EFFECTS AND MITIGATION OF STRONG RESONANCE IN POWER SYSTEMS WITH MULTIPLE PSS AND FACTS CONTROLLERS

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Abstract- The variation of power system parameters causes modal interaction within the power system modes and leads to strong resonance. The effect of this dynamic modal interaction on the oscillatory modes can affect the system stability. This paper examines the performance of these power system modes in the presence of PSS and FACTS controllers, and also provides solution to mitigate this problem. The significant modes of interest are identified using the methods of participation factors and isolated using the multi-modal decomposition. Then strong resonance is observed in complete and reduced system, during the simultaneous tuning of PSS and FACTS controllers. The reduced system is obtained by the method of perturbations, proposed by Seiranyan. The case studies are presented for the New England 10-machine 39 bus system.

Index Terms- Modal interaction, strong resonance, oscillatory modes, PSS, FACTS.

I. INTRODUCTION

The power system stability[1-3] can be evaluated by an examination of its modes consequent to the system linearization. When one or more controller parameters are varied, interaction or coupling between the power systems modes take place. The modes that are reasonably distant from each other come closer, coalesce, deviate and one of the modes subsequently becomes unstable. This could be due to the similarity of eigenvectors and eigenvalues [4-5]. Strong resonance is the outcome of coincidence of eigenvectors and eigenvalues, and the system input along one eigenvector will stimulate the other mode. Due to the modal interaction, it is observed that the increase in the damping of a mode results in the decrease of the damping another mode. The modal interactions can make the system unstable and hence it is essential to tune the controller parameters effectively to mitigate the problem of strong resonance. Also, from the engineer’s point of view it is significant for an early detection of strong resonance. The modes become exceedingly sensitive to parameter variations and the trajectory of the eigenvalues turns through a right angle near the strong resonance. Interestingly, an eigenvalue that varies in frequency before the resonance can vary in damping after the resonance and become oscillatory unstable. The strong resonance instigates oscillatory instability [6-8] in the sense that the resonance causes the eigenvalues to change the size and direction of their movement in such a way to make the system unstable. Practically, the power system may experience a near strong resonance, and its effects will be similar to exact strong resonance: the eigenvalues will move quickly and change direction as they interact thus leading to oscillatory instability. Dobson et al. [6-8] have examined the interaction of oscillatory power system modes near strong resonance. It has been observed that few of the interactions are related to sub synchronous resonance and this can result in oscillatory instability. Padiyar [4-5] has investigated strong resonance due to the variation of STATCOM controller parameters. The eigenvalue sensitivity often observed in oscillatory systems during investigation of parameters is analyzed by Seyranian [9-10]. The nature of eigenvalues of oscillatory systems which are dependent on several parameters is studied in the vicinity of a multiple point. The interaction of eigenvalues near this point, based on the theory recommended by Seiranyan has been applied to systems with feedback gain controller. The possibility of strong resonance among swing modes (SM) and excited modes (EM) in multimachine systems with PSS design have been analyzed by Nomikos and Vournas [11]. T.R. Jyothsna and K Vaisakh [12] have made an indepth analysis of strong resonance in presence of single as well as multiple PSS and have presented solution to mitigate strong resonance. T.R. Jyothsna and K. Vaisakh [13] have also investigated strong resonance with the supplementary modulation controller of SSSC in multimachine systems. The work presented in the current paper aims at investigating the strong resonance phenomenon while simultaneously tuning the parameters associated with a PSS and FACTS controllers [14-18] and it would be clearly observed from the results that strong resonance is a generic phenomenon. By a careful tuning of the controller parameters, the problem of strong resonance can be mitigated. The illustrative example include the New England 10-machine 39-bus system.
II. MODELLING OF FACTS AND PSS

A. Supplementary Modulation Controller for STATCOM

The STATCOM supplementary modulation controller considered in this paper is shown in Figure 1. The Thevenin voltage is the control signal to the SMC, and is obtained from the locally measurable signal. \( K_r \) and \( X_{th} \) are both tunable controller gains while \( T_p \) is the plant time constant. The transfer function of the STATCOM supplementary modulation controller is:

\[
\frac{\Delta I_r(s)}{\Delta V_1(s)} = \frac{-s K_r}{I + s(T_p - K_r X_{th})} \quad (1)
\]

where 

\( V_1 \) is the magnitude of the voltage of the bus where STATCOM is connected and \( I_1 \) is the magnitude of the reactive current injected by the STATCOM into the system.

