International Journal of Engineering

Journal Homepage: www.ije.ir

Delay-Scheduled Controllers for Inter-Area Oscillations Considering Time Delays

R. Asghari[a], S. B. Mozafari*[a], T. Amraee[b]

[a] Department of Electrical, Computer, and mechanical Engineering, Islamic Azad University,Science and Research Branch, Tehran, Iran
[b] Department of Electrical and Electronic Engineering, University of K. N. Toosi, Tehran, Iran

PAPER INFO

Paper history:
Received 02 June 2018
Received in revised form 17 July 2018
Accepted 17 August 2018

Keywords:
Delay Scheduling
Inter Area Oscilations
Maximum Convergence Rate
Time Delay System

ABSTRACT

Unlike the existing views that was introduced the existence of delay caused by the transmission of wide area measurement system data (WAMS) into the controllers input of the power oscilation damping (POD) by communication networks as a reason for poor performance of the POD controllers. This paper shows that the presence of time delay in the feedback loop may improve the performance of a POD controller in reducing inter-area oscilations. In fact, in a situation where the design and implementation of a POD controller for an FACT device is not easy without delays, in order to compensate for the delay effectively. In this work, a delayed scheduling method to design POD controllers is proposed. At first modeling of power system with delay as a design parameter was established. Then, the power oscillation damping delay scheduling (PODDS) based on objective function of the spectral abscissa was designed and the sufficient condition about stability of the closed-loop system is given. To evaluate the accuracy of the proposed control function and feasibility study, a four-machine power system for numerical simulation was used. The simulation results show that the controller designed in a wide range of delay changes decreases the power system oscillations without restricting SVC performance.

***doi**: 10.5829/ije.2018.31.11b.08*

1. INTRODUCTION

Application of a wide-area measurement, wide-area damping control, and increasing the distributed generation with decentralized control can increase the delay effect on the small signals stability in the power system [1]. Fortunately, the WAMS can provide appropriate outputs to the WADC control system. The appropriate outputs are usually non-local and require a communication network to be sent to the controller in order to there will be a delay. The range of delays is reported 100 and 700 ms [2]. Analyzing the delay problem and examining its wide are important and applicable issues in controlling and stabilizing power systems and many studies has been carried out in this regard. The studies can be categorized as follows:

1. Providing a new method to analyze the delay problem and attempting to reduce its effect on the small signal stability [3-6],
2. Providing a method to determine the delay margin in a WADC control system [7-10],
3. Providing a method to achieve a robust WADC control system against the network delays [11, 12].

Moreover, in particular cases, the presence of delay may lead to stable systems, the so-called stabilizing effect of delay. Stabilization methods for linear time-delay has been widely studied [13, 14] and applied in various engineering problems [15, 16]. The paper approach is to solve the delay problem in the SVC supplementary control design by stabilizing effect of delay.

In most cases, the crucial challenge is control system design considering the presence of delays in input signals measured at various locations within the power system. In terms of gaining better control and system stability, giving further delay to the input signal may provide the system with better opportunity to perform. Various design and analysis techniques as well as practical implementations were reported in liteature [17-19] without providing any application in electric power systems. This study takes the advantage of stabilization

*Corresponding Author Email: *mozafari@srbiau.ac.ir* (S. B. Mozafari)

Please cite this article as: R. Asghari, S. B. Mozafari, and T. Amraee,Delay-Scheduled Controllers for Inter-Area Oscillations Considering Time Delays, International Journal of Engineering (IJE), IJE TRANSACTIONS B: Applications Vol. 31, No. 11, (November 2018) 1852-1861

effect of delayed feedback signals in designing a supplementary controller with the highest ability.

In many cases, the robust analysis of a time delay system is very complicated. The main difficulty in characterizing stability of time-delay systems is that the system is infinite-dimensional [20]. Controller design methods can be divided into two main categories. The first category includes methods that yield stability independent of time delay or so called delay-independent stability methods. The second category consists of all the methods that authenticate the conditions in which increasing the delay up to a certain value will guarantee the stability of the system, which are also referred to as delay-dependent stability methods. Since in an actual power system, the amount of delay in feedback loop is limited, the delay-dependent stability methods are more common for designing controllers [21, 22]. In this approach assuming no delay, controller is designed to promote stability. However, system should also be stable in the presence of delay. This requirement is met by readjusting controller parameters while considering the maximum permissible value for delay parameter. The maximum value of time delay is computable. The reason lies in the fact that by some assumptions the spectral abscissa of the system becomes a continuous function of delay parameter and hence the upper bound for delay parameter can readily be obtained. This method, however, decreases the capability of the controller in damping oscillations since the controller parameters should be modified to adopt maximum value for delay parameter. As reported in literature [11] the time delays in the feedback control loop of Power System Stabilizer (PSS) devices do not necessarily imply a deterioration of the dynamic response. Actually, estimating the value of time delay and would a decrease of the gain of the PSS can the effect of the delay on the system dynamic response could be minimized. Despite common approaches, time delay can be viewed in a positive manner when control system design is dealt with it. This means that under some circumstances with increasing the time delay of input signals, performance of the control system and its stability would be improved, which is called delay range stability analysis.

