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Proposed mechanism for performance of power system stabilizers in the condition of strong resonance

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ABSTRACT

This paper suggests a mechanism for the dynamic performance of damping controllers in the condition of strong resonance. The mechanism explains theoretically how the variation of a control parameter can move the resonance point in such a way to stabilize or destabilize the coupled modes. As an application, this mechanism is applied to justify the performance of power system stabilizers (PSSs) in a 2-area 4-machine test system, in which an exciter mode and an inter-area mode interact near a strong resonance. It makes the performance of the PSSs on the stability of the inter-area mode become severely dependent on the place of the PSS and the position of operating point with respect to the resonance point. In this circumstance, the PSSs of one of the system areas destabilize the inter-area mode. Considering the proposed mechanism, the appropriate location of the PSS and its proper gain value are identified to obtain the maximum damping of inter-area mode at each of the operating points. In addition, it is shown that due to the strong resonance, conventional methods make incorrect placement of the PSS; however, by using the *real part of speed participation factors*, suitable machines are chosen to place the PSS. This index provides important information regarding the impacts of strong resonance on the performance of PSSs.

1. Introduction

Interaction of oscillatory modes can make the dynamic behavior of power systems more complicated. It can make the performance of the system controllers unpredictable so leading to instability of the system oscillatory modes. A reason for increasing the coupling and interaction between two modes arises from resonance, in which an exact coincidence of eigenvalues occurs in damping and frequency. There are two types of resonance: strong and weak [1]. If the linearization is not diagonalizable at the resonance point (due to coincidence of eigenvectors), the resonance is called a *strong resonance*; otherwise, it is a *weak resonance*. Strong resonance causes a severe interaction between two modes. In practice, an exact strong resonance is not common in power systems. However, as power system parameters vary, it is quite expected for two complex modes to pass near a strong resonance which gives rise to similar interactions. In this condition, the eigenvalues and eigenvectors of two modes become extremely sensitive to parameter variations and the eigenvalues move quickly and turn by approximately 90 degrees on the complex plane [1]. It can make one of the modes become unstable.

There are various research works regarding the study of the resonance phenomenon in power systems and mechanical systems. Dobson et al. [1] have thoroughly reviewed these works up to the year 2000. They suggest that the modal interaction of two oscillatory modes near a strong resonance can be treated as a mechanism for inter-area oscillations, which can yield instability of modes. At first by mathematical analysis it is demonstrated how the eigenvalues move while passing near strong resonance, and then it is featured in 3- and 9-bus examples as generator power is redispatched. It is important to consider both modes while trying to stabilize the system near strong resonance.

In another work, Dobson [2] has studied the strong resonance effects on normal form based indices, which are used to quantify the nonlinear modal interactions. It is mathematically shown that the indices become very large near a strong resonance. In addition, the paper shows that modal interactions associated with a perturbation of weak resonance can cause subsynchronous resonance instability. These interactions are illustrated as a pair of near strong resonances.

The effect of strong resonance on the normal form analysis is also one of the topics of the next works [3,4]. The perturbations of a weak resonance are analyzed thoroughly in [5]. Two distinct perturbations are mathematically identified and then illustrated with interactions between electromechanical modes in a 2-area 4-machine test system.

Seyranian and Mailybaev [6] have presented a general theory of interaction between eigenvalues of matrix operators depending on multiple parameters. Strong and weak resonances and their geometric interpretations on the complex plane are analyzed when one parameter changes.

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Padiyar and Saikumar [7] have investigated the strong resonance in power systems with STATCOM supplementary damping controller. Examples of 3- and 4-machine show that variations of the controller parameters cause two modes to pass near a strong resonance. Results indicate the importance of considering the effect of strong resonance on the coupled modes in designing of damping controllers.

Shu Liu et al. [8,9] have assessed the nonlinear behavior of a power system and proposed nonlinear approaches for the placement of power system stabilizers (PSSs) by using normal form analysis. They simulated an ample range of operating conditions of a 2-area 4-machine test system in their case study. The power transfer between the interconnected areas is increased from 180 MW to about 410 MW in steps, as a variable parameter which implies the degree of system stress. It is shown that the inter-area mode of the system passes near a strong resonance at operating condition with power transfer of about 350 MW. Authors indicate that unlike the low stress condition (180 MW), at a high stress case (410 MW) the conventional linear methods of PSS placement (using mode shape, residues, and participation factors) do not identify suitable machines to place PSS, so lead to destabilization of the inter-area mode. As the authors in their studies have not considered the effect of passing near strong resonance on the performance of the system PSSs, they have concluded that this inefficiency of the conventional linear methods is due to the increase of system stress and growth of nonlinearity resulting from nonlinear modal interactions near second-order resonances. Accordingly, they suggest that the nonlinear approaches to be used in determining the most effective machines for placing PSSs.

In the present paper, the same case study as [8,9] is employed, while focusing on the linear phenomenon of strong resonance. Attempt has been made to clarify PSSs performance using linear analysis and to solve the problem of PSS placement for system inter-area mode by using a new linear index. In Section 2, theoretically a mechanism is suggested through which the stabilizer controllers can apply the condition of near strong resonance to stabilize or destabilize the system oscillatory modes. In Section 3, as a case study, the mechanism is illustrated in the performance of PSSs of a 2-area 4-machine test system. The problem of PSS placement in this system at various operating conditions is another topic of this section. Finally, the conclusion is offered in Section 4.

