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Appropriate Placement of Series Compensators to Improve Small Signal Stability of Power System

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Abstract—Series FACTS devices like thyristor controlled series capacitors (TCSC) equipped with appropriate supplementary damping controller can improve the small signal stability of power system if they are located properly. In this paper, trajectory sensitivity analysis (TSA) is used to determine the best locations for installing TCSC to damp out the inter-area mode of oscillation. Based on the modal analysis, an equivalent angle is defined by determining critical and non-critical machines, and then using trajectory sensitivities of this angle with respect to the impedances of the transmission lines; appropriate locations for placing TCSC are found. To verify the accuracy of the proposed method, the residue technique for optimal placement of FACTS devices is also implemented in this paper. Both methods are applied to the IEEE 3-machines 9-buses test system, and the obtained results show the validity and efficiency of the proposed method.

Index Terms—Trajectory sensitivity analysis (TSA), Thyristor Controlled Series Capacitor (TCSC), Small Signal Stability.

I. INTRODUCTION

SMALL signal stability is the ability of the power system to keep its synchronism after being subjected to small disturbances. In a large scale power system, there are several electromechanical oscillations which are usually classified into inter-area modes and local modes. Local modes of oscillation are related to the oscillation of a single generator or a very small group of generators while in the inter-area mode of oscillation, the generators of one area oscillate against generators of another area. Power system stabilizers (PSS) can effectively damp out the local oscillation modes but they are not capable enough to control and damp the inter-area modes of oscillation, which usually take place at lower frequencies, appropriately. On the other hand, Flexible AC Transmission Systems (FACTS) equipped with the proper controller can have a significant impact on the power oscillation damping corresponding to the inter-area modes [1]. Using these devices most effective, it is vital to find the best locations for their installation [2].

Several methods have been proposed for the placement of FACTS devices in the previous literatures. Most of the research in this area have only considered static criterion, for instance, [3] has modified the optimal reactive power dispatch formulation considering FACTS devices as additional parameters and then defined sensitivity indices for optimal placement of FACTS devices to minimize the total system real power loss. In [3], TCSC, Static Var Compensator (SVC), and Thyristor Controlled Phase Angle Regulator (TCPAR) were studied. [4]

has derived injection models of TCSC and TCPAR and also introduced the real power flow performance index to find the optimal locations of TCSC and TCPAR for improving Total Transfer Capacity (TTC) of the system. [5] has represented sensitivity index of loading margin with respect to the transmission line impedances and described a method to find the lines for series compensation leading to the largest ATC. In [6], Particle Swarm Optimization (PSO) technique has been used to find number of FACTS devices, their setting and their best places for maximum system loadability and minimum installation cost in the case of using single type and multi type FACTS devices.

There are also some papers which considered dynamic criterion for optimal placement of FACTS devices. For instance, [7] has proposed controllability indices which show the impacts of FACTS devices on the improvement of inter area mode and have been calculated for SVC, TCSC and Unified Power Flow Controller (UPFC). After calculation of these controllability indices for each of FACTS devices in different locations and also for different operating conditions, the optimal places for installation of these devices have been determined. [8] has used an eigenvalue sensitivity approach to find the best locations of controllable series capacitors for damping power system oscillation. The calculated eigenvalue sensitivities are based on the product of the modal controllability of series reactance modulation and the observability factor of the input signal. [9] has applied trajectory sensitivity analysis to the power system for optimal placement of series FACTS devices to improve transient stability of power system. Computed trajectory sensitivities of rotor angles of generators with respect to the impedances of transmission lines show the effect of each transmission lines on the transient stability of power system when subjected to severe faults.

This paper is a continuation of [9] and uses trajectory sensitivity analysis to determine the best locations for installing series compensators to enhance power oscillation damping. It indicates that when there is no fault in the system, the trajectory sensitivities of generators' rotor angles to the impedance of transmission lines can be used as a powerful tool to find the most effective transmission lines for small signal stability improvement. The most important point is that the methods described here and in [9] can be used together as a powerful and efficient tool to analyze the effects of series FACTS devices on both transient and small signal stability of power system and also can be extended in a way to cover the other types of FACTS devices.