In electric power systems, measured signals have always time delays, which directly enter into the control loop. This may cause power system to be more vulnerable under unstable conditions. Under these circumstances, a supplementary controller is usually designed to increase distance to instability boundaries of the system. The structure of this controller is usually requires a good perception of the system performance and having precise model of it. In this paper, a new method for designing robust controller based on the premise of delay range stability is proposed. Straight forward design procedure and easy implementation are key benefits of the proposed method. Since a small change in delay could bring the system to instability region, as discussed in literature [23], the controller is so optimized to become robust against a limited time delay variation. The backbone idea and method of obtaining the controller parameters are discussed as well.

In the following, the delayed power system is modeled in section two. In the third section, the theoretical foundations and the equations governing the stability analysis are reviewed. After that, the controller's design technique is described through the optimization of the robust spectral abscissa against delay changes. Then, the method of feedback signal selection is described using a second-order system. In section six, after the evaluation of the designed controlled system using a linear simulation in MATLAB, the proposed controller is implemented in a two-area power system and the efficiency of the suggested design is proved by a nonlinear simulation. Finally, some conclusions are reviewed in section seven.

2. MODELING THE CONTROL PROBLEM

The controller system structure to damping the power oscillation according to the transmission of the non-local signals by communication networks is shown in Figure 1. While 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 and τ is the delay control parameter applied to the control signal or at the actuator input, the actuator can be such equipment like HVDC, FACTS and generator's excitation system. The linear dynamic in the power system block can be rewritten as follows:

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

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

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, block state space model related to the controller via a fixed structure and fixed order can be formulated, as follows:

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

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

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.

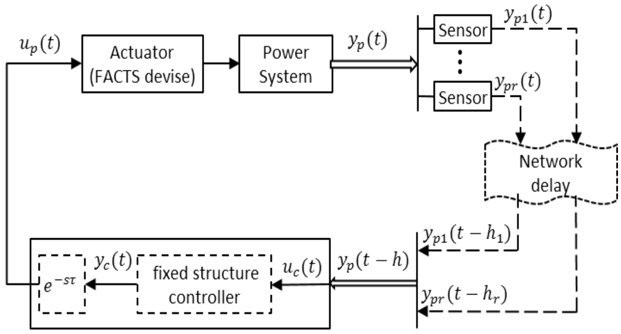

Figure 1. The structure of delayed POD control system

According to Figure 1, can be written, as follows:

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

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

The state-space equations of the control system can be rewritten using (3) as follows:

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

where,

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

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

Note that $\mathbf{A}(k)$ is a function at controller matrixes, i.e. $k \in (\mathbf{A}_c, \mathbf{B}_c, \mathbf{C}_c, \mathbf{D}_c)$.

3. STABILITY ANALYSIS OF TIME DELAY SYSTEMS

The placement results in solvation the candidate $x(t) = u\, e^{-\lambda t}$ via a u vector and λ scalar in Equation (4) are summarized, as follows:

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

As 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 Equation (4). The eigen values Equation (6) consist of some values of scalar parameter λ, where $u \neq 0$. 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 Equation (7) is called the characteristic equation. Consider $\{\lambda\}$ as sequence of the characteristic roots, the necessary and sufficient conditions for the asymptotic stability of the system (4) is defined, as

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

4. MAXIMAL CONVERGENCE RATE CONTROL

As already noted, the paper approach regarded to designing power oscillation damping controller based on SVC is utilizing the delay scheduling method in control signal. The optimized controller is designed in a way that will have a very slow convergence rate without delay and delay increased to a certain value leads to enhance overall convergence rate of the closed loop system. 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 will be solved:

$$\begin{aligned} &\min\ \alpha(k,\tau), \\ &\text{provided that:} \\ &\max \mathrm{Re}\{\lambda\} < 0,\ \tau > 0,\ h_i > 0,\ i = 1, 2, \ldots, r \end{aligned} \tag{9}$$

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

Consider $s = \alpha \pm j\beta$ as the simple rightmost root of the characteristic Equation (7), the vectors v^T and u are the left and right eigenvectors corresponding to s, using the theorem of the implicit function, we can calculate the partial derivative (5), as follows:

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

Multiplying both sides by v^T and noting that $v^T u = 1$

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 can write

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

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

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

It worth noting that the spectral abscissa in a delay system like (4) is a continuous function in k and τ but it is not always derivative, the above gradient is not derived only where the number of eigenvalues which it is real part is equaled to the spectral abscissa, be one more than the one [24].

5. SIGNAL SELECTION FOR STABILIZING DELAY EFFECT PROBLEM

Feedback signal selection is one of the important steps of a successful design and implementation of supplementary controllers for large-scale power systems. Signal selection based on a linear model is the easiest and most efficient approach. Various methods and criteria have been presented for the selection of the feedback signal, including higher Hankel singular values in reported in literature [25]; the residue amount and visibility in literature [12]; and, so on. In many cases, local signals do not demonstrate proper sensitivity to oscillation modes. Therefore, distant measured signals with acceptable values are selected. Control systems are usually designed with the approach of delay-dependent stabilization. Thus, the basis of feedback signal selection also lies in the frame of systems without time delays. However, it may be ineffective, since a linear time-delay system may limit controller capabilities. On the other hand, the proposed control method is designed with the approach of time delay-affected stabilization. Clearly, a linear delay system is matched with an infinite dimensional system, and common criteria for selecting inputs and outputs can only be used for finite-dimensional systems [26]. For linear time-delay systems operating close to equilibrium, methods for linear systems are useful for initial screening to signal selection. Considering the above-mentioned facts, the proposed method of feedback signal selection is described through an example.

