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A TCSC Control Based on Stabilizing Delay Effect for Inter-Area Oscillation Damping in a Power System with Time Delay

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Abstract

As opposed to the existing approaches which recognize communication network time delays, when they are introduced into the feedback signals, as a main cause of instability or poor performance in power system wide-area damping controller (WADC), this paper shows that if time delay in feedback loops is properly determined, the WADC performance to damp out inter-area oscillations will be improved. In other words, in situations where it is not easy to design and implement the WADC for Flexible AC Transmission Systems (FACTS) devices without delay, in order to effectively compensate the delay, in this paper, a new Wide-Area Damping Controller Delay Effect (WADCDE) is designed. First the model of power system with delay as a design parameter is established. Then, the WADCDE based on objective function of the rightmost real part of eigenvalues is designed and the sufficient condition about stability of the closed-loop system is given. A four-machine power system for numerical simulations has been used to evaluate the accuracy of the proposed control function and the feasibility study. The simulation results showed that the controller designed in a wide range of delay feedback reduces the oscillation of power system without restricting TCSC operation.

Keywords: Stabilizing Delay Effect Problem, Power Oscillation Damping, Delay Scheduling.

1. INTRODUCTION

Implementation of wide-area measurement system (WAMS) and wide-area damping control(WADC) in power systems as well as development of decentralized control strategies in smart grids exacerbate delay effects in control system considerations and small-signal stability analysis [1]. Fortunately, the WAMS has the ability to provide appropriate outputs required for WADC system. Access to remote signals is essential for WADC implementation and

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this is done by communication networks where some delay is inserted inevitably into the submitted signals to the controllers. The communication delays in such systems almost range from 100 to 700 ms as reported in [3]. Maintaining stability and controlling the power system in presence of time delayed signals is an important issue and many studies have been carried out in this regard. The studies can be categorized as follows:

i. Providing a new method to analyze the delay problem and attempting to reduce its effect on the small signal stability [4-7].
ii. Providing a method to determine the delay margin in a WADC control system [8-11].
iii. Providing a method to achieve a robust WADC control system against the network delays [12-13].

In spite of general methods, it should be emphasized that in particular cases, delay may lead to a stable condition which is called stabilizing effect of delay in literatures. Stabilization methods for linear time-delay has been widely studied [14-15] and applied in various engineering problems [16-17]. In this paper our approach is to solve the delay problem defined in a power system equipped with TCSC supplementary controller and design a control system by using the stabilizing effect of delay.

In general, compared to conventional systems, the stability analysis of the delayed control systems are more complicated. The description of the state-space equations of delayed systems is done through a combination of the current and past sate variables. Analysis and design of these systems is one of the important issues and several research studies have been conducted to address the problem. Regarding the design approach, two types of stability criteria may be applicable to the problem. The first one focuses on delay-independent stability conditions, which may be conservative for small delay. The second category employs delay-dependent stability conditions which lead to less conservative solutions. Delay-dependent stability technique is almost always used in power systems since there is often a limited delay in practice [18]. The controller's performance designed by employing delay-dependent stability technique would be maximum only when no delay is interposed into the system, which rarely occurs in practice. Thus, in delay dependent approach, to increase the stability margin, the controller gain factor should be decreased. This, however, will lead to a poor performance of the closed-loop system and therefore a compromise on supporting a level of convergence rate of electromechanical modes and providing more reliable delay margin is required [19-20]. Unlike the ordinary stabilizing methods, where delay is treated by a constraint, our idea is to show that utilization of delay as a design control parameter would yield to a better robust performance. The main advantage of this method is that the controller is relatively easy to design and less complexity will be appeared in implementation phase. This approach is referred to as delay-range stability [21]. As a matter of fact, this paper is looking for necessary and sufficient conditions to control system in a specific range of delays of signals.

Signal selection is one of the important steps to a successful design of the wide-area controller. There are various methods and criteria to select proper signals. For example, modal analysis and selection of feedback signals based on the geometric measures [22], the residue method and visibility method [23-24] are widely employed. Nevertheless, these measures are

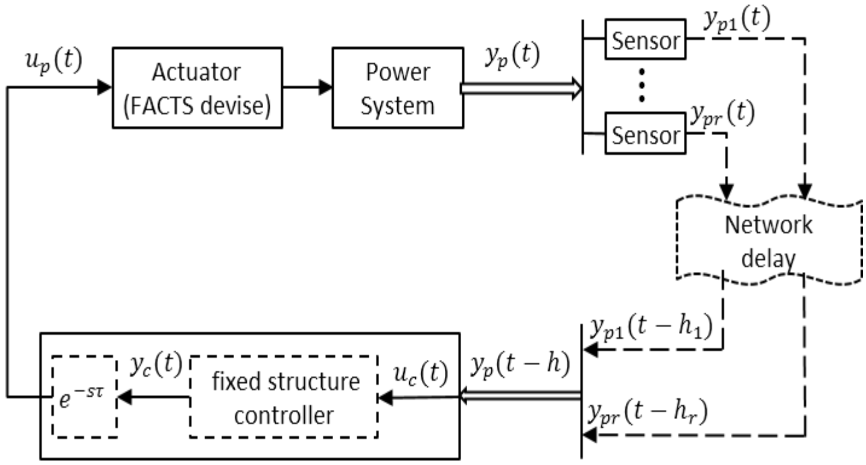

Fig. 1. The structure of WADCDE control system.

applicable for finite dimensions linear systems. Now, the main question is if the input/output signal selection affected by delays; the WADC is a kind of delayed system with infinite dimensions. An attempt is made in this paper to show that the delay will affect the result of signal selection. We propose a simple and effective approach to select input/output control signals based on what obtained for a single generator infinite bus test system.