2. Theoretical concepts

2.1. Modal interaction near a strong resonance

Occurrence of a strong resonance can be illustrated in the complex eigenvalues of a matrix like M in (1) which is parameterized by the real number α [1]

$$M = \begin{pmatrix} r & s & 0 & 0 \\ \alpha & r & 0 & 0 \\ 0 & 0 & r^* & s^* \\ 0 & 0 & \alpha & r^* \end{pmatrix}. \tag{1}$$

where r and $s \neq 0$ are constant complex numbers. Also M can be written as

$$M = \begin{pmatrix} M_\alpha & 0 \\ 0 & M_\alpha^* \end{pmatrix}. \tag{2}$$

in which the 2×2 complex matrixes M_α and M_α^* are complex conjugate. The eigenvalues of M are the set of eigenvalues of M_α (are calculated by $r \pm \sqrt{\alpha.s}$) and their complex conjugates. Choosing $r = -1.5 + 4j$ and $s = 1 - j$ in (1) gives

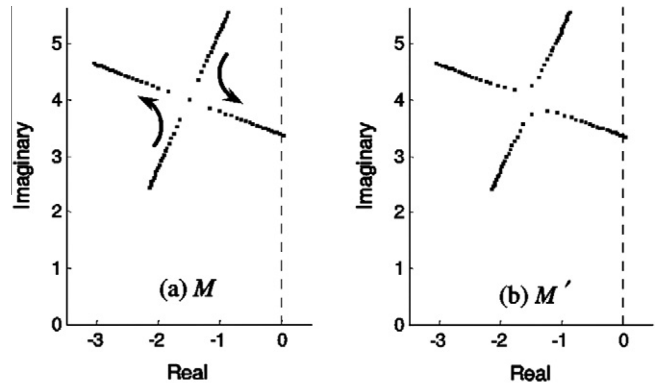

Fig. 1. Movement of two eigenvalues of matrices M and M' as α varies.

$$M = \begin{pmatrix} -1.5+4j & 1-j & 0 & 0 \\ \alpha & -1.5+4j & 0 & 0 \\ 0 & 0 & -1.5-4j & 1+j \\ 0 & 0 & \alpha & -1.5-4j \end{pmatrix}. \tag{3}$$

Note that M can be structured as the real matrix

$$\begin{pmatrix} -1.5 & 1 & 4 & -1 \\ \alpha & -1.5 & 0 & 4 \\ -4 & 1 & -1.5 & 1 \\ 0 & -4 & \alpha & -1.5 \end{pmatrix}.$$

As α varies from -2 to 2 in steps of 0.1, two eigenvalues of M move on the complex plane as shown in Fig. 1a. By increasing α from -2 to zero, the eigenvalues approach each other and coincide at $\alpha = 0$ as strong resonance at the point of $-1.5 + 4j$. As α increases through zero, the eigenvalues change their direction by 90° and separate from each other and subsequently one of them crosses the imaginary axis and becomes unstable. Around the resonance point, eigenvalues are extremely sensitive to parameter variations and move quickly.

By adding a perturbation to the matrix M, the eigenvalues interact near a strong resonance [1]. Consider a matrix M' as follows:

$$M' = M + \Delta M, \Delta M = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 \end{pmatrix}. \tag{4}$$

Substitution of (3) in (4) yields

$$M' = \begin{pmatrix} -1.5+4j & 1-j & 0 & 0 \\ \alpha & -1.5+4j & 1 & 0 \\ 0 & 0 & -1.5-4j & 1+j \\ 2 & 0 & \alpha & -1.5-4j \end{pmatrix}. \tag{5}$$

Fig. 1b shows the movement of two eigenvalues of M' on the complex plane as α varies from -2 to 2. Passing near strong resonance leads to interaction between eigenvalues similar to one caused by exact strong resonance except that the right paths of eigenvalues movement change into two parabolic curves around an operating point at which the distance between two interactive eigenvalues is minimum. We call this point as an *interaction center*, which is associated with $\alpha = 0.0$ in the present case. Eigenvalues turn quickly and one of the modes subsequently becomes unstable.

Fig. 2 shows the damping ratio of the modes of matrix M' as the parameter α varies from -2 to 2. Although passing near strong resonance causes one of the modes to become unstable, it provides an appropriate damping for the mode in the vicinity of the interaction center.

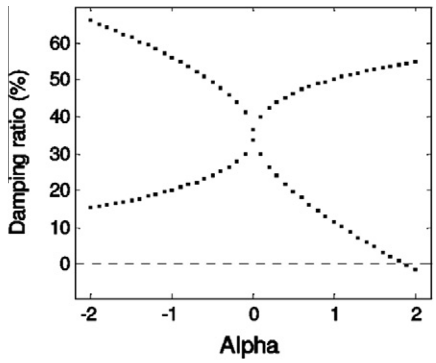

Fig. 2. Damping ratio of the modes of matrix M' as α varies.