Now, we only consider the linear system of the (SMIB) electromechanical model in describing the state space with delay input:

$$\dot{x}_1(t)=x_2(t) \quad (11a)$$

$$\dot{x}_2(t)=-\omega_n^2 x_1(t)+u(t-\tau) \quad (11b)$$

$$y_1(t)=x_1(t) \quad (11c)$$

$$y_2(t)=x_2(t) \quad (11d)$$

where, $x_1(t)$ is the rotor angle deviation, $x_2(t)$ is the rotor speed deviation, $u(t-\tau)$ is the manipulated input, and ω_n is the non-damped natural frequency. This system has a pair of imaginary poles when no control input is applied. If the desire is to damp out the oscillations by $u(t-\tau)$ selecting feedback signal and its impact on moving the rightmost eigenvalue due to variation of τ becomes very important. Nevertheless, we assume that either $y_1(t)$ or $y_2(t)$ can be used as a measured variable to design a static output controller. The proportional gain is determined for an incremental delay through an optimization model whose objective is to minimize the spectral abscissa at each step of delay increment. The results indicating minimum spectral abscissa versus delay parameter is shown in Figure 2.

Figure 2 reveals that choosing y_2 as an input for the control is more beneficial since more damping is introduced when the $\tau\omega_n$ falls in the range of 0 to 0.678 Radian. However, when the $\tau\omega_n$ falls in the range of 0.678 to 2.36 Radian, y_1 becomes more effective to be used as an input of the control system.

Hence, assuming that an appropriate input is available, in order to increase the damping of oscillations in a delayed power system, the best signal to control the parameters of an actuator, such as FACTs, is the angle signal of generators.

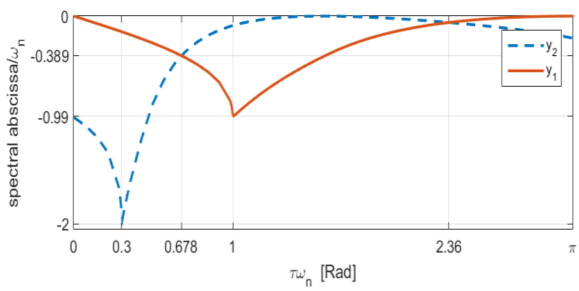

Figure 2. The spectral abscissa per ω_n as a function at $\tau\omega_n$

In this work, the input signal to a SVC supplemental controller was selected based on a simple and innovative method. The steps to be taken are as follows:

First, consider the representation of the minimal transfer function between each of the output and input signals of the system (1) as follows:

$$G(s)=\sum_{i=1}^{k}\frac{a_i s+b_i}{(s+\sigma_i)^2+\omega_i^2}+\sum_{i=k+1}^{np}\frac{c_i}{s+p_i} \tag{12}$$

then, for each of the complex dominant poles, calculate the following index:

$$\mathrm{CI_i}=\left\{\frac{a_i}{norm(a_i,b_i)}\right\} \tag{13}$$

finally, taking into account the weight of each of the dominant modes in the $\mathrm{CI_i}$ value, select the input signal for the supplementary controller with the lowest $\mathrm{CI_i}$. It is worth noting that this solution is useful when the approach of time delay-affected stabilization is taken.

6. CASE STUDY

A typical two area power system is shown in Figure 3; which is used to demonstrate the capability of the proposed design approach in damping inter-area power oscillations. The single line diagram of the studied power system is shown in Figure 4. System characteristics including transmission lines data, generators dynamic specifications and loads information are given in literature [27]. The structure of the primary system is modified by augmenting a SVC at bus 8 and in the middle of power corridor connecting two areas to each other. The primary function of the SVC is to regulate voltage at bus 8. This regulation is performed by proportionally adjusting the susceptance of the SVC. It is assumed that the capacity of the SVC is partly dedicated to low frequency damping purposes. This needs to define a new supplementary task for the controller that measures and processes remote signals so as to make suitable reference voltage. When reference voltage is applied to the SVC, the overall damping against low frequency oscillations increases. Figure 4 also illustrates the main concepts of the supplementary controller for the SVC. In this figure, H(s) are the controller that input signals from remote locations and make suitable signals for modulation of the SVC reference voltage. Since remote signals are associated with inherent delays, a delayed controller based on delay stabilization effect is designed to increase system damping. Simulations are carried out by considering base values for voltage and power as 230 kV and 230 MVA, respectively and the system frequency is 50 Hz. It is assumed that every generator is equipped with an AVR whose simplified transfer function has a gain of 200 and a time constant of 0.01 s, PSS is not included in the study. The installed SVC at bus 8 has a capacity of 200 MVAR. Without considering the supplementary controller, small signal analysis of the system in Figure 4 shows that the system has three critical oscillatory modes. The spectral abscissa is obtained 0.0099 and hence the current state of the system is unstable.One solution is to add a supplementary control on SVC as shown in Figure 4 with the aim of improving system performance and damping critical modes. Stabilization due to input delay is only effective when a proper input signal is selected. To select input signals, we have used the methodology described in section 5. Therefore, the CI index is first computed for all critical modes of the system. The results are given in Table 1. Comparing the obtained values for CIs, Table 1 showsthat measuring rotor angles for G2 and G4 are the best. Referring to the first column of Table 1, the best signal isthe rotor angle of G2.