![Figure 1: Supplementary modulation controller for the STATCOM](image)

B. PSS Model

The PSS considered is the same as in [1] and its center frequency \( f_c \) is given by:

\[
f_c = \frac{1}{2\pi \sqrt{T_{1T}}} \quad (2)
\]

and the transfer function of the system with PSS is given by:

\[
\frac{\Delta V_{pss}}{\Delta S_m} = \frac{s T_w}{1 + s T_w} \quad (3)
\]

C. Supplementary Modulation Controller for SSSC

The output of SSSC a voltage-sourced converter is a series voltage in the transmission line. The injected voltage magnitude can be controlled by itself for the purpose of regulating the total reactive voltage drop in the line. \( E_q \) is the injected reactive voltage magnitude and \( I_{ln} \) is the magnitude of line current. The input control signal to the SMC (shown in Figure 2) is the Thevenin angle, \( \Delta \phi_s \) and is produced from the local signal. Both the controller gains \( K_r \) and \( X_{th} \) can be tuned while \( T_c \) and \( T_p \) are time constants of the system. The SMC is placed in SSSC to improve the damping of unstable modes. The transfer function of SSSC controller is:

\[
\Delta E_q(s) = \frac{k_q (X_{th} + X_{br}) s}{1 + s(T_c + T_p + k_q) + s^2 T_c T_p} \quad (4)
\]

where \( I_{ln} \) is the current in the transmission line and \( E_q \) is the reactive voltage into the system.

![Figure 2: The supplementary controller for the SSSC](image)

III. REDUCED ORDER MODEL BASED ON MULTIMODAL DECOMPOSITION

The state-space representation for the linearized system can be expressed as:

\[
\dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u} \quad (5)
\]

\[
y = \mathbf{C} \mathbf{x} + \mathbf{D} \mathbf{u} \quad (6)
\]

where \( \mathbf{x} \) is a state variable vector, \( \mathbf{u} = [\Delta I_i, \Delta E_q, \Delta V_{psl}] \) and \( \mathbf{y} = [\Delta V_i, \Delta I_i, \Delta T_c] \) for STATCOM, SSSC, PSS respectively are the system input and output variables. The subscript \( f \) for the matrices in equations (5) and (6) correspond to the complete system. The states in equations (5) and (6) can be reorganized as \( \mathbf{x} = [\Delta \delta_1, \Delta \delta_2, ..., \Delta \delta_{ng}, \Delta S_{m1}, \Delta S_{m2}, ..., \Delta S_{mng}, Z^T]^T \), where \( \Delta \delta \) s and the \( \Delta S_m \)s correspond to the machine rotor angles and slips, \( Z \) is the vector of remaining states, and \( ng \) is the number of generators in the system respectively.

The interface between the swing and the exciter modes near the strong resonance is obtained, by using the concept of multi-modal decomposition [16]. Then a reduced system, in which modes that contribute to strong resonance are retained, can be represented by the state equations:

\[
\dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u} \quad (7)
\]

\[
y = \mathbf{C} \mathbf{x} + \mathbf{D} \mathbf{u} \quad (8)
\]

where \( \mathbf{x} = [\Delta \delta_{m1}, \Delta S_{m1}, \Delta E_{q1}, \Delta E_{f1}] \) \( \Delta \delta_{m1} \) : angle of \( i^{th} \) swing mode 
\( S_{m1} \) : angle of \( i^{th} \) swing mode 
\( E_{q1} \) : quadrature axis voltage of \( j^{th} \) generator 
\( E_{f1} \) : field voltage of \( j^{th} \) generator
IV. SINGLE MACHINE EQUIVALENT OF THE REDUCED MODEL

In the reduced system model the modes of interest as well as any one of the controllers is preserved and is then used to analyze the nature of the oscillatory modes in the point of strong resonance. The modes, that are responsible for strong resonance, are considered while the remaining are neglected. The reduced system shown in the figure 3 corresponds to a single machine infinite bus system.