The main contributions of this paper are summarized as follow:

1. Existing methods use delay as a constraint in stability optimization problems, while our approach with delays as a design parameter can provide a more realistic solution.
2. This paper expands the proposed delay-range stability analysis method in [30] to design a delay scheduled WADC for TCSC equipment.
3. Usually delay is known as a source of instability in WADC systems. This paper shows that delay is not always a destructive factor, but it may also have a stabilizing effect in some cases.

2. MODELING THE CONTROL PROBLEM

A controller system structure to damp the power oscillation according to the transmission of non-local signals by communication networks is shown in Fig. 1. The output of sensors can be any of bus voltages, line currents, available state variables and the other known variables. The delay time due to the output signal transmission through communication network to the input controller is modeled with h variable where τ is the delay control parameter applied to the control signal or at the actuator input. The actuator is referred to such equipment like HVDC, FACTS and generator's excitation system. The linear dynamic model of the power system block can be written as,

$$\dot{x}_p(t)=\mathbf{A}_p\, x_p(t)+\mathbf{B}_p\, u_p(t)\,, \tag{1a}$$

$$y_p(t)=\mathbf{C}_p\, x_p(t)\,, \tag{1b}$$

where $u_p(t)\,,y_p(t)\in R^r$, and $x_p(t)\in R^n$ are the input vector, output vector and state vector, respectively. Generally, the state space model of the fixed structure controller can be formulated as:

$$\dot{x}_c(t)=\mathbf{A}_c\, x_c(t)+\mathbf{B}_c\, u_c(t)\ , \tag{2a}$$

$$y_c(t)=\mathbf{C}_c\, x_c(t)+\mathbf{D}_c\, u_c(t)\,, \tag{2b}$$

where $y_c(t)\,,u_c(t)\in R^r$, and $x_c(t)\in R^m$ denote state vector, input vector and output vector, respectively. According to Fig. 1, it can be written as:

$$u_c(t) = \sum_{i=1}^{r} \mathbf{C}_i \, x_p(t-h_i), \tag{3a}$$

$$u_p(t) = y_c(t-\tau), \tag{3b}$$

where,

$$\mathbf{C}_1 = \begin{bmatrix} \mathbf{C_{p1}} \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \end{bmatrix}, \mathbf{C}_2 = \begin{bmatrix} \mathbf{0} \\ \mathbf{C_{p2}} \\ \vdots \\ \mathbf{0} \end{bmatrix}, \ldots, \mathbf{C}_r = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \vdots \\ \mathbf{C_{pr}} \end{bmatrix}.$$

By utilizing (3), the state-space equation of control system with a zero reference input is,

$$\mathbf{E}\,\dot{x}(t) = \mathbf{A}(k)\,x(t) + \mathbf{A}_\tau\, x(t-\tau) + \sum_{i=1}^{r} \mathbf{A}_i \, x(t-h_i) \tag{4}$$

where

$$\mathbf{E} = \begin{bmatrix} \mathbf{I}_{n\times n} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_{m\times m} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 0 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix},$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_p & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_c & \mathbf{B}_c & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_c & \mathbf{D}_c & -1 \\ \mathbf{0} & \mathbf{0} & -\mathbf{I}_{r\times r} & \mathbf{0} \end{bmatrix},$$

$$\mathbf{A}_i = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{C}_i & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix},$$

$$\mathbf{A}_\tau = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{B}_p \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}, x = \begin{bmatrix} x_p \\ x_c \\ u_c \\ y_c \end{bmatrix}.$$

It should be noted that $\mathbf{A}(k)$ is function of controller matrixes, i.e. $k \in (\mathbf{A}_c, \mathbf{B}_c, \mathbf{C}_c, \mathbf{D}_c)$.

1. Stability Analysis of Time Delay Systems

Substituting $x(t) = u\,e^{-\lambda t}$ as a solution candidate in (4) where u is a vector and λ is a scalar yields:

$$(\lambda\mathbf{E} - \mathbf{A}(k) - \mathbf{A}_\tau e^{-\lambda\tau} - \sum_{i=1}^{r} \mathbf{A}_i e^{-\lambda h_i})u = \mathbf{0}. \tag{5}$$

By definition

$$\mathbf{M}(\lambda) = \lambda\mathbf{E} - \mathbf{A}(k) - \mathbf{A}_\tau e^{-\lambda\tau} - \sum_{i=1}^{r} \mathbf{A}_i e^{-\lambda h_i} \tag{6}$$

is called the characteristic matrix of system (4). The eigenvalues of characteristic matrix, λ, are obtained when (5) possibly has non-trivial responses ($u \neq 0$). The solutions of

$$\left| \lambda\mathbf{E} - \mathbf{A}(k) - \mathbf{A}_\tau e^{-\lambda\tau} - \sum_{i=1}^{r} \mathbf{A}_i e^{-\lambda h_i} \right| = 0, \tag{7}$$

are called the characteristic roots, where (7) is called the characteristic equation. The number of roots in Eq. (7) is infinite because the equation is transcendental. Fortunately, Eq. (7) only has a finite number of characteristic roots on the right of any vertical line at the complex plane [25]. However, consider $\{\lambda\}$ as a sequence of the characteristic roots, the necessary and sufficient conditions for the asymptotic stability of the system (4) is defined as:

$$\alpha = \max\left\{ \mathrm{Re}\{\lambda\} : \left|\mathbf{M}(\lambda)\right| = 0 \right\} < 0, \tag{8}$$

where α is called the spectral abscissa.