However, for other critical modes by referring to column 2 and column 3, it is indicated that the best signals could be rotor angle of G4 and again G2. Thus, rotor angles of G2 and G4 are selected and combined to make a proper input signal to the H(s).

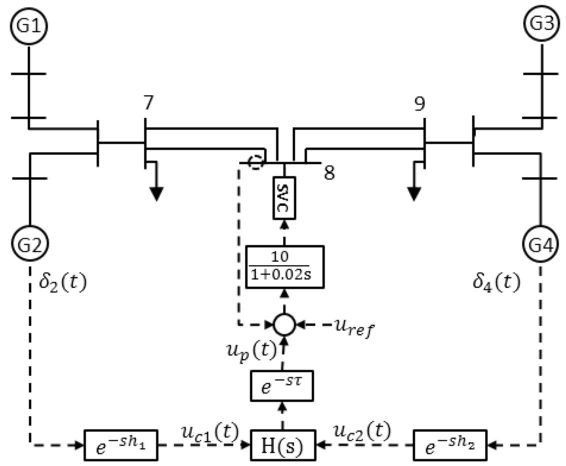

Figure 3. Two area power system

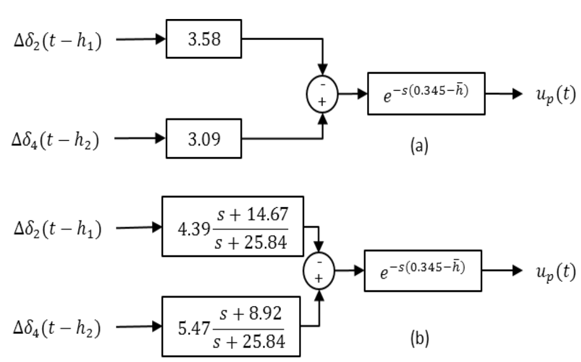

Figure 4. Supplementary control block diagram

TABLE 1. Comparison Between The Results of Signal Selection from the Generator Angle Based with on CI

Critical modes	0.0099±j3.66	-0.697±j6.52	-0.703±j6.32
G1	0.0545	-0.242	0.879
G2	-0.0011	0.180	-0.774
G3	-0.0186	0.559	0.162
G4	-0.0211	-0.432	-0.107

To design the controller function, we first need to obtain the open-loop transfer function between the SVC input and outputs that are rotor angles of generators as shown in Figure 4. The PST software package has been used to model the power system [28]. The reason lies in the fact that it has the capability of generating the linearized system matrix. In modeling, generators are defined by their sixth order model. The generators' excitation system and the SVC voltage regulator models are of the first order. Therefore, the overall dynamic model of the system would be of the twenty-ninth order.

The open loop transfer functions between the selected output signals and the SVC input are given in follows:

$$G_1(s)=\frac{\Delta\delta_2(s)}{u_p(s)},\ G_2(s)=\frac{\Delta\delta_4(s)}{u_p(s)} \tag{14}$$

Let, we rewrite Equation (14) in the form as follows:

$$\dot{\hat{x}}(\mathrm{t})=\hat{\mathbf{A}}\hat{x}(\mathrm{t})+\hat{\mathbf{B}}\hat{u}_p(\mathrm{t}) \tag{15a}$$

$$\hat{y}(\mathrm{t})=\hat{\mathbf{C}}\hat{x}(\mathrm{t}) \tag{15b}$$

Order reduction methods are generally used to simplify system equations by reducing number of state variables. Order of the system equations can be reduced by different approaches. Here, we use balanced residualization method to obtain a reduced order model [35]. Unlike the modal residualization method in which the location of mode is used as a criterion to discard ineffective modes, the balanced residualization method takes into account singular value of the residual matrices as a criterion. Due to high sensitivity of fast high frequency modes to delay value, the residual approach is employed so that the impact of high frequency modes are considered in the reduced order system.

The reduced order state space realization is given in Equation (16). One way to compute coefficient matrices in this representation is to use MATLAB functions named "balreal.m" and "modred.m". Prior to execution of "modred.m" function, it is necessary to make decision on the value of order-reduction error. We set this value to 0.001. The numerical results for the studied system are given in Appendix A. The final order of the system model is reduced to 8. The reduced-order model of the power system can be generally represented as,

$$\dot{x}_p(\mathrm{t})=\mathbf{A}_p x_p(\mathrm{t})+\mathbf{B}_p u_p(\mathrm{t}) \tag{16a}$$

$$y_p(\mathrm{t})=\mathbf{C}_p x_p(\mathrm{t})+\mathbf{D}_p u_p(\mathrm{t}) \tag{16b}$$

where, $y_p(\mathrm{t})=\begin{bmatrix}\delta_2(\mathrm{t})\\ \delta_4(\mathrm{t})\end{bmatrix}$.

