A unified power flow controller-based robust damping controller considering time delay in electrical power systems

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ABSTRACT

Nowadays, different power systems are connected to each other due to technical and economic reasons and form a complex developed network. Such networks measure and send system data to decision-making centers for control and protection. This information transmission is accompanied by a delay and causes the performance of the system's damping controllers to be affected. To improve power system dynamic stability, the supplementary controller in flexible alternating current transmission system (FACTS) devices is designed to account for information transmission delays. In these methods, to increase the controllability and observability of the inter-area mode, the remote signals extracted from the wide area measurement system (WAMS) are used as the input of the modulator. WAMS systems' time delay reduces power system stability and even causes instability, so it's crucial to find the maximum delay margin that ensures stability. Therefore, it is necessary to carefully study the role of FACTS tools in stabilizing the power system and damping inter-regional fluctuations, considering the delay. This research shows that supplementary controller design can dampen frequency and load angle fluctuations in multi-zone power systems despite information transmission delays. The method works in power system analysis toolbox (PSAT) simulation and MATLAB programming.

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1. INTRODUCTION

The mutual effects of the network's components, such as the oscillations of the rotors in various power plants relative to one another, are what give rise to the various oscillatory modes in today's power systems. There are two distinct types of fluctuations in power systems that will cause problems for the system. These fluctuations are known as local mode fluctuations and inter-regional mode fluctuations. Local mode fluctuations occur when a generator (or a set of generators) in a power plant under the control of the voltage regulator starts to fluctuate in the presence of other parts of the system. Inter-regional fluctuations include combined fluctuations of the machines of one part of the system compared to the machines of other parts of the system. The characteristic frequency of inter-regional modes is usually in the range of 0.1 to 1 Hz. Local modes, control modes, and traction modes are usually induced by the opposition between the electrical and mechanical modes of the turbine-generator system. Inter-regional modes may be induced by high-gain generator exciters or heavy power transmission through weak lines [1]–[9].

Large power systems usually contain dominant inter-regional oscillatory modes that are related to power transmission dynamics and include a group of machines that oscillate relative to each other. When inter-regional modes are stimulated, power transfer between regions, including generators, will be limited. With the increase in connections and energy exchange in electric networks, the low-frequency fluctuations between regions will be weakly damped, and the stability of the power system will become one of the concerns of power industry specialists [10]–[16]. Major disturbances have caused challenging fluctuations in power grids around the world: 0.6 Hz in the Hydro-Québec system, 0.2 Hz in the Northwestern American national network, 0.15 Hz-0.25 Hz in Brazil, and 0.19 Hz-0.36 Hz in the UCTE-Central European connections. Recent large blackouts in Canada and Europe have occurred at oscillating frequencies of 0.4 Hz. Over many years, these shutdowns caused by low-frequency fluctuations have been recorded. The following examples show some of the fluctuations leading to the failure of the power system:

- In the early 1960, when the Detroit Edison and Ontario Hydro systems were connected, frequency fluctuations were observed in the network.
- In 1969, under different working conditions, low-frequency fluctuations were observed in the Finland-Sweden-Denmark integrated network.
- In 1971 and 1972, more than 70 events that led to frequency fluctuations in the mid-continent power grid were observed in North America.
- In 1979, unstable oscillations at 0.6 Hz were observed in the states of Wales and South Victoria.
- In 2010 and 2011, the South Australian energy commission reported low-frequency oscillations that were slowly dampening. The frequency of these oscillations was between 0.2 and 0.3 Hz.
- In August 2012, the pacific network experienced unstable regional oscillations in the Pacific Ocean, which led to the complete disconnection of the 400 kV network.

The old and usual method that is used to dampen low-frequency fluctuations in the power system is to install a power system stabilizer (PSS) in the network. PSS provides additional control for the excitation part of synchronous generators. In recent years, additional modulation controllers have been added to the flexible alternating current transmission systems (FACTS) to dampen inter-regional fluctuations. In addition to controlling the power flow in the system regardless of the system conditions, FACTS devices also improve the dynamic stability of the system by damping power fluctuations. In addition, they can act as a barrier against successive disturbances in the system and prevent shutdowns. With the development of power semiconductor technology, it is possible to use voltage source converters at high powers. Among the advantages of these converters, we can mention the independent control of active and reactive power as well as the transmission of active power in both directions (input to the converter and output from it) without changing the direction of the DC voltage [1]–[4], [10], [17]–[32].

