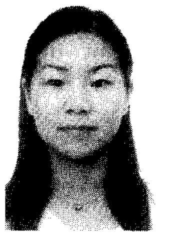

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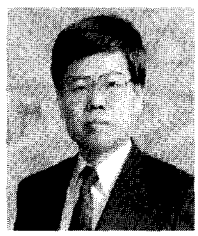

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