Two structures are examined for the controller to stabilize the closed loop system. The first structure is a static controller ($nc=0$) whose equation is defined as follows:

$$u_p(\mathrm{t})=k_1\delta_2(\mathrm{t}\text{-}\mathrm{h}_1\text{-}\tau)+k_2\delta_4(\mathrm{t}\text{-}\mathrm{h}_2\text{-}\tau) \tag{17}$$

the second structure is a one-order controller ($nc=1$) whose equations are described as follows:

$$\dot{x}_c(\mathrm{t})=k_1x_c(\mathrm{t})+k_2\delta_2(\mathrm{t}\text{-}\mathrm{h}_1)+k_3\delta_4(\mathrm{t}\text{-}\mathrm{h}_2) \tag{18a}$$

$$u_p(\mathrm{t})=k_4x_c(\mathrm{t}\text{-}\tau)+k_5\delta_2(\mathrm{t}\text{-}\mathrm{h}_1\text{-}\tau)+k_6\delta_4(\mathrm{t}\text{-}\mathrm{h}_2\text{-}\tau) \tag{18b}$$

In our design procedure, first we assume $h_1=h_2=h$ and static structure for the controller and by solving Equation (9), optimal values for parameters of k_1, k_2 and $\tau+h$ are determined. To design one-order controller parameters, delay parameter is fixed to what obtained for the static controller , $\tau+h$, and then using Equation (9) other control parameters are determined. The designed controller block diagrams for both structures are shown in Figure 5 where (a) and (b) represent block diagrams of designed controllers with zero and one order, respectively.

Up to now, dynamic controller parameters and transfer functions can be used for a fixed value of input delay. In the next stage to evaluate the robustness and stability region of the designed controller with respect to input delay variations, upper and lower bands of input delay is obtained by developing eigAM.m MATLAB function [36]. Table 2 summarizes the results for upper and lower bands, optimal delay value and associated spectral abscissa for both controllers.

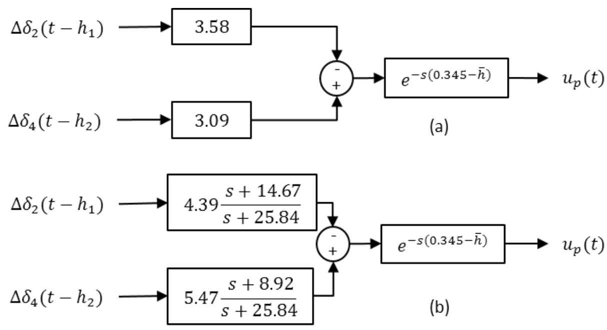

Figure 5. Supplementary control block diagram

TABLE 2. Results of Minimizing the Spectral Abscissa

symbol	Definition	$nc = 0$	$nc = 1$
τ_l	Lower bound delays [ms]	1	45
τ_h	Upper bound delays [ms]	654	695
$\tau_h - \tau_l$	Delay- range stability [ms]	653	650
$\tau_{op} + h$	Optimized solution delays [ms]	345	345
F_{op}	Optimized spectral abscissa	-0.801	-1.413

Referring to Table 2, given value for optimal spectral abscissa indicates that all closed loop system eigenvalues in the case of static controller, are always on the left-hand side of spectral abscissa with -0.801 and -1.413 in the case of dynamic controller.

The rightmost eigenvalues of the system are depicted in Figures 6 and 7 as a function of input delay variations, by taking into account the static and dynamic controllers, respectively. With the static controller and for τ>1 ms, the spectral abscissa shows that not only stability would be guaranteed, but continuously improving with a delay increase of up to 345 ms.

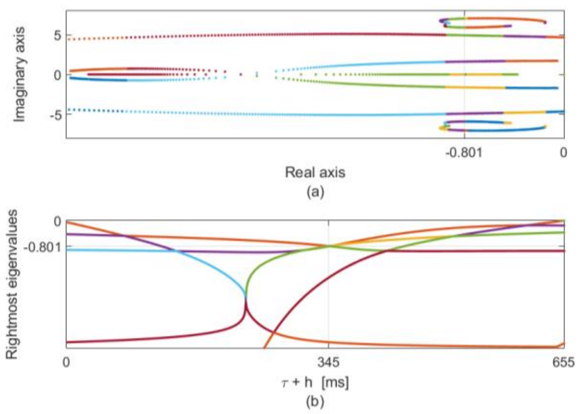

Figure 6. Rightmost modes as a function of $h + \tau$bync=0

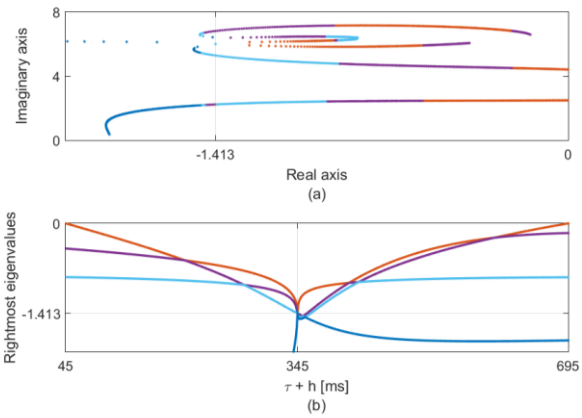

Figure 7. Rightmost modes as a function of $h + \tau$bync=1

More precisely, for delay between 1-85 ms, inter-area mode is determinative as a rightmost eigenvalue to show the stability condition and this role goes to the local mode between G1 and G2 when delay increases from 85ms up to 345ms. In the range of 345-590 ms, the local mode between G3 and G4 takes a determinative role. For delays more than 600 ms, it is observed that a complex pole resulting from the delay causes the system to go into instability. Since at optimal delay value, 345 ms, inter-area mode has moved more than local modes to the left side of complex plane, it could be concluded that the selected signal is more effective on the inter-area mode although it has a positive effect on local modes. In similar way, Figure 7 shows the rightmost eigenvalues places for closed loop system with $nc = 1$ in terms of delay variations.