Nowadays, the use of these converters is considered in the structure of FACTS devices, and therefore, over time, FACTS devices designed based on this type of converter (VSC-based FACTS) will replace the classic FACTS systems [1], [20], [23]. Darabian *et al.* [33], the authors have modeled a multi-machine system, and finally, based on the proposed method of the article, they have done the placement and optimal settings of PSS. The results of this article show the effective performance of the designed PSS in low-frequency fluctuations and improve the dynamic and transient stability of the power system. Although in this article, the method proposed by the authors has not been compared with other common methods, and the degree of influence of the proposed method is not completely clear, it can be concluded that, apart from the issue of parameter design, the optimal placement of PSS directly affects its performance. Ren *et al.* [34], the particle swarm optimization algorithm is used to design the stabilizer of the power system. In this article, the dominant electromechanical poles that are the cause of low-frequency fluctuations are identified, and the frequency responses of the system are shown in both open-loop and closed-loop modes. Ghosh *et al.* [35], a method based on the use of a genetic algorithm is proposed to obtain the optimal coefficients of the PSS controller. In this article, the controller is Lead-Lag, and studies have been done on a multi-machine system. Jordehi [36], the authors have examined the selection of the appropriate input signal for use in the purposes of damping low frequency fluctuations in the power system and point out that, in addition to the PSS controller, its input can also be effective in damping low frequency fluctuations. Of course, in these articles, various inputs such as rotor speed, terminal frequency, output active power, and linear combinations of the mentioned items have been suggested for use in PSS. However, since the main purpose of PSS is the damping of rotor speed fluctuations, rotor speed changes have been introduced as a suitable option for damping purposes. Although it has been mentioned in these articles that the use of rotor speed changes in the design of damping controllers can have an effect on the excitation of rotor rotational modes. In this regard, the position of using PSS is also known to be effective in damping fluctuations [37] and practically in damping fluctuations.

In the field of regulating the parameters of damping controllers, it is necessary to pay attention to the fact that a controller must have the ability to function correctly and effectively in different working conditions. In this regard, the design of the auxiliary controller has been done in the following three categories: methods based on linear control such as pole positioning and linear square regulator [38], [39]; methods based on non-linear control such as adaptive control and fuzzy control [40]; and methods based on complementary and experimental algorithms such as neural networks and bird particles. Singh *et al.* [41], the power system equipped with thyristor-controlled series capacitor (TCSC) has been investigated. In this article, a genetic algorithm is used to adjust the controller parameters. The damper controller is also assumed to be a integral and derivative (PID). Mohammadpour *et al.* [42], the study of the nonlinear unified power flow controller (UPFC) system for noise reduction is discussed. In this study, the linearization of the power system has also been done, the effect of UPFC controllers on the damping of fluctuations has been studied, and finally, it has been shown that the designed supplementary controllers, along with the designed damping controllers, can play the role of PSS in the power system. Tiron *et al.* [43], has used interline power flow controller (IPFC) to improve power system fluctuation damping. In this article, a complementary fuzzy-type controller is considered. The final results of this article show the proper performance of IPFC in voltage regulation and damping of low-frequency fluctuations in the power system. It should be noted that in the study of dynamic stability, the linearized model of the system is used, and in order to design the controllers that dampen fluctuations based on FACTS devices, these devices must be included in the linear model of the system. Among the works in the field of linearization of FACTS devices, we can refer to [44], which deals with the linear modeling of synchronous series compensator (SSSC), static synchronous compensator (STATCOM), and UPFC in single-machine and multi-machine power systems and the modification of the Heffron-Phillips model so that all three devices have reached a similar structure with minor differences for the modified Heffron-Phillips model [1], [3], [10], [15], [17], [22], [25], [27], [31], [45]-[71]. In these articles, several methods have been used to select the feedback signal for the complementary controller. The method introduced by Larsen [72] has been used in most of his articles. The supplementary controller used in these articles is designed for only one work point, which is tested at several work points in the nonlinear model to evaluate the performance of this controller.