2.2. A mechanism for stabilizers performance

Suppose that matrix M' is the Jacobian of a nonlinear dynamic system which is linearized at the equilibrium point corresponding to an operating point. Moreover, suppose that the value of α is a function of the system dominant parameters which determine the system operating point (such as load and generation dispatch in a power system). Therefore, each value of α corresponds to an operating point of the system. Fig. 2 shows that for operating points corresponding to (approximately) $\alpha \succ 1.5$, the status of stability is critical. It is obvious that if there is a control parameter whose variation causes the interaction center to be shifted towards operating point with $\alpha \succ 0$, the system stability increases. Such a parameter can be denoted by a real number k which is subtracted from α in the matrix M'. The new matrix M'_k in (6) shows this parameter.

$$M'_k = M' + \begin{pmatrix} 0 & 0 & 0 & 0 \\ -k & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -k & 0 \end{pmatrix} = \begin{pmatrix} -1.5+4j & 1-j & 0 & 0 \\ \alpha & -1.5+4j & 1 & 0 \\ 0 & 0 & -1.5-4j & 1+j \\ 2 & 0 & \alpha & -1.5-4j \end{pmatrix}. \quad (6)$$

In simple words, parameter k makes the interaction center move to the operating point of $\alpha = k$. Obviously, positive value of k causes the curve of Fig. 2 to move to the right so the critical mode damping at $\alpha \succ 1.5$ increases. In contrast, negative value of k shifts this curve to the left; hence the critical mode damping is reduced.

Fig. 3 shows two examples for the effect of the variations of the parameter k on damping of M'_k modes. In each case, only those modes having the lowest damping are shown. In this figure, the curve corresponding to $k = 0$ (the middle one) is the same as Fig. 2, which is associated with the original matrix M'. The right-shifted curve is associated with $k = 1$ and shows a good stabilization of the mode for $\alpha \succ 1$. However, the mode damping has decreased at the operating points with $\alpha \prec 0$. On the contrary, the left-shifted curve associated with $k = -1$ shows a destabilization of the mode for $\alpha \succ 0$. It also has increased the mode damping at the operating points with $\alpha \prec -1$. For two cases of the above example, Fig. 4 shows the movement of two eigenvalues of M'_k on the complex plane.

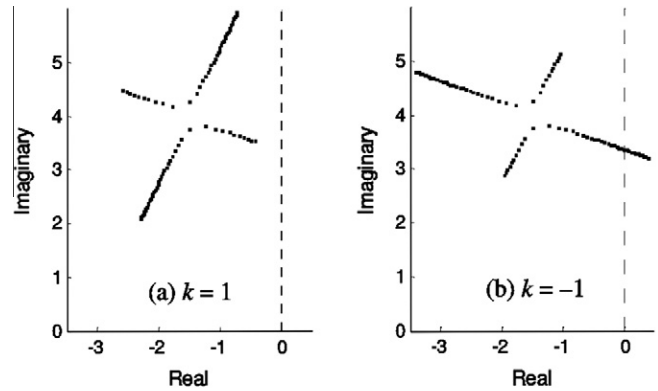

Fig. 4. Two eigenvalues of matrix M'_k as α varies from -2 to 2: (a) $k = 1$ and (b) $k = -1$.

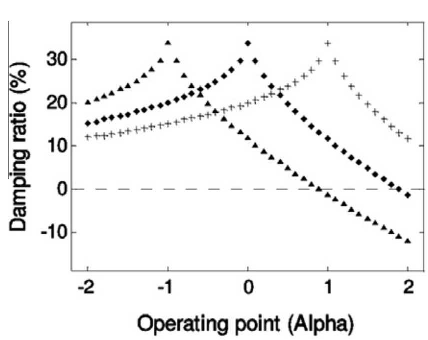

Fig. 3. Damping ratio of M'_k modes for different values of k as α varies; ▲: $k = -1$, ♦: $k = 0$, +: $k = 1$.

The above results show that at all operating points, due to the strong resonance, the effect of the parameter k on the damping of M'_k modes is dependent on two factors: (1) the position of operating point with respect to the original interaction center and (2) the magnitude and the sign of the parameter k. Thus, for any certain operating point, by choosing an appropriate value for k, the condition of strong resonance can be employed to enhance the system stability. It implies that if the control parameter of a stabilizer such as the gain value of a PSS has the same effect as the parameter k, it is essential to consider the effects of strong resonance on the stabilizer performance.

Other parameters also can be considered which affect on the damping ratio of M' modes by changing the resonance condition. For example, in the original matrix M in (1), variation of r causes the resonance point to move on the complex plane; Moreover, variation of s turns the eigenvalues movement paths round the resonance point and changes the length of eigenvalues branches. Furthermore, variation in the perturbation of ΔM in (4) changes the diameter of the parabolic curves of the eigenvalues movement and the distance between them. This variation can also alter the turn direction of eigenvalues paths so causes the transference of instability between eigenvalues branches [10]. Therefore, it is important to investigate the effect of stabilizers parameters on the above mentioned variations while trying to stabilize system oscillations in the condition of strong resonance. Reference [7] presents a similar investigation in power system examples.

3. Case study

3.1. Test system

The developed theorem is applied on a 2-area 4-machine test system from [11]. This system has been widely used for studying inter-area oscillations and power system dynamics [12–15]. This system includes two areas which are connected together via a weak tie line. Each area has a local mode, and an inter-area mode

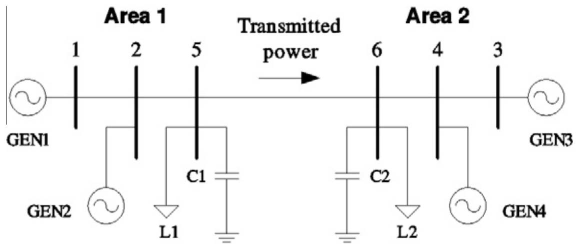

Fig. 5. Schematic of 2-area 4-machine test system.

is common between two areas. Fig. 5 shows a simplified single-line diagram of this system. In this study, all generators are modeled by the two-axis model [16]. Each of them is equipped with a static exciter and automatic voltage regulator (AVR) as shown in Appendix A.1. All loads are modeled as constant impedances. The system parameters and power flow data are given in Appendix A.2.