For these two cases, a nonlinear simulation is conducted when a three-phase short circuit occurs at bus 7 for a maximum time of 50 ms. In order to evaluate the simulation results, inter-area oscillations are observed by measuring angle difference between the first and the third generators. However, to inspect local oscillations, difference angle between the fourth and the third generators is used. On the other hand, to examine maximum permissible input signal amplitude in terms of delay, the signal u_c is measured during all simulations. It is obvious that the amount of time delay in remote signals is uncertain but limited. The communication link and the physical distance between the points have a significant effect on the time delay. There are various types of communication links such as telephone lines, optical fibers, power-line communications, and microwave and satellite links. We assume that the controller receives the output signal through a Power Line Communication (PLC) with a delay in the range of 150 to 350 ms. If we take 250 ms as the average delay, we can create a 100 ms time delay in the SVC input according to the results obtained in the previous section for optimal time delay value. Hence, the overall value of total delays including of SVC input delay and measuring feedback signals would be nearly 350ms. In order to demonstrate the robustness and efficiency of the proposed method, the simulation results are illustrated in Figures 8 to 10. As one can see, employing both proposed controllers exhibit a proper performance and an acceptable robustness against delay changes in the feedback. As shown in Figure 10, it can also be seen that the peak of the control signal decreases as the delay increases. In other words, the performance is also improved in terms of actuator saturation. Now, it is time to demonstrate how the parameter τ influences the convergence rate of the states. It is seen in Figures 8 and 9 that when h is increased from 150 to 250 ms, the convergence rate of states of the closed-loop system increases. However, for h=350 ms, the corresponding convergence rate decreases, indicating that for h=250

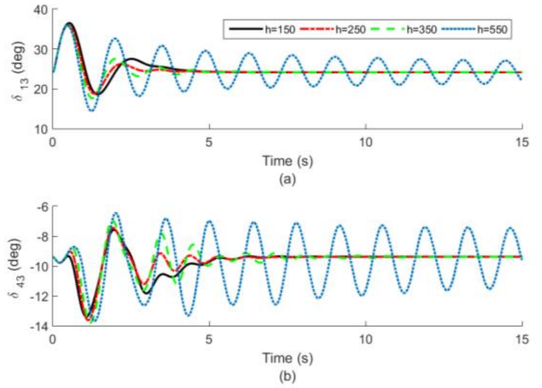

Figure 8. System response as a function at h for $\tau = 100\ ms$ by nc=0

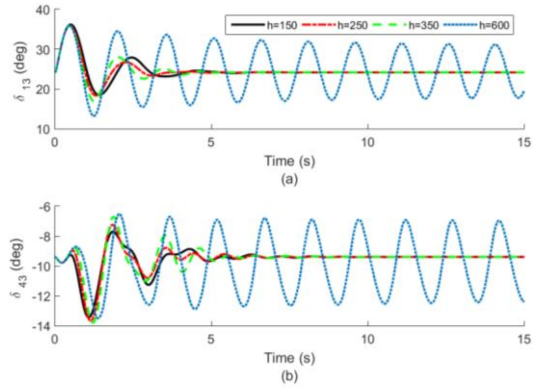

Figure 9. System response as a function at h for $\tau = 100\ ms$ by nc=1

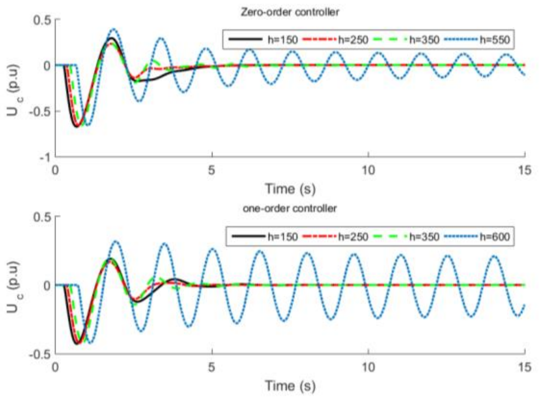

Figure 10. The output of each controller as a function at h for τ = 100 ms

ms we achieve the highest convergence rate of the closed loop system. As shown in Figures 5 and 6, a worse case condition is achieved when the maximum permissible value of the overall delay is about 650 ms for the static and 700 ms for the dynamic controllers, respectively.

To examine the system response in this case, h is set to 550 ms when using the static controller and h is set to 600 ms for the dynamic controller. It can be observed that the ability of the controllers to damp power oscillation will be lost.This is due to the fact that in these conditions the overall delay exceeds the upper band.

7. CONCLUSION

In this work, the approach of delay-scheduled stabilization is studied and shown that by means of this approach a delayed input supplementary controller could be designed to damp out dynamic oscillations in a power system. In this study the supplementary controller has been installed on an SVC device. 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 in the 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 SVC input. Simulation results in different cases showed that by entering a proper delay to the actuator (SVC) input, performance of the system to damp power oscillations will be improved.