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II. POWER SYSTEM MODELING AND TRAJECTORY SENSITIVITY ANALYSIS

As explained comprehensively in [10], power systems can be modeled by the following differential algebraic equations

$$\dot{x} = f(x, y; \lambda) \quad (1)$$

$$0 = \begin{cases} g^-(x, y; \lambda) & s(x, y; \lambda) < 0 \\ g^+(x, y; \lambda) & s(x, y; \lambda) > 0 \end{cases} \quad (2)$$

$$x(t_0) = x_0, y(t_0) = y_0 \quad (3)$$

Where x are the dynamic states, y are the algebraic states and λ are the parameters of the system. Rotor angles of the generators (δ), magnitude and angle of bus voltages and impedances of the transmission lines are the examples of the dynamic states, algebraic states and parameters of the power system, respectively. x_0 and y_0 are initial conditions of dynamic and algebraic states. Function f is the set of differential equations which model the dynamics of equipments like generators. Events like a three phase short circuit fault occurs when $s(x, y; \lambda) = 0$. The algebraic equations g consist of the network equations based on Kirchhoff's current law, i.e. the sum of all current (or powers) flowing into each bus must be equal to zero, g^- and g^+ show the algebraic equations before and after occurrence of events.

To write the equations in a more organized way, vectors of $\underline{x}$ and $\underline{f}$ are defined as follows

$$\underline{x} = \begin{bmatrix} x \\ \lambda \end{bmatrix} \quad \underline{f} = \begin{bmatrix} f \\ 0 \end{bmatrix} \quad (4)$$

And therefore

$$\dot{\underline{x}} = \underline{f}(\underline{x}, y) \quad (5)$$

$$0 = \begin{cases} g^-(\underline{x}, y) & s(\underline{x}, y) < 0 \\ g^+(\underline{x}, y) & s(\underline{x}, y) > 0 \end{cases} \quad (6)$$

To calculate the trajectory sensitivities analytically, the derivatives of (5), (6) are calculated with respect to $\underline{x}_0$

$$\dot{\underline{x}}_{\underline{x}_0} = \underline{f}_{\underline{x}}(t) \underline{x}_{\underline{x}_0} + \underline{f}_y(t) y_{x_0} \quad (7)$$

$$0 = g_{\underline{x}}(t) \underline{x}_{\underline{x}_0} + g_y(t) y_{x_0} \quad (8)$$

where $\underline{x}_{\underline{x}_0}$ and y_{x_0} represent the trajectory sensitivities of dynamic and algebraic states with respect to the vector of power system parameters and initial conditions of dynamic states. The system is assumed to be away from the events. It is clear that the initial value for the trajectory sensitivities of dynamic states is an identity matrix. Using this matrix the initial values for the trajectory sensitivities of algebraic states can be also computed.

$$\underline{x}_{\underline{x}_0}(t_0) = I \quad (9)$$

$$y_{x_0}(t_0) = -(g_y(t_0))^{-1} g_{x_0}(t_0) \quad (10)$$

$\underline{f}_{\underline{x}}$, $\underline{f}_y$, $g_{\underline{x}}$ and g_y are time varying functions which are calculated along the system trajectories. When an event like a short circuit fault occurs in the power system, jump condition should be derived for computation of the trajectory sensitivities which is fully described in [10]. To find the trajectory sensitivities, the differential algebraic equations (5), (6), (7) and (8) should

be solved simultaneously with the initial conditions described above.

In this paper, since power system is going to be analyzed before fault occurrence, the system works in its operating point and all the state and algebraic variables are fixed. The trajectory sensitivities are computed using (7) and (8) with the initial condition described in (9) and (10), and as a result of non zero initial values, trajectory sensitivities will oscillate around their operating points. These oscillations exactly show how sensitive are state and algebraic variables to the system parameters for small disturbances in the system and will be used here as a tool for optimal placement of series compensators to improve small signal stability of power system.