In the field of designing a supplementary controller for smoothing the system fluctuations, nonlinear models of the power system equipped with FACTS devices have also been used, and due to the complexity of the smoothing controller design, evolutionary algorithms have been used for the design. Many designs have been proposed for the design of the controller of the oscillation damper for FACTS devices. Padhy [73], Heng started to design a conventional pre-phase post-phase controller with fixed parameters for UPFC installed in the communication line of a two-zone system for damping the inter-zone oscillation mode. Paul *et al.* [74], has considered the design of an adaptive fuzzy controller for the same purpose. Gupta *et al.* [75], suggests the use of neural network for UPFC in order to improve the damping performance of the system. Robust control designs, such as H∞ and singular value analysis, have also been investigated [75]. To avoid zero-pole elimination in relation to the H∞ approach, the singular value analysis presented in [76] is used to select the parameters of the UPFC controller to have robust stability against model disturbances. The stability of the system has a close relationship with the performance of the controllers used in the system for the dynamic stabilization of the system. Therefore, many efforts have been made in the field of optimizing and improving the performance of these controllers. In this context, controller design methods using optimal control have been used to improve the dynamic stability performance of the system. Also, some activities have been done using non-linear methods such as Taboo search [77]. Some of the developed methods use innovative search methods such as genetic algorithm, particle swarm optimization. These methods optimize the parameters of the controller around a specific working point. But the use of the power system is such that it cannot be used in a particular working point during the entire working life of the power system. Therefore, if the system deviates from the regulatory working point, its stability cannot be guaranteed. As a result, methods are needed to adjust controller parameters floatingly. One of these methods is to readjust the controller parameters whenever the system status changes. But this method will require a huge number of calculations and information from the complete system. Among the control methods used today, neural networks are considered a very powerful tool. The advantages of neural networks are: adaptability and high learning capability. With the advances made in the field of processor technology and their parallel processing capabilities, neural networks are becoming a viable option. Since the recurrent neural network (RNN) is a non-linear system using sigmoid functions, it is widely used in system identification, modeling and control [78]. Any offline training method such as the method used in [79] can be suitable for neural network training if the changes in system parameters and composition are small, otherwise repeated training will be needed to adapt to the system. In such cases, the online training method is preferred as suggested in [80]. The online training method increases the dynamic performance and adaptability, but it is computationally a slow process and depends on the training data. In the case of the power system, the error cannot be reproduced, so the neural network has to learn and adapt quickly. Another way to increase adaptability is to use another neural network as an identifier to model power systems. This model is continuously updated to behave like a real power system and then the model is used to provide control signals. But these methods are computationally heavy, and the identifying neural network is trained several times offline, and as a result, its adaptability is limited.

Today, with the emergence of a competitive electricity market, electric power producers compete with each other to sell power, and on the other hand, consumers are looking to get the energy they need at the lowest possible cost. However, transmission lines have limitations in terms of security and power transmission capacity. If these restrictions are not controlled, then the electricity market will lose its competitive status and will be guided exclusively. Permanent control of the performance of transmission lines to monitor their problems is perhaps the best way to prevent it from being monopolized. In this regard, transmission system operators try to use the latest tools and facilities to manage problems in the system. In order to reach management goals, instrumental transmission systems such as phase shift transformers and FACTS devices are used. The use of the mentioned tools can eliminate the need to build new transmission lines and at the same time increase the capacity of the existing transmission lines. The place of installation of these devices will have a significant effect on the performance of the transmission system, and therefore, many studies have been conducted using different techniques. Among these methods, we can mention optimal load distribution in the presence of FACTS devices [81] and the use of methods based on non-linear optimization [79]. Tsai *et al.* [82], the authors have used the reactive power index to reduce power losses in the power system equipped with TCSC. Makvandi *et al.* [83], the performance of UPFC with phase shift transformers for power market management by reducing line losses and also increasing power transmission capacity has been studied. One of the shortcomings of the mentioned references is the failure to examine the stability of the power system (voltage and frequency stability) in the presence of the FACTS devices under study. Shojaeian *et al.* [84] have studied the improvement of the transmission capacity of the lines by considering the problem of stability of the power system. If only using the maximum capacity of the transmission line and reducing losses and economic costs is considered by the power system operators, then the final solution may lead to the reduction of the system's stability margin and as a result the optimal points obtained are not operational.