3.2. Providing the condition of near strong resonance

Bilateral symmetry in the original version of the 2-area 4-machine system would cause a weak resonance between local modes [5]. In [8,9] by choosing different values for the damping coefficient and the exciter gain of the machines, the condition of near strong resonance has been provided. In the present study, the same defined parameters are used.

The variable parameter is the power transfer between areas, which is varied from 180 MW to 420 MW. To establish this condition, the installed load at bus 5 is decreased from 1120 MW to 880 MW (in steps of 5 MW) and the installed load at bus 6 is increased from 1180 MW to 1420 MW (in the same steps). The system generator data for the first and the last operating points (with 180 MW and 420 MW transmitted power respectively) is given in Appendix.

Tables 1 and 2 show the information of the system oscillatory modes for the first and the last operating points respectively. We use the knowledge of participation factors to identify the type of oscillatory modes By this method, distinguishing between two modes, which interact near strong resonance is too difficult around the interaction center because of the growth of coupling between modes. However, it is possible to identify these modes at operating points far from the interaction center on both sides and pursue them until the interaction center.

In order to recognize the existence of resonance between system modes and study its modal interaction, linear modal analysis is performed for all operating points. Fig. 6 shows the eigenvalues movement of the system dominant modes on the complex plane. The damping ratio of all system modes in terms of the power transfer of the tie line is shown in Fig. 7. According to Fig. 6, with a gradual increase in the transmitted power, the modes pass near strong resonance twice. The first one occurs between two exciter modes around the transmitted power of 225 MW. Its interaction center is defined by guide-line (1) in Figs. 6 and 7. It doesnot cause instability in the related modes. However, the second one takes place between the inter-area mode and one of the exciter modes around the transmitted power of 345 MW. Its interaction center is denoted by guide-line (2) in Figs. 6 and 7. As seen in Fig. 6, a severe interaction occurs between these modes and leads to instability of the inter-area mode at high transmitted powers. The eigenvalues movement and approximate eigenvectors coincidence of these modes are also featured in [8, Fig. 3].

Fig. 7 shows that the damping of the inter-area mode increases before the interaction center and decreases afterwards so becomes unstable at the transmitted power of 420 MW. It should be noted that although passing near strong resonance leads to instability of inter-area mode at high transmitted powers, it causes the mode damping to increase to a maximum value at the operating points around the interaction center.

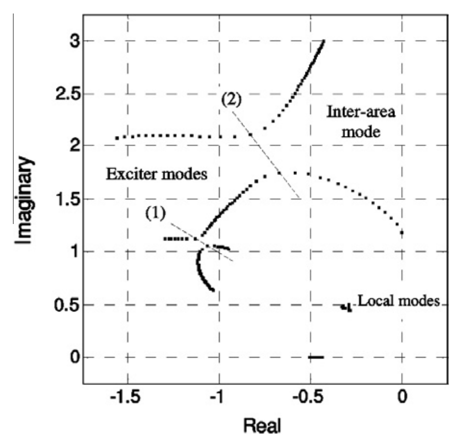

Fig. 6. Eigenvalues movement of dominant modes as transmitted power varies.

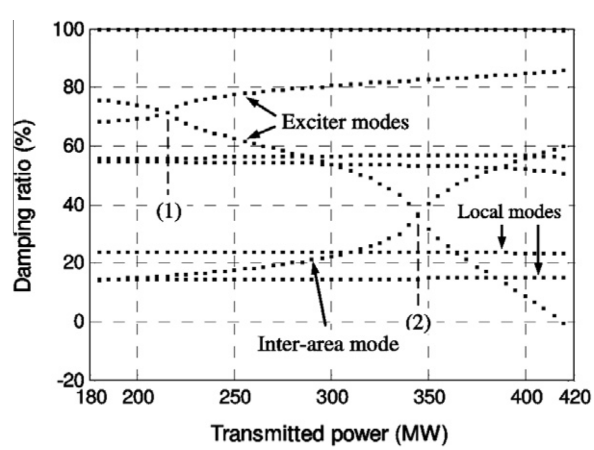

Fig. 7. Damping ratio of the modes as transmitted power varies.

Table 1
Oscillatory modes of system at the first operating point.

Mode no.	Eigenvalues	Frequency (Hz)	Damping (%)	Mode type
11, 12	$-1.114 \pm j7.71$	1.227	14.30	Local, area1
13, 14	$-1.815 \pm j7.42$	1.182	23.75	Local, area2
16, 17	$-0.426 \pm j2.99$	0.476	14.11	Inter-area
19, 20	$-1.296 \pm j1.12$	0.179	75.54	Exciter
21, 22	$-0.949 \pm j1.02$	0.163	68.05	Exciter
25, 26	$-0.306 \pm j0.46$	0.073	55.71	–
27, 28	$-0.285 \pm j0.44$	0.069	54.68	–

Table 2
Oscillatory modes of system at the last operating point.