III. SMALL SIGNAL STABILITY ASSESSMENT USING TRAJECTORY SENSITIVITY ANALYSIS

One way to investigate the small signal stability is to monitor rotor angles of generators (dynamic states δ) under small disturbances. If their oscillation are positively damped and decay with time, the power system is stable. Otherwise, there will be a negative damping in electromechanical oscillation which results in oscillatory instability. To improve the small signal stability, power system parameters can be controlled (if applicable) in a way to have positive effects on the power oscillation damping when the system is subjected to small disturbances and prevent power system from being oscillatory unstable. Impedance of transmission line is one of these parameters which can have a considerable effect on the stability of power system by controlling power flows in the transmission lines. Series FACTS devices like TCSC can control the impedance of transmission lines in a way to enhance the small signal stability of power system. Due to heavy cost of these devices, it is not economical to install several TCSCs in a power system, and therefore, the TCSC should be installed in the transmission line whose reactance modulation will be more effective to damp out the oscillatory modes of interest.

Since the goal of this paper is to calculate the trajectory sensitivities of rotor angles of generators to the impedances of transmission line, the matrices of power system parameters and trajectory sensitivities of dynamical states to the system parameters are as follows

$$\lambda = [x_{L_1} x_{L_i} \dots x_{L_{n_l}}] \quad (11)$$

$$\frac{\partial \delta}{\partial \lambda} = \begin{bmatrix} \frac{\partial \delta_1}{\partial x_{L_1}} & \frac{\partial \delta_1}{\partial x_{L_i}} & \dots & \frac{\partial \delta_1}{\partial x_{L_{n_l}}} \\ \frac{\partial \delta_2}{\partial x_{L_1}} & \frac{\partial \delta_2}{\partial x_{L_i}} & \dots & \frac{\partial \delta_2}{\partial x_{L_{n_l}}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial \delta_n}{\partial x_{L_1}} & \frac{\partial \delta_n}{\partial x_{L_i}} & \dots & \frac{\partial \delta_n}{\partial x_{L_{n_l}}} \end{bmatrix} \quad (12)$$

where x_{L_i} is the impedance of i^{th} transmission line, n_l is the number of transmission lines, δ_j is the rotor angle of j^{th} generator, and n is the number of generators. The matrix (12) is a part of solution to the equation (7) described in section II.

A. Definition of equivalent angle

In this part, an equivalent angle is defined and the trajectory sensitivity of this angle to the impedances of transmission lines is introduced for appropriate placement of series compensators. The right eigenvector corresponding to the mode of interest of the system has been used to determine how this mode is distributed among different generators of the system. Based on this modal analysis, generators are divided to two groups named A and B which oscillate against each other and then these two groups is replaced by a single machine equivalent system. B group consist of those generators which are more stable compared to the ones in A group. The equivalent angle includes all the rotor angles and is defined as follows [11]

$$M_A = \sum_{i \in A} M_i, \quad M_B = \sum_{j \in B} M_j \quad (13)$$

$$\delta_A = M_A^{-1} \sum_{i \in A} M_i \delta_i, \quad \delta_B = M_B^{-1} \sum_{j \in B} M_j \delta_j \quad (14)$$

$$\delta_{eq} = \delta_A - \delta_B \quad (15)$$

where M_i and δ_i are the inertia and rotor angle of i^{th} generator, respectively. According to this definition, the trajectory sensitivity of the equivalent angle to the impedances of transmission lines is as follows

$$\frac{\partial \delta_{eq}}{\partial x_{L_i}} = \frac{\partial \delta_A}{\partial x_{L_i}} - \frac{\partial \delta_B}{\partial x_{L_i}} \quad (16)$$

where

$$\frac{\partial \delta_A}{\partial x_{L_i}} = M_A^{-1} \sum_{i \in A} M_i \frac{\partial \delta_i}{\partial x_{L_i}} \quad (17)$$

$$\frac{\partial \delta_B}{\partial x_{L_i}} = M_B^{-1} \sum_{j \in B} M_j \frac{\partial \delta_j}{\partial x_{L_i}} \quad (18)$$

B. The proposed algorithm

- 1) Trajectory sensitivities of rotor angles with respect to the impedances of transmission lines are calculated solving (5), (6), (7) and (8) simultaneously, and without any fault in the system (before fault occurrence time). Simulation time does not need to be so long.
- 2) System modes can be determined using following A matrix

$$A = \underline{f}_x - \underline{f}_y g_y^{-1} g_x \quad (19)$$

$\underline{f}_x$, $\underline{f}_y$, g_x and g_y were defined in (7) and (8). The mode of interest can be found using the above matrix.