Appendix A

The state space representation of the 8th-order reduced linear model of the open loop power system stated as follows:

$$\begin{array}{cc} A & B \\ \begin{bmatrix} 0.010 & -3.66 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 3.663 & 0.010 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & -0.219 & -6.115 & 0.720 & -0.023 & -0.183 & 0.159 \\ 0.000 & 0.000 & 6.1039 & -1.084 & 2.404 & -0.054 & -0.451 & 0.387 \\ 0.000 & 0.000 & 0.6617 & -2.388 & -5.053 & 0.313 & 2.261 & -1.925 \\ 0.000 & 0.000 & 0.0163 & -0.026 & -0.163 & -0.023 & -6.453 & 0.349 \\ 0.000 & 0.000 & -0.095 & 0.1695 & 0.131 & 6.450 & -1.569 & 2.609 \\ 0.000 & 0.000 & 0.1573 & -0.386 & -1.892 & -0.220 & 0.682 & -8.040 \end{bmatrix}, & \begin{bmatrix} -0.0383 \\ 0.2574 \\ -0.4621 \\ -0.9502 \\ 0.866 \\ -0.0244 \\ -0.1957 \\ 0.1689 \end{bmatrix} \end{array}$$

$$\begin{array}{cc} C & D \\ \begin{bmatrix} -3.055 & -0.237 & -0.317 & -0.033 & -0.211 & -0.411 & 0.605 & 0.733 \\ 0.637 & 0.588 & -0.008 & 0.023 & 0.098 & -0.169 & 0.101 & 0.135 \end{bmatrix}, & \begin{bmatrix} -0.0010 \\ -0.0001 \end{bmatrix} \end{array}$$

8. REFERENCES

1. Wu, H., Ni, H. and Heydt, G.T., "The impact of time delay on robust control design in power systems", in Power Engineering Society Winter Meeting, 2002. IEEE. Vol. 2, (2002), 1511-1516.

2. Rabiee, S., Ayoubzadeh, H., Farrokhzad, D. and Aminifar, F., "Practical aspects of phasor measurement unit (pmu) installation in power grids", in Smart Grid Conference (SGC), 2013, IEEE., (2013), 20-25.

3. Leon, A.E. and Solsona, J.A., "Power oscillation damping improvement by adding multiple wind farms to wide-area coordinating controls", ***IEEE Transactions on Power Systems***, Vol. 29, No. 3, (2014), 1356-1364.

4. Mokhtari, M., Aminifar, F., Nazarpour, D. and Golshannavaz, S., "Wide-area power oscillation damping with a fuzzy controller compensating the continuous communication delays", ***IEEE Transactions on Power Systems***, Vol. 28, No. 2, (2013), 1997-2005.

5. Preece, R., Milanovic, J.V., Almutairi, A.M. and Marjanovic, O., "Damping of inter-area oscillations in mixed ac/dc networks using wams based supplementary controller", ***IEEE Trans. Power Syst***, Vol. 28, No. 2, (2013), 1160-1169.

6. Cai, G., Yang, D. and Liu, C., "Adaptive wide-area damping control scheme for smart grids with consideration of signal time delay", ***Energies***, Vol. 6, No. 9, (2013), 4841-4858.

7. Hadidi, R. and Jeyasurya, B., "Reinforcement learning based real-time wide-area stabilizing control agents to enhance power system stability", ***IEEE Transactions on Smart Grid***, Vol. 4, No. 1, (2013), 489-497.

8. Stahlhut, J.W., Browne, T.J., Heydt, G.T. and Vittal, V., "Latency viewed as a stochastic process and its impact on wide area power system control signals", ***IEEE Transactions on Power Systems***, Vol. 23, No. 1, (2008), 84-91.

9. Chaudhuri, N.R., Ray, S., Majumder, R. and Chaudhuri, B., "A new approach to continuous latency compensation with adaptive phasor power oscillation damping controller (POD)", ***IEEE Transactions on Power Systems***, Vol. 25, No. 2, (2010), 939-946.

10. Milano, F., "Small-signal stability analysis of large power systems with inclusion of multiple delays", ***IEEE Transactions on Power Systems***, Vol. 31, No. 4, (2016), 3257-3266.

11. Bokharaie, V., Sipahi, R. and Milano, F., "Small-signal stability analysis of delayed power system stabilizers", in Power Systems Computation Conference (PSCC), 2014, IEEE., (2014), 1-7.

12. Yao, W., Jiang, L., Wen, J., Wu, Q. and Cheng, S., "Wide-area damping controller for power system interarea oscillations: A networked predictive control approach", ***IEEE Transactions on Control Systems Technology***, Vol. 23, No. 1, (2015), 27-36.

13. Yao, W., Jiang, L., Wen, J., Wu, Q. and Cheng, S., "Wide-area damping controller of facts devices for inter-area oscillations considering communication time delays", ***IEEE Transactions on Power Systems***, Vol. 29, No. 1, (2014), 318-329.

14. Li, J., Chen, Z., Cai, D., Zhen, W. and Huang, Q., "Delay-dependent stability control for power system with multiple time-delays", ***IEEE Transactions on Power Systems***, Vol. 31, No. 3, (2016), 2316-2326.

15. Yang, B. and Sun, Y., "A novel approach to calculate damping factor based delay margin for wide area damping control", ***IEEE Transactions on Power Systems***, Vol. 29, No. 6, (2014), 3116-3117.