2. Maximal Convergence Rate Control

As already noted, the paper approach regarded to designing the power oscillation damping controller based on TCSC is utilizing the delay scheduling method in control signal. The optimized controller is designed in a way that it will have a very slow convergence rate without delay and when delay is increased to a certain value, the overall convergence rate of the closed loop system will be enhanced. In other words, the controller parameters, k, and the delay input parameter, τ, are chosen in such a way that the spectral abscissa of the system (4) shifts to the left of the complex plane as much as possible. To determine k and τ, the following optimization problem must be solved:

$$\min\ \alpha(k,\tau), \tag{9}$$

which provided that:

$\max \mathrm{Re}\{\lambda\}, \tau > 0, \mathrm{h_i} > 0, \mathrm{i} = 1,2,...,\mathrm{r}$.

Since the search speed increases to find the answers of the optimization problem based on the objective function gradient, the gradient (9) is required.

Now consider $s = \alpha \pm \mathrm{j}\beta$ as the simple right-most root of the characteristic equation (7), the vectors v^{T} and u are the left and right eigenvectors corresponding to s, using the implicit function theorem, the partial derivative of (5) can be computed, as in

$$(\mathbf{E} + \tau\mathbf{A}_{\tau}\mathrm{e}^{-s\tau} + \sum_{i=1}^{r} h_i \mathbf{A}_i \mathrm{e}^{-sh_i})u\mathrm{d}s = (\dot{\mathbf{A}}(k)\mathrm{d}k - s\mathbf{A}_{\tau}\mathrm{e}^{-s\tau}\mathrm{d}\tau)u - (s\mathbf{E} - \mathbf{A}(k) - \mathbf{A}_{\tau}\mathrm{e}^{-s\tau} - \sum_{i=1}^{r}\mathbf{A}_i \mathrm{e}^{-sh_i})\mathrm{d}u.$$

Multiplying both sides by v^{T} and noting that $v^{\mathrm{T}}u = 1$ and $\mathrm{v}^T(s\mathbf{E} - \mathbf{A}(k) - \mathbf{A}_{\tau}\mathrm{e}^{-s\tau} - \sum_{i=1}^{r}\mathbf{A}_i \mathrm{e}^{-sh_i}) = 0$, we have:

$$\mathrm{d}s = \frac{\mathrm{v}^T(-\dot{\mathbf{A}}(k)\mathrm{d}k + s\mathbf{A}_{\tau}\mathrm{e}^{-s\tau}\mathrm{d}\tau)u}{\mathrm{v}^T(\mathbf{E} + \tau\mathbf{A}_{\tau}\mathrm{e}^{-s\tau} + \sum_{i=1}^{r} h_i \mathbf{A}_i \mathrm{e}^{-sh_i})u}.$$

Since $\mathrm{d}s = \mathrm{d}\alpha \pm \mathrm{j}\mathrm{d}\beta$ we get:

$$\mathrm{d}\alpha = \mathrm{Re}\left(\frac{\mathrm{v}^T(-\dot{\mathbf{A}}(k)\mathrm{d}k + s\mathbf{A}_{\tau}\mathrm{e}^{-s\tau}\mathrm{d}\tau)u}{\mathrm{v}^T(\mathbf{E} + \tau\mathbf{A}_{\tau}\mathrm{e}^{-s\tau} + \sum_{i=1}^{r} h_i \mathbf{A}_i \mathrm{e}^{-sh_i})u}\right).$$

The above relation can be rewritten from the definition of partial derivatives as follows:

$$\begin{bmatrix}\dfrac{\partial\alpha}{\partial k}\\[2mm] \dfrac{\partial\alpha}{\partial\tau}\end{bmatrix} = \mathrm{Re}\begin{bmatrix}\dfrac{-\mathrm{v}^T\dot{\mathbf{A}}(k)u}{\mathrm{v}^T(\mathbf{E} + \tau\mathbf{A}_{\tau}\mathrm{e}^{-s\tau} + \sum_{i=1}^{r} h_i \mathbf{A}_i \mathrm{e}^{-sh_i})u}\\[2mm] \dfrac{\mathrm{v}^T s\mathbf{A}_{\tau}\mathrm{e}^{-s\tau}u}{\mathrm{v}^T(\mathbf{E} + \tau\mathbf{A}_{\tau}\mathrm{e}^{-s\tau} + \sum_{i=1}^{r} h_i \mathbf{A}_i \mathrm{e}^{-sh_i})u}\end{bmatrix}. \tag{10}$$

It worth noting that the spectral abscissa in a delay system like (4) is a continuous function in terms of k and τ but it is not always derivative, the above gradient is not valid when the number of eigenvalues with equal real parts to spectral abscissa are more than one [25].

3. STABILIZING DELAY EFFECT PROBLEM

In this section, the basic concepts of $\Delta\Omega$ stability analysis and stabilization method along with delay scheduling approach are briefly described by an example.