Mode no.	Eigenvalues	Frequency (Hz)	Damping (%)	Mode type
9, 10	$-1.157 \pm j7.74$	1.232	14.78	Local, area1
11, 12	$-1.794 \pm j7.56$	1.203	23.09	Local, area2
15, 16	$-3.806 \pm i0.42$	0.067	99.39	–
17, 18	$-1.561 \pm j2.07$	0.330	60.13	Exciter
19, 20	$0.005 \pm j1.18$	0.188	-0.40	Inter-area
21, 22	$-1.033 \pm j0.63$	0.100	85.55	Exciter
24, 25	$-0.291 \pm j0.50$	0.079	50.53	–

The curves of the exciter mode and inter-area mode around the guide-line (2) in Figs. 6 and 7 are quite similar to those of the matrix M' modes in the Figs. 1b and 2 respectively. There is a perfect similarity between the inter-area mode and the lowest damping mode of M'. As Fig. 7 shows, the inter-area mode needs to be stabilized at the critical operating points associated with transmitted powers higher than 400 MW. According to the proposed mechanism presented in Section 2, if the parameter variation of designed stabilizer shifts the interaction center into the operating points with greater transmitted powers, the stabilizer utilizes the resonance condition to stabilize the inter-area mode at the critical operating points. In the next part, the performance of PSSs on damping of inter-area mode is studied.

3.3. Studying the performance of PSSs

In order to analyze the performance of PSSs in the condition of strong resonance, we assume a single PSS at a time on one of the system machines and in each case, modal analyses are carried out for all operating points, considering different gain values of the PSS. In this study, a simple type of PSS as shown in Fig. 8 is used. We utilize the same PSSs which have been designed in [8, Table VIII]. Analyses by use of MATLAB Power System Toolbox (PST) [17] show that for all operating points, the phase characteristics of the PSSs appropriately provide the needed phase compensation over the large range 0.1–2 Hz.

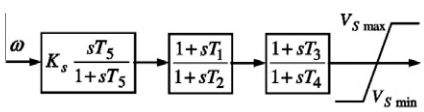

Fig. 8. Block diagram of the PSS.

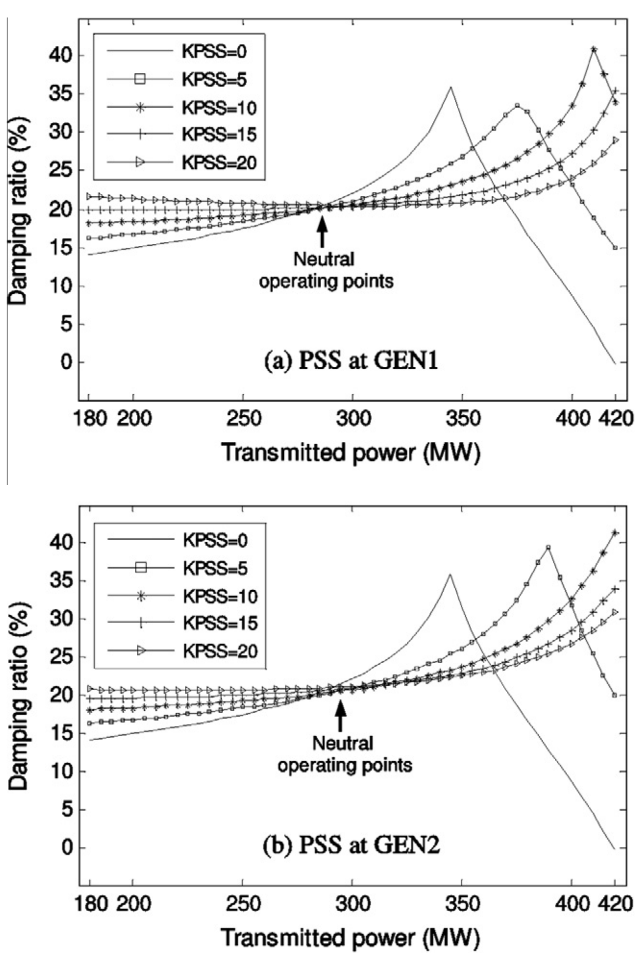

Fig. 9. Damping ratio of inter-area mode as transmitted power varies for different gain values (KPSS) of PSSs of Area1: (a) PSS at GEN1 and (b) PSS at GEN2.

3.3.1. PSSs of Area1

The simulation results indicate that the overall performance of the PSSs of GEN1 and GEN2 in Area1 are similar. Fig. 9 shows how the damping ratio of inter-area mode varies at different operating points as the gain values of these PSSs (KPSS) vary gradually from 0 to 20. The curve associated with KPSS = 0 is the same as one obtained in Fig. 7 which is associated with the original system without any PSS.

In Fig. 9, there are operating points in which the damping ratio of inter-area mode is approximately independent of the gain values of the PSSs. We call these operating points as *neutral operating points*, which correspond to the transmitted power of about 285 MW in Fig. 9a and about 295 MW in Fig. 9b. At operating points before the neutral operating points, especially those with transmitted power less than 250 MW, the PSSs have the expected performance so by increasing the gain values of the PSSs, more positive damping is provided for inter-area mode.