The increase in the costs of a large blackout in a country whose damages can reach billions of dollars has prompted specialists to make maximum use of the features of FACTS devices in today's power systems. According to the characteristic features of these devices, such as high-speed performance and the possibility of changing the admittance, size, and angle of the network voltage, it is possible to control the power flow and voltage of all buses and branches in the system. In comparison with local controllers, damping control systems for large areas will have significant advantages. Various studies have shown that these controllers are more efficient in preventing network synchronization failure, and their regulatory gain is smaller than local controls, which will bring more stability and reduce controller design costs. It should be noted that the use of inter-regional signals to control the damping of fluctuations is associated with a delay in information exchange. Considering this delay is very important for controller design, usually, in control engineering, the systems associated with delay are known as time delay systems. Such systems, which are sometimes called systems with memory, delay effects, or dead time, represent a group of systems with infinite dimensions, which are divided into two types: delay and parallel. Time delay systems of the parallel type, which include delay both in the state and in its derivatives, are the most complex states. The stabilization of these systems plays an important role in control engineering and has attracted considerable attention. It is common to model the delay in a dynamic system using a zero on the right. The presence of zero on the right side of a dynamic system will create limitations for the design of a suitable controller. Among these limitations, we can point out the absorption of the curve of the location of the roots to the right and, as a result, the reduction of the stability of the system. In this article, the use of auxiliary controllers in one of the most important FACTS devices, i.e., UPFC, is discussed in order to improve the damping of inter-regional oscillatory modes. In this regard, the issue of delay in information exchange will also be considered. This can affect the design of the supplementary controller in UPFC with the aim of damping inter-regional fluctuations.

2. RESEARCH METHOD

As mentioned in the introduction section of this article, with the increase in electric power demand, these systems are operating within their stability limits. On the other hand, unavoidable mechanical fluctuations can limit the ability to transmit power and thus endanger the security and stability of the power system. In such systems, strengthening the flexibility and stability characteristics of the power system is an important action that is performed by power network specialists. Therefore, it is necessary to use some stabilizing tools to provide reliable working margins for the power system. In general, there are two types of system oscillation dampening controllers: PSS and FACTS devices. These stabilizers, which strengthen the power system, are usually used as controllers and compensators that can be designed in different ways. Considering the performance of smart algorithms that have been used in optimization problems in recent years, as well as the non-linear nature of power systems, the use of smart algorithms in the design of industrial controllers has attracted the attention of specialists. On the other hand, power systems are always exposed to disturbances and errors caused by the surrounding environment (e.g., lightning), consumers (industrial and domestic loads), and even power plant production centers (turbine-related issues and control loops related to synchronous generators). Therefore, it can be said that all power networks operate within their stability limits, and the working point of these systems is always changing. Therefore, the use of additional controllers in the power system that have the ability to adapt their parameters to different working points of the system can be quite effective in improving the stability of the power system. To increase transmission in the power system, the use of a continuous energy transmission network seems necessary. The power system has turned into a huge and complex network, and on the other hand, the effective supply of load, meaning the transmission of power with the necessary quality and its economical transmission, has increased the complexity of the power system. As a result of this, the system in the working points of Astana finally works on its own, therefore the limits of stability are reduced and the transmission lines are used at their maximum capacity, which can be concluded because any unwanted event, including an error on the line or a line outage, can easily cause large and unpredictable dynamic fluctuations in the system. These transient fluctuations can act as a destructive factor for power tools in the system and also cause islanding and instability in the power system. The dynamic instability of the power system is caused by the disturbance of the balance between the input mechanical power and the output electrical power and the lack of damping torque, which causes local and inter-regional oscillations with a low frequency of about 0.2 to 2 Hz in the power system. PSS and FACTS devices are used to smooth out fluctuations between regions. In these methods, to increase the controllability and observability of the inter-area mode, the remote signals extracted from the wide area measurement system (WAMS) are used as the input of the modulator. But the time delay in WAMS systems reduces stability and even instability in the power system, which makes it very important to find the maximum delay margin when the power system remains stable. Therefore, it is necessary to carefully study the role of FACTS devices in stabilizing the power system and damping inter-regional fluctuations, considering the problem of delay.