\( \Delta \delta_m, \Delta S_m \): state variable of the \( i^{th} \) mode
\( \Delta E_q, \Delta E_{fd} \): state variables associated with the \( j^{th} \) machine
\( H_m \): modal inertia at the \( j^{th} \) machine corresponding to \( j^{th} \) mode
\( D_m \): modal damping associated with \( i^{th} \) mode
\( T_{do} \): open circuit transient time constant
\( K_A \): Automatic voltage regulator gain
\( T_A \): exciter time constant
\( \Delta I_r \): output of damping controller

where \( A_{ij} \) is the \( (ij)^{th} \) element of \( A_{ij} \).
Also the gains, \( K_r = \partial T / \partial \delta \), \( K_v = \partial V / \partial u \) and \( K_{pv} \) can be expressed in terms of \( B_{ij} \) matrix as follows:

\[
K_{Fr} = T_{do} b_r 3
\]
\[
K_{Tr} = -2 H m b_r 2
\]
\[
K_{Vr} = -b_r 4 \frac{T_A}{K_A}
\]

where \( b_{ij} = B_{ij} \).
The state equations of the reduced system can be expressed as:

\[
\Delta \delta_a = \frac{s \Delta \delta_a}{\omega_s} \quad (9)
\]
\[
\Delta S_a = \frac{K K}{2H} \Delta \delta - \frac{K K}{2H} \Delta S - \frac{K K}{2H} \Delta E - \frac{K K}{2H} \Delta N \quad (10)
\]

\[
\Delta E_a = \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} \quad (11)
\]

\[
\Delta N_a = \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} \quad (12)
\]

Taking Laplace transform of equations (9) and (12), we get

\[
\Delta S_a = \frac{s \Delta \delta_a}{\omega_s} \quad (13)
\]

\[
\Delta E_a = \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} - \frac{K K}{T_e} \frac{K E}{K E} \quad (14)
\]

Substituting equation (13) in the Laplace transformed equation of (10), we get

\[
M \Delta \delta + \frac{D}{\omega_s} \Delta \delta + K \Delta E + K \Delta N = -K \Delta L \quad (15)
\]

where \( M = \frac{2H}{\omega_s} \). Similarly, substituting equation (14) in the Laplace transformed equation of (11) and simplifying the resulting equation, we get

\[
(1 + K K K K K K) \Delta \delta + (1 + K K K K K K) \Delta \delta + (1 + K K K K K K) \Delta \delta + (1 + K K K K K K) \Delta \delta + (1 + K K K K K K) \Delta \delta = -K \Delta L \quad (16)
\]

Taking inverse Laplace transform of equations (15) and (16) and arranging the resulting equations in the matrix form we get

\[
M \Delta \delta + D \Delta \delta + A q = B u \quad (17)
\]

where \( q = [\Delta \delta_m, \Delta E_q]^T \), \( u = [\Delta I_r, \Delta E_q, \Delta V_{psl}] \); for STATCOM, SSSC, PSS respectively.