However, at operating points after the neutral operating points, because of the resonance condition, the performance of the PSSs on the inter-area mode is quite dependent on the position of the operating points with respect to the interaction center of the system without PSS (with KPSS = 0). At these operating points it is clearly seen that by increasing the gain value of the PSSs, the interaction center moves towards operating points with a higher transmitted power. This function is similar to moving the curve of the system without PSS to the right. At operating points before the interaction center of the system without PSS, increase in the gain value of the PSSs reduces the damping of inter-area mode. Therefore, in these operating points, the performance of the PSSs becomes converse so decreases the stability of this mode. The neutral operating points are those at which this converse performance is balanced with the common function of the PSSs to enhance the damping of the mode. However, at operating points after the interaction center of the system without PSS, by choosing an appropriate gain value for the PSSs, it is possible to provide the maximum damping for the inter-area mode in the vicinity of an interaction center. Therefore, at these operating points especially those with transmitted power higher than 400 MW (critical operating points), the performance of the PSSs of Area1 is quite satisfactory in stabilizing the inter-area mode.

3.3.2. PSSs of Area2

Simulation results show that the general performance of the PSSs of GEN3 and GEN4 in Area2 are similar. Fig. 10 shows how the damping ratio of inter-area mode changes at different operating points as the gain values of these PSSs vary gradually from 0 to 20. Figure indicates that unlike the PSSs of Area1, the PSSs of Area2 have a significant effect on the damping ratio of inter-area mode at all operating points, which implies the high contribution of the machines of this area to the oscillations of this mode.

According to Fig. 10, the performance of the PSSs on the stability of inter-area mode is greatly affected by the resonance condition. This performance is quite dependent on the position of operating points with respect to the interaction center of the system without PSS (with KPSS = 0). By increasing the gain value of PSSs, the interaction center moves towards operating points with lower trans-

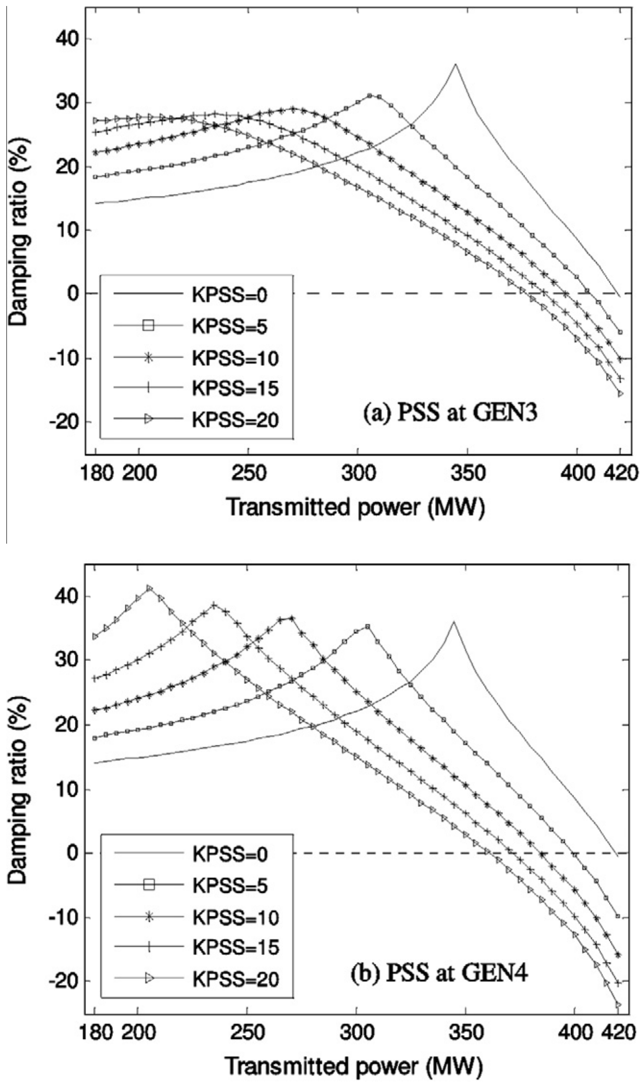

Fig. 10. Damping ratio of inter-area mode as transmitted power varies for different gain values (KPSS) of PSSs of Area2: (a) PSS at GEN3 and (b) PSS at GEN4.

mitted power. This function is similar to moving the curve of the system without PSS to the left as it is more obvious in Fig. 10b. At operating points before the interaction center of the system without PSS, by choosing an appropriate gain value for the PSSs, it is possible to provide the maximum damping for inter-area mode in the vicinity of an interaction center. Therefore, in these operating points, the performance of the PSSs of Area2 is very effective in stabilizing the inter-area mode. However, at operating points after the interaction center of the system without PSS, increasing the gain value of the PSSs severely reduces the damping of inter-area mode. Therefore, at these operating points, the performance of the PSSs becomes converse and causes to destabilize this mode.

3.4. Discussion

The results obtained from investigating the performance of PSSs show that passing near strong resonance causes the performance of PSSs on the inter-area mode to become extremely dependent on the location of the PSS and the operating point of the system. The interaction center of the system without PSS (original system) is an index of defining the performance of the PSSs. At operating points after the interaction center, the performance of the PSSs of Area1 is stabilizing and of Area2 is destabilizing. At operating points before the interaction center, the performance of the PSSs of Area2 is stabilizing.

Passing near strong resonance also causes a maximum damping ratio of inter-area mode at operating points in the vicinity of the interaction center. By placing the PSS on an appropriate machine and setting its gain by a suitable value, it is possible to move the interaction center so that the maximum damping ratio to be obtained at each of the operating points. It is in agreement with [18, Figs. 2–4] which choose the gain value of a PSS corresponding to an interaction center (if exists) as the optimum gain value obtained by experiment.