2.1. Modeling of single machine power system equipped with UPFC

The power system studied in this article is shown in Figure 1. As can be seen, the different parts of the turbine-generator shaft are shown with symbols G (synchronous generator). The generator is connected to the transmission line equipped with UPFC through the reactance transformer (X_{1E}). UPFC series and parallel converters with modulation indices and phase angle m, δ is shown. The impedance of the line is X_{E2}, which connects the UPFC set and the synchronous generator to the infinite bus with voltage V_B. It should be noted that in order to avoid procrastination, the details of the equivalent coefficients are avoided in this section [84]. All coefficients, which are not explained, are given in full in the appendix of the article. In Figure 1, the components $m_E, m_B, \delta_E, \delta_B$ are the modulation ratio and the phase angle of the control signal of each of the voltage source converters and are considered as the inputs of the UPFC system. It should be noted that the power system equipped with FACTS devices has a non-linear characteristic. To analyze such a system, it is necessary to extract the nonlinear dynamic equations of the system and describe the state space of the network based on the state variables. Then the nonlinear equations are linearized around a working point so that it is possible to calculate the oscillation modes. in such a case, it is possible to design a suitable damping controller and use it for the purposes of improving the stability of the power grid [85].

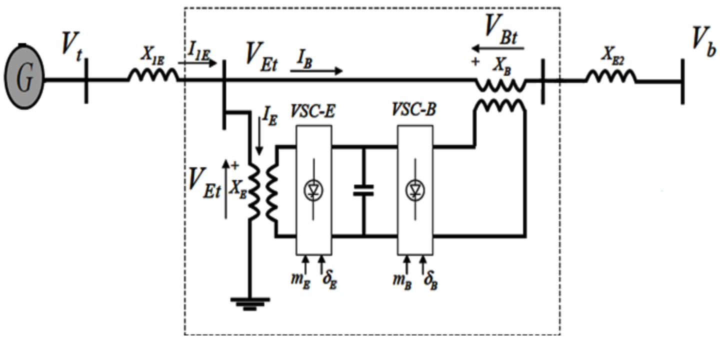

Figure 1. Single machine power system equipped with upfc [85]

To study the dynamic stability of the power system, the linearized model of the system can be used. Based on this, the dynamic model of UPFC is also necessary to be able to study its effect on improving the small signal stability of the power system. To study the stability of power system fluctuations, transient states of the transformer and also their losses are ignored. The complete dynamic model of the single machine power system connected to the infinite bus and equipped with UPFC can be described by the [86].

$$
\begin{aligned}
\dot{\delta} &= \omega_0 \Delta\omega \\
\Delta\dot{\omega} &= \frac{P_m - P_e - D\omega}{2H} \\
\dot{E_q'} &= \frac{-E_q + E_{qe}}{T_{do}'} \\
\dot{E_{qe}} &= \frac{K_A (V_{t0} - V_t)}{1 + sT_A}
\end{aligned} \tag{1}
$$

In (1) relations:

$$
\begin{aligned}
T_e &= P_e = V_d I_d + V_q I_q, V_{dt} = x_q i_{qt}, V_{qt} = E_q' - x_d' i_{dt} \\
E_q &= E_q' + (x_d - x_d') i_{dr} \\
v_t &= \sqrt{v_{dt}^2 + v_{qt}^2}, i_{dt} = i_{Ed} + i_{Bd}, i_{qt} = i_{Eq} + i_{Bq}
\end{aligned} \tag{2}
$$

in these relations, P_m ،P_e ،M ،D ،ω_b ،δ ،ω ،E_{fd}, E_q'،V_t،T_{do}'،X_d, X_d'،X_q ،K_A،T_A و V_{ref} are respectively for the input and output power of the machine. Inertia, damping coefficient, synchronous speed, rotor angle and speed, excitation voltages, internal field and machine terminal, time constant of open field circuit, transient reactance and reactance's in d and q axes, gain and time constant of exciter and reference voltage. By combining the (1) and (2) and linearizing the relationships, the state space of the system can be written as (3).