Consider the simplified electromechanically model for a synchronous machine:

$$2\mathrm{H}\frac{\mathrm{d}\Omega}{\mathrm{dt}} = \mathrm{p_m} - \mathrm{p_e}, \tag{11}$$

where Ω is the rotor speed, H is the machine inertia constant, $\mathrm{p_m}$ indicate mechanical power, and $\mathrm{p_e}$ refers to the electromagnetic power which is expressed as,

$$\mathrm{p_e} = \frac{\mathrm{e_q'}\mathrm{v}}{\mathrm{x_d'}}\sin(\delta - \theta), \tag{12}$$

where δ is the rotor angle, v and θ are the generator's amplitude and phase angle of the output voltage, $\mathrm{e_q'}$ is the internal voltage and $\mathrm{x_d'}$ is the transient reactance of the stator d-axis. For small disturbances, (11) can be linearized around the operating point. So we have:

$$2\mathrm{H}\frac{\mathrm{d}\Delta\Omega}{\mathrm{dt}} = -\frac{\partial\mathrm{p_e}}{\partial\delta}\Delta\delta - \frac{\partial\mathrm{p_e}}{\partial\mathrm{e_d'}}\Delta\mathrm{e_d'} - \frac{\partial\mathrm{p_e}}{\partial\mathrm{v}}\Delta\mathrm{v} \tag{13}$$

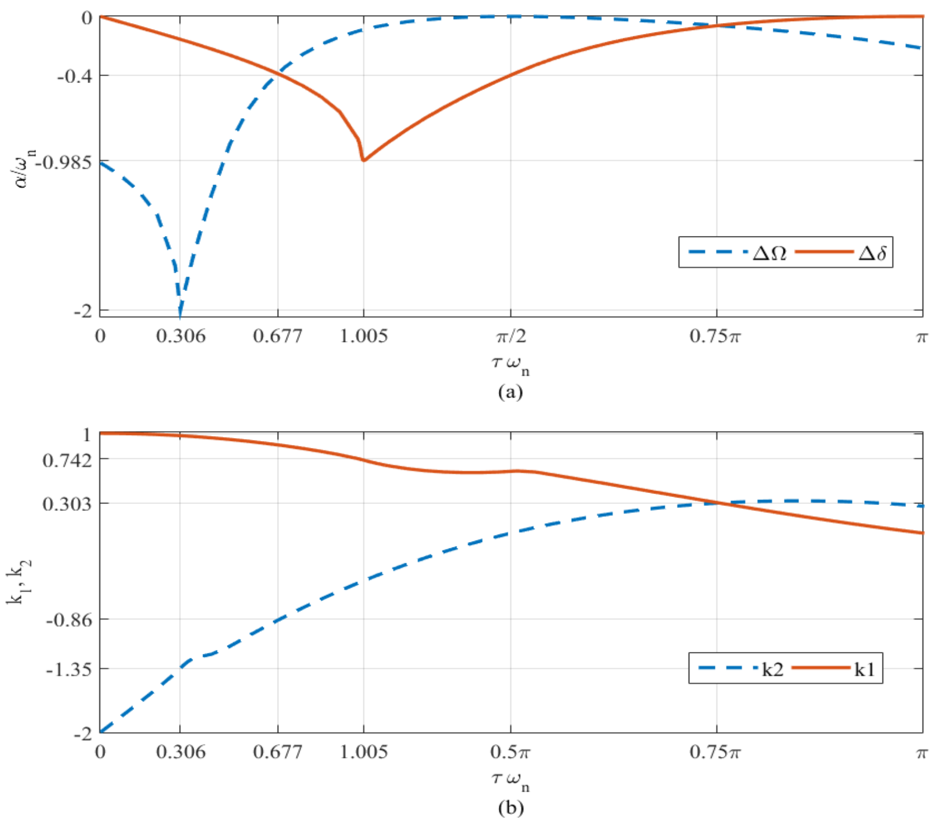

Fig. 2. Minimizing the spectral abscissa as a function at $\tau\omega_n$.

Assuming a fast automatic voltage regulator, $e_q^{'}$ and v are constant, hence:

$$2H\frac{d\Delta\Omega}{dt} = -N\Delta\delta\,, \tag{14}$$

where $N = \frac{e_q^{'} v}{x_d^{'}}\cos(\delta_0 - \theta_0)$, δ_0 and θ_0 are the rotor and bus voltage phase angles at the operating point. As $\Delta\Omega = s\Delta\delta$, the open-loop characteristic equation will be obtained as:

$$\Delta = s^2 + \omega_n^2\,, \tag{15}$$

where, $\omega_n^2 = \frac{N}{2H}$.

Substituting $s = \lambda\omega_n$ into the characteristic equation (15), the following normalized characteristic equation is achieved:

$$\hat{\Delta} = \lambda^2 + 1 \tag{16}$$

Equation (16) has a complex polygon pair on imaginary axis, so the system is unstable. In order to make it stable, the common approach is to take the generator speed deviations as a feedback signal. Choosing the proportional structure for the controller in this example, the characteristic equation of the system holds the relation below assuming the delay in the feedback loop,

$$\Delta_2(k_2,\tau) = \lambda^2 + \lambda k_2 e^{-\lambda\tau} + 1 \tag{17}$$

But if we choose the rotor angle variations of the generator as the feedback signal feeding into the zero-order controller, the system characteristic equation becomes:

$$\Delta_1(k_1,\tau) = \lambda^2 + k_1 e^{-\lambda\tau} + 1\,. \tag{18}$$

Assume that $\lambda(k_2) = \alpha \pm j\beta$ and $\lambda(k_1) = \alpha \pm j\beta$ are the right-most roots of the characteristic equations (17) and (18) respectively. Now we try to determine k_1

and k_2 for each $\tau \in (0, \pi)$ in such a way that α moves to the left side of the complex plane as much as possible. To this end, the optimization problem given in (9) has been implemented as a function of τ to determine k_1 and k_2 parameters and the results are shown in Fig. 2 where part (a) indicates the minimum spectral abscissa as a function of τ and part (b) shows k_1 and k_2 values as a function of τ.