The dominant function of the PSSs is shifting the interaction center of the inter-area mode toward the operating points with higher or lower transmitted power. However, there are some deviations from this function, which cause the maximum damping ratio of the mode to vary. This dominant function is quite consistent with the proposed mechanism in Section 2, wherein placing a PSS in the system corresponds to a non-zero value of the parameter k in the matrix M'_k. The magnitude of k is proportional to the gain value of the PSS and the sign of k is dependent on the location of the PSS: positive sign for PSSs of Area1 and negative sign for PSSs of Area2.

Results also imply the necessity of appropriate placement of the PSS in the condition of strong resonance. The placement method should be able to consider the effects of passing near strong resonance on the performance of the PSS. The next part of the paper is devoted to assessing this topic.

3.5. Problem of PSS placement

3.5.1. Using conventional methods

Using mode shapes, residues, and participation factors are conventional placement methods for common PSSs [19,20]. These methods are based on linear analyses, which utilize the information of linearized equations of the power system in the absence of the considered PSS. As it was mentioned in Section 1, authors of [8,9] have examined these conventional methods for placement of a PSS at two operating points of the 2-area 4-machine system with transmitted powers of 180 MW and 410 MW. They showed that these methods identify the machines of Area2 as the best location to place the PSS at both the operating points. As we showed in the previous part, PSSs of Area2 provide appropriate stabilization at operating point with transmitted power of 180 MW (before the interaction center). However, at transmitted power of 410 MW (after the interaction center), these PSSs have an adverse effect and lead to destabilizing the inter-area mode. Therefore, the conventional methods have identified incorrect machines for PSS placement at this operating point. Because the authors of these papers have not considered the effect of linear interactions caused by passing near strong resonance on the performance of PSSs, they have assumed that the inefficiency of conventional linear methods is due to the increase of system stress and growth of nonlinearity. Upon this assumption, they have suggested that in this operating point the nonlinear approaches should be used in placement of PSSs.

We have investigated the capability of the conventional methods of PSS placement at all operating points. As an example, we show the speed participation factors of machines in the inter-area mode for different operating points in Fig. 11. In order to show the effect of the resonance condition on the values of the indices, normalization is not performed. It is seen that GEN3 and GEN4 have the largest relative values at all operating points (except the last one). Therefore, this method chooses the machines of Area2 to place PSS at all operating points (except the last one) The methods of mode shapes and residues provide similar results (figures are not shown) and identify a machine of Area2 as the best location

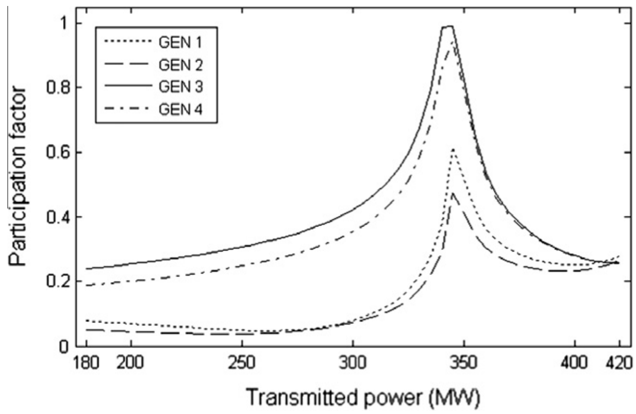

Fig. 11. Speed participation factors of inter-area mode as transmitted power varies.

to place PSS for all operating points. As it was demonstrated in the previous part, PSSs of Area2 cause destabilization of the inter-area mode at the operating points after the interaction center of this mode. Therefore, these methods choose incorrect machines to place the PSS at these operating points. This inefficiency of the methods is due to their inability to identify the destabilizing performance of the PSSs on the mode. This inability is intrinsic to all placement methods which utilize only the relative values of the magnitude of linear indices.

In the present case, passing near strong resonance causes the destabilizing performance of the PSSs of Area2 at the operating points after the interaction center so leads to inefficiency of the conventional methods of PSS placement.

3.5.2. Using the real part of the speed participation factors

Ref. [21] uses the real part of the speed participation factor as an index for PSS placement. The magnitude of this index quantifies the contribution of the considered machine in the oscillations of the electromechanical mode, and its sign identifies the stabilizing or destabilizing performance of PSS on the oscillations of the mode. Positive index implies the stabilizing performance, and negative index implies the destabilizing performance [21].

Because of incapability of conventional methods to identify the accurate location for PSS to enhance the damping of the inter-area mode at operating points after the interaction center, we propose using the real part of speed participation factors as a linear index to solve this problem.

Fig. 12 shows the real part of the speed participation factors of machines in the inter-area mode (values are not normalized). It is seen that GEN3 and GEN4 have the largest, positive values at operating points before the interaction center. By contrast, GEN1 and GEN2 have the largest, positive values at operating points after the interaction center. Therefore, this method chooses the machines of Area2 to place PSS at operating points before the interaction center and the machines of Area1 at operating points after the interaction center. These results confirm the efficiency of this method to identify the accurate location for PSS to stabilize the inter-area mode.

In addition, Fig. 12 shows that the indices of GEN1 and GEN2 change in sign from positive to negative at operating points with transmitted power about 270 MW and 255 MW respectively. This indicates that the real part of speed participation factors can estimate the neutral operating points of Fig. 9. Moreover, the negative values of indices of GEN3 and GEN4 at the operating points after the interaction center confirm the destabilizing performance of the PSSs of Area2 at these operating points. Changing the sign of the indices at the interaction center accurately indicates the inversion of the PSSs performance due to passing near strong resonance. These results confirm that this index provides important information about the effects of strong resonance on the performance of the PSSs.