- 3) The mode of interest which is usually the one with poor damping and lower frequency is chosen. Based on modal analysis, A and B groups of generators are determined. It can be done using right and left eigenvector corresponding to the mode of interest and depicting compass plot.
- 4) According to (16), trajectory sensitivities of equivalent angle to the impedances of transmission lines are plotted using the obtained data in step 1. The ones which have the maximum positive amplitudes of oscillation are the most effective locations for placement of TCSC to improve the small signal stability.

IV. OPTIMAL PLACEMENT OF TCSC USING RESIDUE FACTOR

This method is based on the fact that shift of the eigenvalue caused by the TCSC controller is proportional to the magnitude of the corresponding residue. To verify the validity of the proposed algorithm in this paper, the method described in [7] is implemented according to the following procedure to find the best places to install TCSC.

- 1) Power system is linearized around its operating point and the mode of interest which is going to be improved is determined. The industrial software SIMPOW@11 is used for this simulation [11].
- 2) TCSC is placed at different transmissions lines and for each location, the power system is linearized around its operating point considering the active power of that line as the input signal and equivalent speed of generators ω_{eq} as the output signal. Equivalent speed can be calculated based on (13)-(15) using generator speeds instead of rotor angles.
- 3) For each location of TCSC, Residue factor associated with the mode of interest (λ_i) is calculated as follows

$$R_i = |CV_i^r V_i^l B| \quad (20)$$

where C and B are the output and input matrices after linearization, respectively. V_i^r is the i^{th} column of right eigenvector and V_i^l is the i^{th} row of left eigenvector.

- 4) The transmission line with the maximum positive value of residue is the most suitable place to improve the mode of interest and therefore small signal stability [7].

V. SIMULATION AND RESULTS

A. Proposed method implementation

The IEEE 3-machine 9-bus system shown in Fig. 1 is used to evaluate the proposed algorithm, the system data is available in [12]. The reactances of transformers are included in transient reactances of generators. Classical model is used for generators. Table I shows the most important modes of the system based on the linearization around the operating point. The compass plots depicted in Fig. 2 shows that for modes 1 and 2 which are the ones with lower frequencies, generator 1 oscillate against generator 2 and 3. Modes 1 and 2 are selected as modes of interest. Since the goal is to improve the mode of interest, equivalent angle is defined based on (15) considering generator 2 and 3 as the A group and generator 1 as the B group. Equations (5), (6), (7) and (8) are solved simultaneously using system parameters introduced in (11). Figure 3 shows the trajectory sensitivity of the equivalent angle to the impedances of different transmission lines. Table II demonstrates the priorities to install TCSC for improving small signal stability based on the peak values of the calculated trajectory sensitivities. It can be seen that line 3, 6 and 4 have the largest values, respectively and are the best places to install TCSC for improving small signal stability. Table II also shows that putting TCSC in the transmission line 1, 2 and 5 have a negative effect on the mode of interest and can worsen the small signal stability.

Fig. 1. Modified IEEE 3-machines test system.

TABLE I
Oscillatory modes of the test system

Mode no	Eigenvalue	Oscillating generators
1,2	$0 \pm 1.6339i(Hz)$	Gen1 vs Gen2 and Gen3
3,4	$0 \pm 2.4626i(Hz)$	Gen2 vs Gen3

TABLE II
Trajectory sensitivities of equivalent rotor angle to the impedance of different transmission lines - Peak to bottom values

Line no	Peak to bottom value
1	-0.0575
2	-0.0649
3	2.4623
4	0.3873
5	-0.0605
6	1.6402