According to Fig. 2, the following can be concluded for the output signal selection.

Conclusion 1: if delay value in feedback control loop satisfies $\omega_n\tau < 0.677$, $\Delta\Omega$ is a proper signal for the controller input.

Conclusion 2: if the range of delay variations be within $0.677 < \omega_n\tau < 2.361$, $\Delta\delta$ will be a suitable signal for the controller input.

Now based on the obtained results, we can analysis a specific case. Assume that $\omega_n = 2$ and the delay time in feedback control loop, h, is 338 ms. From the results shown in Fig. 2, one can conclude that by making a delay of $\tau = 164\,\text{ms}$ at input and setting $k_1 = 0.742$, there is a possibility to reach to the spectral abscissa, $\alpha = -0.196$ if $\Delta\delta$ is selected as the input signal to the controller. However, assigning $k_2 = -0.86$ and $\tau = 0$ ms, meaning that no delay in input, there is only the possibility to reach to the spectral abscissa, $\alpha \simeq -0.8$ by choosing $\Delta\Omega$ as the input signal. Since the high-order systems can be modeled in terms of second-order subsystems, the criteria obtained in this section for signal selection will be employed for the studied cases. According to the analysis, it can be said that the performance of WADC system will be decreased by increasing the delay in feedback control loop if the selected signal for the feedback is rotor speed variations. The situation becomes vice versa when the generator's rotor angle signal is considered in feedback control loop. Thus, in this paper the generator's rotor angle variations with higher visibility and residual value in inter-are oscillatory modes are dedicated to input signal selection to the supplementary control of TCSC. This method is very simple, effective and practical.

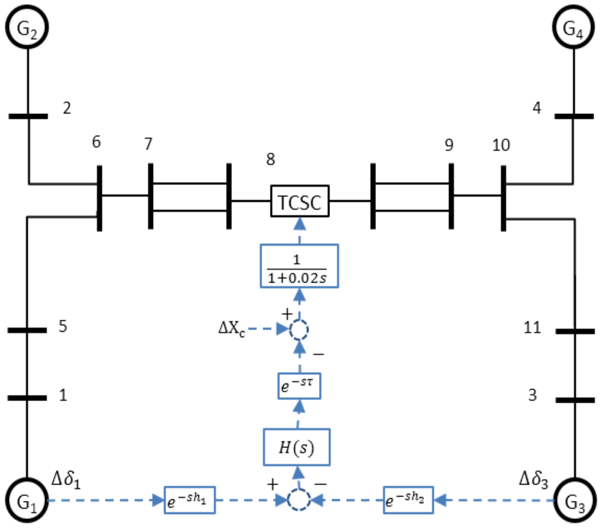

Fig. 3. The structure of the test control system.

4. SIMULATION RESULTS

The proposed method has been applied on a sample system and the results are analyzed in this section. The studied system in this paper is expressed as a two-area power system which was the first choice of the most researchers in similar studies. The related information of the system is derived from [26]. Fig. 3 shows a single-line diagram of the test system along with the TCSC POD controller. The capacity of TCSC is considered for maximum 25% compensation of the line reactance connecting two areas to each other.

The dynamic model of generators is of six-order and, the excitation system and TCSC dynamic models are of first-order representation. The other dynamics such as turbines, governors and PSS are neglected. So the dynamical order of the test system is 29 and its characteristic equation is:

$$\Delta = s^2(s+4.23)(s+4.13)(s+26.65)(s+27.68)$$
$$(s+32.38)(s+32.41)(s+50)(s+53.54)$$
$$(s+53.59)(s+54.59)(s+55.18)$$
$$(s^2+7.935s+15.74)(s^2-0.0071s+18.1)$$
$$(s^2+34.23s+323.4)(s^2+34.07s+330.3)$$
$$(s^2+1.43s+49.7)(s^2+1.42s+52.6)$$
$$(s^2+28.59s+497)(s^2+23.63s+663.6) \quad (19)$$

According to the eigenvalues analysis (19), it could be observed that the system is not stable at the operating point, and therefore the necessary actions should be taken in this regard. In order to stabilize the test system, one solution is to use TCSC capabilities in the network by adding a supplementary controller for this purpose. Referring to the considerations for signal selection, as described in Section 4, the best pair is rotor angles of generators 1 and 3.

The controller design is done by making transfer functions between inputs/outputs. To find the open circuit transfer function between TCSC's input and the chosen output, a subroutine is developed and added to Power Systems Toolbox (PST) [27]. The results are as follows:

$$G(s) = \frac{N(s)}{D(s)}, \quad (20)$$

where D(s) is given by (19) and N(s) is,

$$N(s) = 4.2108\times10^{-5} s^2(s+55.17)(s+55.15)$$
$$(s+53.59)(s+53.34)(s+34.6)$$
$$(s+32.34)(s+26.87)(s+26.21)$$
$$(s+4.177)(s+3.963)(s^2+7.792s+15.22)$$
$$(s^2+33.44s+300.7)(s^2+34.08s+330.4)$$
$$(s^2+1.365s+50.39)(s^2+1.7s+63.75)$$
$$(s^2+28.86s+635.1)(s^2+23.62s+663.7)$$
$$(s^2+49.4s+9.02\times10^7)$$

Referring to Eq. (20), one can conclude that every minimal realization of the test system is of an order of 27. There are two zeroes and poles at the origin in (20) which are easily removed before designing the control problem. One pair is due to the fact that each rotational system requires a reference to measure angles. The other is related to this fact that the input mechanical power is assumed constant in the studied system. In following, the proposed method for designing the controller is illustrated.