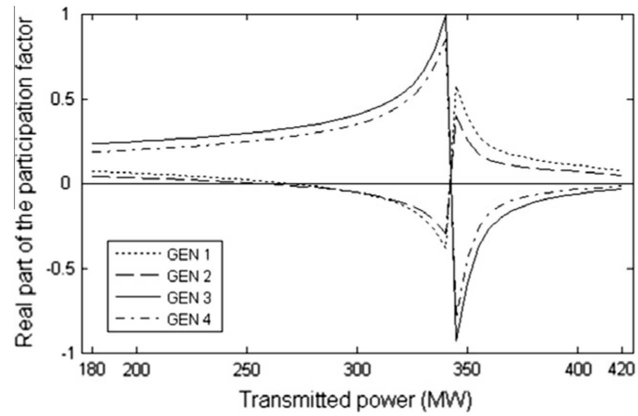

Fig. 12. Real part of the speed participation factors of inter-area mode as transmitted power varies.

In the application of the real part of the speed participation factors it is notable that the useful information is provided by both the magnitude and the phase of the participation factors.

4. Conclusion

In this paper, from a new viewpoint, the effects of the strong resonance phenomenon on the stability of dynamic systems have been considered. Based on a proposed mechanism, the performance of stabilizer controllers in the condition of near strong resonance has been investigated. The mechanism describes how the variation of a control parameter can move the interaction center of the resonance in such a way to stabilize or destabilize the coupled modes. As an application, this mechanism has been applied to justify the performance of PSSs in a 2-area 4-machine power system. It has been shown that interaction of an exciter mode and the inter-area mode near a strong resonance has significant effects on the performance of the PSSs on the stability of inter-area mode and makes it become severely dependent on the place of the PSS and the position of operating point with respect to the interaction center of the resonance. Especially, at critical operating points, the PSSs of one of the system areas destabilize the inter-area mode. It has been illustrated that by considering the proposed mechanism, the appropriate location of the PSS and its proper gain value are identified to obtain the maximum damping of inter-area mode at each of the operating points.

In addition, it is shown that the conventional methods of PSS placement are not able to identify the destabilizing performance of the PSSs caused by the strong resonance, so choose inappropriate machines to place the PSS. We have suggested the real part of speed participation factors as an index for placement of the PSS. The obtained results showed that by utilizing this index, the appropriate machines are identified to place the PSS. This index provides important information regarding the impacts of strong resonance on the performance of the PSSs. Using this index is easier than the nonlinear indices proposed by [8,9] for placement of PSS in the same case study.

Appendix A

A.1. Block diagram of the AVR/exciter

See Fig. A.1.

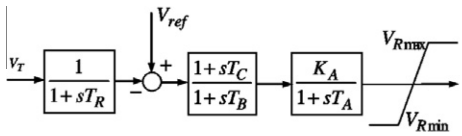

Fig. A.1. Block diagram of the exciter and AVR.

A.2. Numerical parameters of the case study

Tables A.1–A.5 give the numerical parameters of the system which are the same as that given in [8].

We supposed that the amplitude of steady state terminal voltage of generators is constant at all operating points. Table A.6 shows the steady state generator data for the first and the last operation points.

Table A.1
Generator parameters in per unit on generator base 900 MVA.

GEN	D	H	R_a	x_d	x_q	x'_d	x'_q	τ'_{d0}	τ'_{q0}
1	4	6.5	0.0025	1.8	1.7	0.3	0.3	8.0	0.4
2	2								
3	11								
4	10								

Table A.2
Line parameters in per unit on system base 100 MVA.

Bus bars	R	X
1, 2 and 3, 4	0.0025	0.025
2, 5 and 4, 6	0.0010	0.010
5, 6	0.0220	0.220

Table A.3
Load data of ith operating point ($1 \leqslant i \leqslant 49$).

Load bus	Load (MW)	Load (MVAR)	Shunt susceptance on system base
5	$1120 - 5(i - 1)$	250	2.551
6	$1180 + 5(i - 1)$	250	2.543

Table A.4
Exciter/AVR parameters.

GEN	K_A	T_A	T_B	T_C	T_R	V_{Rmin}	V_{Rmax}
1	180	0.01	10.0	1.0	0.01	-5.0	5.0
2	100						
3	130						
4	220						

Table A.5
PSS parameters.

GEN	T_1	T_2	T_3	T_4	T_5	V_{Smin}	V_{Smax}
1	0.1	0.01	0.9	0.07	13	−0.1	0.1
2	0.1	0.03	1.5	0.03	10		
3	0.1	0.05	1.3	0.03	10		
4	0.3	0.05	0.18	0.03	3		

Table A.6
Steady state generator data.

GEN	The first operation point				The last operation point			
	|V| p.u.	∠V deg	P_{gen} MW	Q_{gen} MVAR	|V| p.u.	∠V deg	P_{gen} MW	Q_{gen} MVAR
1	1.0200	27.3	664.4	13.2	1.0200	72.0	664.4	13.2
2	1.0136	18.1	664.4	283.2	1.0136	62.8	664.4	524.4
3	1.0200	0.0	523.4	2.9	1.0200	0.0	575.8	4.6
4	1.0146	−7.3	500.0	221.1	1.0146	−8.0	500.0	528.6

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