B. Residue method implementation

Industrial software SIMPOW®11 is used to calculate the absolute value of residue in the presence of TCSC at different transmission lines. First, it is necessary to describe shortly how TCSC has been modeled in this study. Fig. 4 shows a transmission line equipped with a TCSC. The active power flow through transmission line between bus i and bus m when impedance of line is just a reactance is equal to

$$P_{im} = \frac{U_i U_m}{X_{eff}} \sin(\theta_{im}) \quad (21)$$

$$X_{eff} = X_{line} - X_{TCSC} \quad (22)$$

Where, X_{eff} is the value of effective reactance of the transmission line between Bus i and Bus m , X_{line} is the reactance of the transmission line, X_{TCSC} is the reactance of TCSC, U_i and U_m are the voltage magnitude of Bus i and Bus m , and θ_{im} is the angle difference between Bus i and Bus m .

Fig. 2. Compass plot corresponding to the modes no. 1,2 and no. 3,4

Fig. 3. Trajectory sensitivity of equivalent rotor angle to the impedances of different transmission lines

Since the transmitted active power is inversely proportional

Fig. 4. TCSC steady-state circuit series with a transmission line

to X_{eff} , variation of X_{eff} (due to the TCSC) results in variation of the power flow in the line. Therefore, TCSC can be used as a powerful means for controlling power flows in the transmission lines and for improving power oscillation damping in power systems. X_{TCSC} is

$$X_{TCSC} = X_{TCSC_0} + \Delta X_{TCSC} \quad (23)$$

where X_{TCSC_0} is the TCSC steady state reactance and ΔX_{TCSC} is the stability control modulation reactance. Controller which is used in this paper is based on the control lyapunov functions defined in [13]. According to these functions

$$\Delta X_{TCSC} = k_{TCSC} \sin(\delta_{eq}) \omega_{eq} \quad (24)$$

where k_{TCSC} is a positive gain and ω_{eq} is the equivalent speed of generator.

After implementing TCSC in the industrial software, TCSC is placed in different transmission lines. For each location, the magnitude of residue has been calculated and shown in Table III. The results are very similar to the ones shown in Table II, and Line 3, 6 and 4 are the most effective places to install TCSC for improving small signal stability, respectively. It should be mentioned that this method cannot show the installation locations that have a negative effect on the mode of interest and therefore small signal stability.

TABLE III
Absolute value of residue in the presence of TCSC at different transmission lines

Line no	Residue Index
1	0.0397
2	0.0443
3	1.6911
4	0.2434
5	0.0338
6	1.1082

To verify the correctness of obtained results, the exact changes of mode of interest after installing a TCSC in different transmission lines have been calculated. As it can be seen in Figure 5 and also Table 4, putting TCSC at line 3 can move the mode of interest to the more desires position.

VI. CONCLUSION

This paper proposes a novel method which uses trajectory sensitivity analysis as a tool to determine the effects of changing impedances of different transmission lines on the small signal stability of power system. Using the proposed

Fig. 5. Effects of installing TCSC in different transmission lines on the mode of interest

TABLE IV
Changes in mode of interest after installing a TCSC in different transmission lines

TCSC Location	Mode of interest
without any TCSC	0.0000 ± 10.2721i
TCSC installed in transmission line 1	0.0076 ± 10.2706i
TCSC installed in transmission line 2	0.0100 ± 10.2704i
TCSC installed in transmission line 3	-0.3853 ± 10.3306i
TCSC installed in transmission line 4	-0.0550 ± 10.2812i
TCSC installed in transmission line 5	0.0089 ± 10.2708i
TCSC installed in transmission line 6	-0.2512 ± 10.3130i

method, it is possible to find the most effective places to install series compensator with just one simulation instead of repetitive simulations, which will reduce significantly the computational cost. It has also been shown that installing series compensators in the transmission lines does not always improve the small signal stability of power system. The proposed method has been applied to the IEEE 3-machine 9-bus system using thyristor controlled series compensator. MATLAB®10b has been used for implementation of the proposed method, and finally results have been verified using industrial software SIMPOW®11. This method can be extended in a way to be applied to the other types of FACTS devices and along with the method described in [9] can be used as a powerful package to analyze the effects of any types of FACTS devices on both small signal and transient stability of power system.

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