16. Yang, B. and Sun, Y.-z., "A new wide area damping controller design method considering signal transmission delay to damp interarea oscillations in power system", ***Journal of Central South University***, Vol. 21, No. 11, (2014), 4193-4198.

17. Sipahi, R., Niculescu, S.-I., Abdallah, C.T., Michiels, W. and Gu, K., "Stability and stabilization of systems with time delay", ***IEEE Control Systems***, Vol. 31, No. 1, (2011), 38-65.

18. Vyhlídal, T. and Hromčík, M., "Parameterization of input shapers with delays of various distribution", ***Automatica***, Vol. 59, (2015), 256-263.

19. Vyhlídal, T., Olgac, N. and Kučera, V., "Delayed resonator with acceleration feedback–complete stability analysis by spectral methods and vibration absorber design", ***Journal of Sound and Vibration***, Vol. 333, No. 25, (2014), 6781-6795.

20. Kamen, E., Khargonekar, P. and Tannenbaum, A., "Stabilization of time-delay systems using finite-dimensional compensators", ***IEEE Transactions on Automatic Control***, Vol. 30, No. 1, (1985), 75-78.

21. Yao, W., Jiang, L., Wu, Q., Wen, J. and Cheng, S., "Delay-dependent stability analysis of the power system with a wide-area damping controller embedded", ***IEEE Transactions on Power Systems***, Vol. 26, No. 1, (2011), 233-240.

22. Yang, B. and Sun, Y., "Damping factor based delay margin for wide area signals in power system damping control", ***IEEE Transactions on Power Systems***, Vol. 28, No. 3, (2013), 3501-3502.

23. Cheng, L., Chen, G., Gao, W., Zhang, F. and Li, G., "Adaptive time delay compensator (atdc) design for wide-area power system stabilizer", ***IEEE Transactions on Smart Grid***, Vol. 5, No. 6, (2014), 2957-2966.

24. Kunjumuhammed, L., Singh, R. and Pal, B., "Robust signal selection for damping of inter-area oscillations", ***IET Generation, Transmission & Distribution***, Vol. 6, No. 5, (2012), 404-416.

25. Van De Wal, M. and De Jager, B., "A review of methods for input/output selection", ***Automatica***, Vol. 37, No. 4, (2001), 487-510.

26. Hale, J.K. and Lunel, S.M.V., "Introduction to functional differential equations, Springer Science & Business Media, Vol. 99, (2013).

27. Cheung, K., Chow, J. and Rogers, G., "Power system toolbox, v 3.0", Rensselaer Polytechnic Institute and Cherry Tree Scientific Software, (2009).

28. Laub, A., Heath, M., Paige, C. and Ward, R., "Computation of system balancing transformations and other applications of simultaneous diagonalization algorithms", ***IEEE Transactions on Automatic Control***, Vol. 32, No. 2, (1987), 115-122.

Delay-Scheduled Controllers for Inter-Area Oscillations Considering Time Delays

R. Asghari[a], S. B. Mozafari[a], T. Amraee[b]

[a] *Department of Electrical, Computer, and mechanical Engineering, Islamic Azad University,Science and Research Branch, Tehran, Iran*
[b] *Department of Electrical and Electronic Engineering, University of K. N. Toosi, Tehran, Iran*

PAPER INFO

Paper history:
Received 02 June 2018
Received in revised form 17 July 2018
Accepted 17 August 2018

Keywords:
Delay Scheduling
Inter Area Oscilations
Maximum Convergence Rate
Time Delay System

چکیده

بر خلاف دیدگاه‌های موجود که تأخیر ناشی از انتقال داده‌های سیستم اندازه‌گیری ابعاد وسیع (WAMS) را به ورودی کنترل‌کننده‌های میرایی نوسان توان (POD) توسط شبکه‌های ارتباطی به عنوان دلیلی برای عملکرد ضعیف کنترل‌کننده‌های POD معرفی کرده‌اند، این مقاله نشان می‌دهد که حضور تاخیر زمانی در حلقه بازخورد می‌تواند عملکرد یک کنترل‌کننده POD را در کاهش نوسانات بین ناحیه‌ای بهبود دهد. در حقیقت، در شرایطی که طراحی و پیاده‌سازی یک کنترل‌کننده POD برای دستگاه FACT بدون تاخیر آسان نیست، به منظور جبران‌سازی تاخیر به طور موثر، این مقاله یک روش برنامه‌ریزی تاخیری را برای طراحی کنترل‌کننده‌های POD پیشنهاد داده است. ابتدا مدلسازی سیستم قدرت با تاخیر به عنوان پارامتر طراحی صورت گرفته است. سپس، برنام‌ریزی تاخیری برای طراحی میراساز نوسان توان (PODDS) بر اساس تابع هدف ابعاد طیفی و شرایط کافی در مورد پایداری سیستم حلقه بسته ارائه شده است. امکان‌سنجی کنترل‌کننده پیشنهادی با شبیه‌سازی‌های عددی بر روی سیستم قدرت چهار ماشینه تایید شده است. نتایج شبیه‌سازی نشان می‌دهد که کنترل‌کننده طراحی‌شده نوسانات سیستم قدرت را در طیف گسترده‌ای از تغییرات تاخیر بدون محدود کردن عملکرد SVC میرا کند.

doi*: 10.5829/ije.2018.31.11b.08*