A. Controller design

Since our goal is to use delay as a design parameter, it must be entered into system equations. Consider Fig. 3, whereas by assuming h_1=h_2=h, the feedback delays can be transmitted to the input and also added to control parameter τ, the state space model of the test system can be expressed as,

$$\dot{x}_p(t)=\mathbf{A}_p x_p(t)+\mathbf{B}_p u_p(t-\tau-h), \quad (21a)$$
$$y_p(t)=\mathbf{C}_p x_p(t). \quad (21b)$$

The following simultaneous equations model can be used to display the controller:

$$\dot{x}_c(t)=\mathbf{A}_c x_c(t)+\mathbf{B}_c y_p(t), \quad (22a)$$
$$u_p(t)=\mathbf{C}_c x_c(t)+\mathbf{D}_c y_p(t). \quad (22b)$$

Notice that the above simplification assumption is made to clarify the problem of process analysis and will have a negligible effect on the controlling results.

To determine $\mathbf{A}_c,\mathbf{B}_c,\mathbf{C}_c,\mathbf{D}_c$, and τ+h, a special computing program is required. Generally, spectral abscissa in a delayed system such as (4) is a continuous function in terms of $\mathbf{A}_c,\mathbf{B}_c,\mathbf{C}_c,\mathbf{D}_c$, and τ+h, but, it may not be unique for certain values of $\mathbf{A}_c,\mathbf{B}_c,\mathbf{C}_c,\mathbf{D}_c$ and $\tau+h$ [25]. One solution to this problem is using the gradient-based algorithm for non-smooth optimization. One of the powerful software to deal with this problem is GRANSO's [28]. Because GRANSO is intended to be an efficient solver for constrained non-smooth optimization problems, without any special

Table 1. ***Delay at Special Points.***

symbol	Definition	$H_0(s)$	$H_2(s)$
τ_l	Lower bound delays [ms]	0	181
τ_h	Upper bound delays [ms]	604	719
τ_{DRS}	Delay- range stability [ms]	604	538
$(\tau+h)_{op}$	Optimal solution delays [ms]	445	445

structure or assumptions imposed on the objective or constraint functions, based on the development of eigAM.m [29], the MatLab software environment is used to calculate the value and gradient vector of the objective function.

However, the optimal value for $\tau+h$ is equal to 445 ms, the optimal value for the zero-order controller and for second-order controller was respectively found equal to $H_0(s)$ and $H_2(s)$ which are:

$$H_0(s)= 0.0504\,, \tag{23a}$$

$$H_2(s) = -\frac{0.056\left(s^2-5.69s+23.83\right)}{\left(s+6.437\right)\left(s+5.227\right)} \tag{23b}$$

It should be noted that with an optimum value of the parameter $\tau+h$(445ms), the spectral abscissa of the test system with the feedback $H_0(s)$ is -0.7 and $H_2(s)$ is -0.784.

B. Robust Stability Analysis

With designed controllers, the system stability analysis has been performed and the results are summarized in Table 1. The lower bound, i.e. the beginning of the stabilizing delay effect, and the upper bound, i.e. the end of the stabilizing delay effect, and also the delay range, i.e. range under which the system is stable, are briefly described in Table 1. As seen, the robust stability of the test system is guaranteed in a wide range of delay variations with the controllers.

Assuming that the output of each designed controller can be applied to the TCSC input without delay time and with optimal delay, the small signal stability has been studied and the critical modes are summarized in the Table 2. As seen, when the output of the zero order controller is applied to the TCSC input without delay, the system convergence rate is poor, but when the delay is 445 ms, the damping coefficient improves, but the without delay performance leads to the system instability, however, the convergence rate will be improved by a delay of 445 ms.

In Fig. 4, the right-most characteristic roots of the controlled system by $H_0(s)$ are displayed as a function of $\tau + h$. For $0<\tau + h<604$ ms, there are the right-most eigenvalues in the open left half plane. Fig. 4(a) illustrates how the real parts of the dominant modes evolve with multiplicity larger than one toward the minimum local ($\alpha=-0.7$) for the optimum delay, i.e. $\tau + h=445$ms, which indicates characteristic of the global minimum.

As seen Fig. 4(b), we can come up to this conclusion that the both local-modes compared to inter-area mode, have a lower sensitivity to delays. It's observed that the inter-area mode with a delay more than 604 ms makes the system to be instable. Fig. 5 shows the stabilization results with $H_2(s)$. In this case, the minimum spectral abscissa is -0.784 whereas the delay is 445ms. As the

Table 2. ***Rightmost Characteristic Roots Without And With Optimal Delay.***

$H_0(s)$		$H_2(s)$	
$\tau+h=0$	$\tau+h=445$ ms	$\tau+h=0$	$\tau+h=445$ ms
-0.051±j3.52	-0.701±j4.95	0.201±j2.989	-0.784±j7.095
-0.703±j7.29	-0.699±j7.13	-0.665±j7.256	-0.784±j7.102
-0.697±j7.03	-0.81±j6.91	-0.692±j7.021	-0.784±j7.81