The reduced system represented by (7) and (8) is expressed by a vector differential equation. The output (8) of the system with the damping controller can also be written as

\[
\Delta V_s = C q(s) + D_q \Delta u(s) \quad (18)
\]

where

\( C = [C_{ij}, C_{ij}] \), \( C_{ij} = C_{ij} = 0 \) and \( C_{ij} \) is the \( (ij)^{th} \)

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element of \( C_{th} \). The mathematical model of the damping controller can be written as:

\[
\Delta V_1(s) = \frac{1 + sT_k - sK_f X_{th}}{-sK_r} \Delta u(s) \tag{19}
\]

Substituting (19) in (18), an equation relating \( \Delta u \) and \( q \) can be obtained as

\[
\Delta u(s) = \frac{-CK_f sq(s)}{1 + sT_k} \tag{20}
\]

Substituting (20) in (17) gives

\[
A_1 \frac{d^4 q}{dt^4} + A_2 \frac{d^3 q}{dt^3} + A_3 \frac{d^2 q}{dt^2} + A_4 \frac{dq}{dt} + A_5 q = 0 \tag{21}
\]

The elements of the matrices \( A \) are functions of the parameter vector \( p \). The phenomenon of strong resonance with the damping controller is studied for the reduced system. The significant hyperbola are formed by making appropriate changes based on the theory suggested by Seiranyan [4-5] and the work presented by Padhy [9-10] and then the dynamic nature of the two oscillatory modes is examined as one or more parameters vary. In the present work, the system and controller dynamics are characterized by vector-matrix differential equation given in equation (17).

T.R.Jyothsna and K.Vaisakh have analyzed the phenomenon of strong resonance with single/multiple PSS [12] and with a single SSSC [13] in depth. The present work extends the strong resonance phenomenon to a simultaneous tuning of PSS and FACTS for a large system.

V. ANALYSIS OF STRONG RESONANCE WITH PSS, STATCOM AND SSSC

The behavior of strong resonance with PSS, STATCOM and SSSC has also been noticed in the 10-machine, 39 bus New England system. PSS is located at generator number 9; STATCOM is located at bus number 29, and SSSC is placed in the line 26-29. Interestingly, simultaneous tuning of all the three controller parameters, results in an interaction between two swing modes #3 and #4 as shown in Figures 4-6.

It is observed from the Figure 4 that, for \( \Delta K_q > 0 \) that before the point of strong resonance both SM #3 and #4 move towards each other the former changing in frequency while the latter changing in damping more. After the point of strong resonance SM #4 is stabilized while SM #3 is unstable.

In a similar manner, it can be observed from the Figure 5 that, for \( \Delta K_q < 0 \) before strong resonance the modes are coming closer together, while after strong resonance, there is still further improvement in the damping as well as increase in the frequency of the mode of SM #3. SM #4 is found to be unstable.

Strong resonance has been observed when \( K_r \) is varied from 0 to 1.5 with \( X_{th} = 0.02 \) and \( K_{th} \) tuned to a value of 1.45 with \( X_{th} \) varying from 0.021 to 0.032 for \( \Delta K_q = 0 \) in figure 25. Hence, while
simultaneously tuning the PPS, STATCOM and SSSC it is observed that there is a strong resonant pair observed between two swing modes.

VI. DISCUSSION

From the above observations it is clearly evident, that variation in parameters of PSS and FACTS devices with their modulation controllers can alter the power system linearization and its eigen modes. The low frequency modes can approach one another and diverge, thus resulting in one of the modes to become unstable. Strong resonance phenomenon takes place when two oscillatory modes overlap and the modes typically become responsive to changing parameters and their movement twists through approximately a right angle. It is clear from the above results that based on the configuration of the system, strong resonance can be detected while simultaneous tuning of PSS and FACTS controllers.

CONCLUSIONS

The work presented in this paper clearly depicts the strong resonance phenomenon in presence of PSS and FACTS and it is clearly observed from the results that strong resonance is a generic phenomenon; While simultaneously tuning a PSS and a FACTS controller, there can be only one strong resonant point. An effective design of PSS and FACTS controllers has been presented to avoid the problem of strong resonance. As a creative solution to the problem of strong resonance, this research suggests that consideration of the collaborative modes is essential during design of PSS and FACTS damping controllers. The pertinent choice for the controller tuning to be optimal, enumerating the consequences of interactive modes is imperative; to buttress the reliability and elevated performance of the power system.

REFERENCES