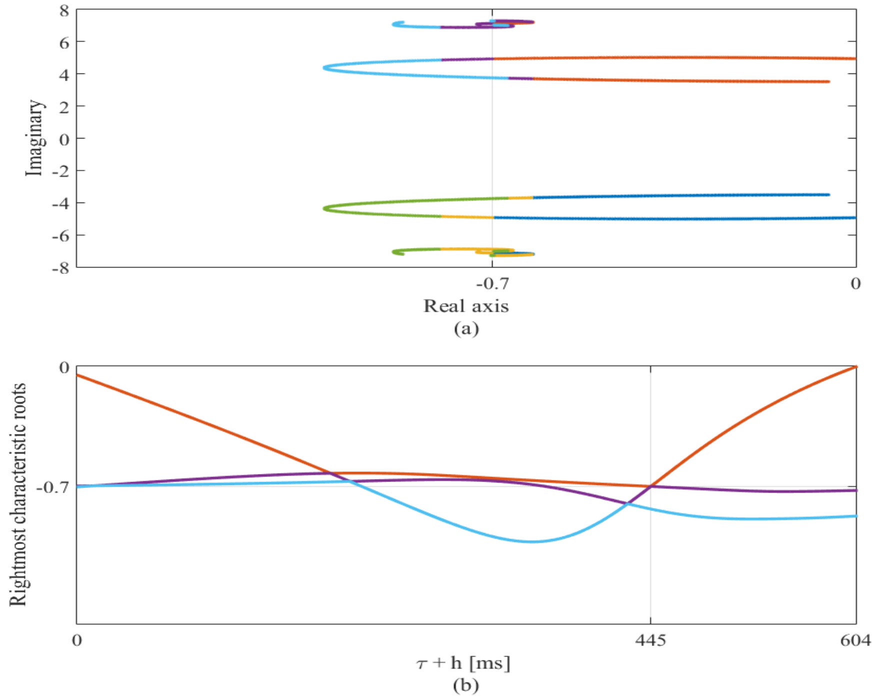

Fig. 4. Right-most characteristic roots with $H_0(S)$.

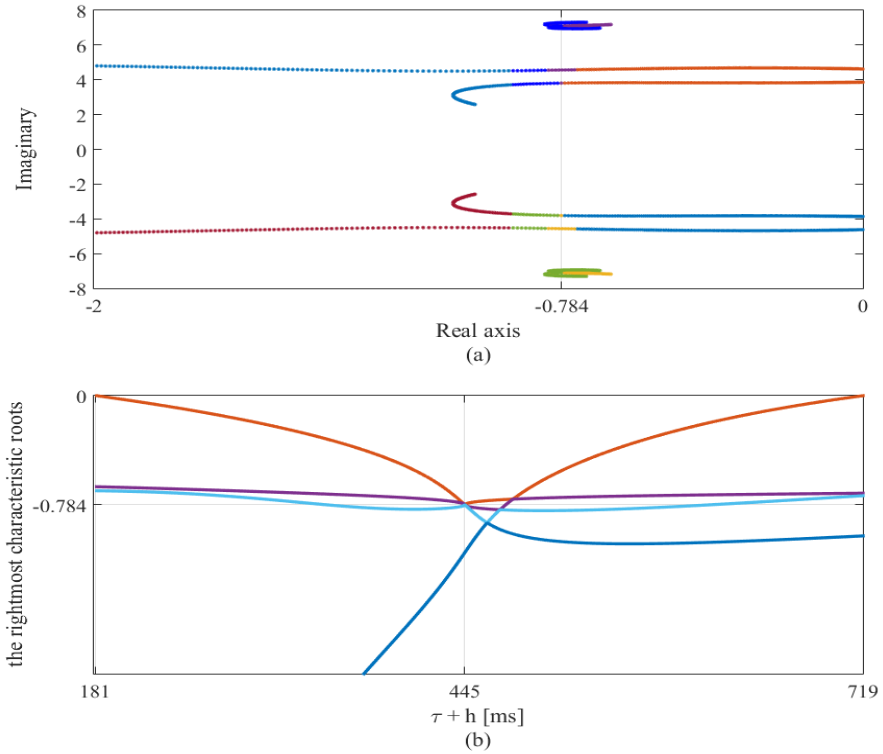

Fig. 5. Right-most characteristic roots with $H_2(S)$.

delay becomes more than 719 ms, the system instability occurs because of a mode caused by the delay.

C. Non-linear Simulation

The non-linear simulation has been performed for both of these cases by considering a three- phase short-circuit with duration of 50ms in seventh bus and the results are shown in Fig. 6 and Fig. 7. In Fig. 6, the difference between the first and third

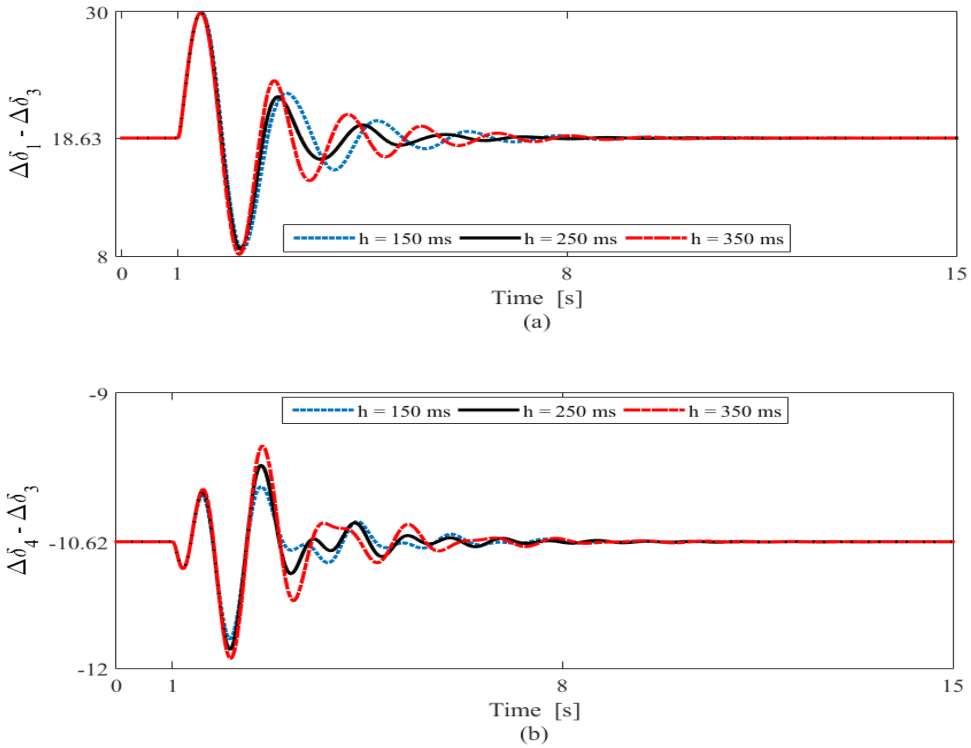

Fig. 6. Rotor angle G_{13} and G_{43} with $H_0(S)$ ***and*** $\tau = 95ms$.

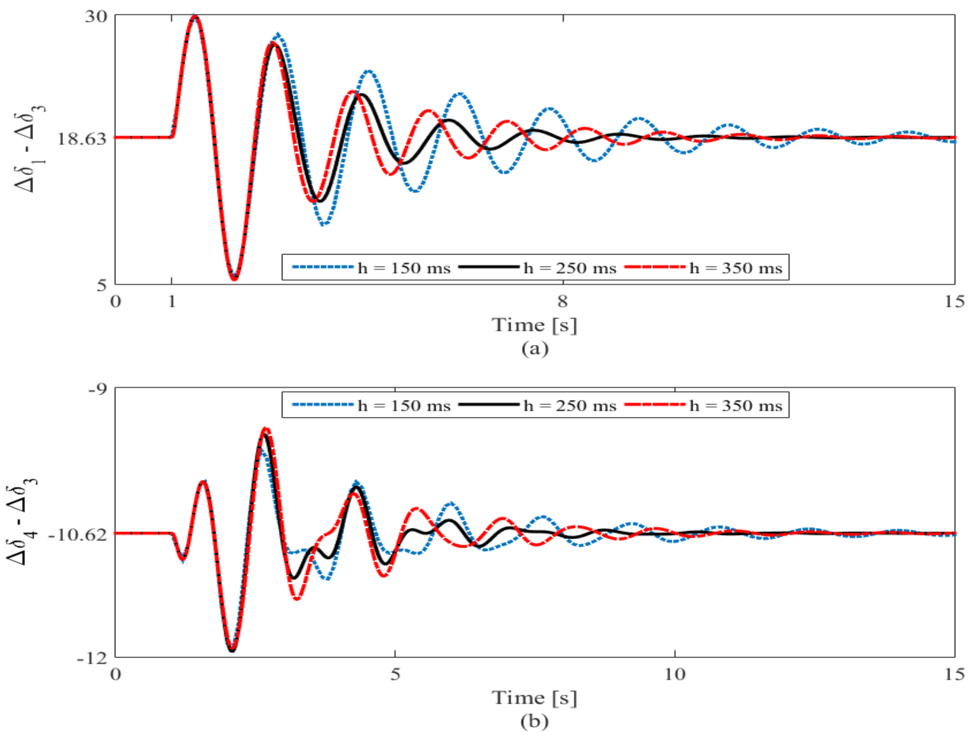

Fig. 7. Rotor angle G_{13} and G_{43} with $H_2(S)$ ***and*** $\tau = 205ms$.

generator' angles are used to display inter-area oscillations, and in Fig. 7, the difference between the G_4 and G_3 angles are used to show the local oscillations.

It was said that the delay in remote signaling has a certain and somewhat indefinite duration. The type of communication network, the physical distance and existing bandwidth all have a great impact on the duration of delays. A communication connection can be made by wired methods such as telephone lines, fiber optics and transmission over the power lines or wireless networks like satellite and microwave. Suppose, the communication network delay in the range of 150 to 350 ms by considering the sensors and transducers. Applying 95 ms delay to the output of the zero order controller ensures that system has nearly the optimal delay value (350+95=445 ms). Delay scheduling for the second order controller can be performed based on the results presented in Fig. 5. Applying 205 ms delay to the output of the second order controller will ensure that the system works near optimal delay value (205+ (150+350)/2=445 ms). Fig. 6 and Fig. 7 show the response of the system by applying the delay to the designed controller outputs to TCSC's input in the presence of various feedback delays. As seen, the control system has an appropriate robust function in a wide range of delay feedback. This indicates that increasing the delay feedbacks not only has undermined the performance of the control system, but also it is useful for damping improvement. The control system is completely robust.

5. CONCLUSION

The poor performance of the power oscillations damping controller against signal delays was eliminated by utilizing the control signal delay scheduling method. A method based on delay scheduling method presented to choose the input signal for TCSC controller in order to achieve a robust performance of the power oscillation damping control system against the constant delays of signal. An eigenvalue based framework is developed to design the controller based on the optimization of the strong spectral abscissa. The input delay and the utilization factor are important parameters for improvement of damping and delay margins. It is determined that increasing the delay margins and the decay rate of low-frequency oscillations in a delayed power system is possible by adjusting the delay in the TCSC input. Simulation results in different cases showed that by entering a proper delay to the control input, the performance of the system to the convergence rate is improved.

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