$$
\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{qe} \end{bmatrix}
=
\begin{bmatrix}
0 & \omega_0 & 0 & 0 \\
-\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 \\
-\frac{K_4}{T_{do}'} & 0 & -\frac{K_3}{T_{do}'} & \frac{1}{T_{do}'} \\
-\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A}
\end{bmatrix}
\begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q' \\ \Delta E_{qe} \end{bmatrix}
+
\begin{bmatrix} 0 \\ -\frac{K_{pd}}{M} \\ -\frac{K_{qd}}{T_{do}'} \\ -\frac{K_A K_{vd}}{T_A} \end{bmatrix}
\Delta v_{dc} +
$$

$$
\begin{bmatrix}
0 & 0 & 0 & 0 \\
-\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\
-\frac{K_{qe}}{T_{do}'} & -\frac{K_{q\delta e}}{T_{do}'} & -\frac{K_{qb}}{T_{do}'} & -\frac{K_{q\delta b}}{T_{do}'} \\
-\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A}
\end{bmatrix}
\begin{bmatrix} \Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta\delta_B \end{bmatrix} \tag{3}
$$

2.2. Modeling of multi-zone power system equipped with UPFC

Without losing the generality of the problem, suppose that a UPFC controller is installed between buses i and j in a system of n machines according to Figure 2. To embed the UPFC function in the admittance matrix of the Y network, where only n generator nodes are kept, the admittance matrix of the primary system Y_t, which is the vector of nodes i and j, is written as (4).

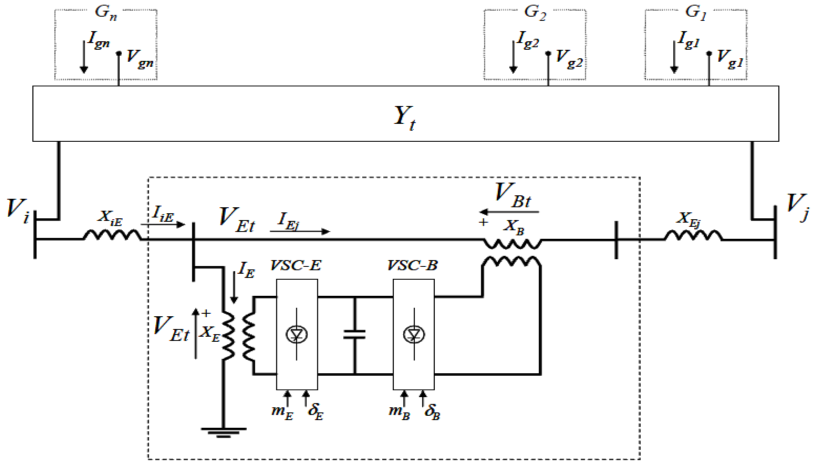

Figure 2. Power system with n generators along with UPFC

$$\begin{bmatrix} 0 \\ 0 \\ I_g \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{ij} & Y_{ik} \\ Y_{ji} & Y_{jj} & Y_{jk} \\ Y_{ki} & Y_{kj} & Y_{kk} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \\ V_g \end{bmatrix} = Y_t \begin{bmatrix} V_i \\ V_j \\ V_g \end{bmatrix} \tag{4}$$

where,

$$I_g = [I_{g1} \quad \cdots \quad I_{gn}]^T, V_g = [V_{g1} \quad \cdots \quad V_{gn}]^T, k = 1,2,\dots,n \ and \ k \neq i, k \neq j$$

after installing UPFC between nodes i and j, the power system network will be written as (5):

$$\begin{aligned} & Y'_{ii}V_i + I_{iE} + Y_{ik}V_g = 0 \\ & Y'_{jj}V_j - I_{Ej} + Y_{jk}V_g = 0 \\ & Y_{ki}V_i + Y_{kj}V_j + Y_{kk}V_g = I_g \end{aligned} \tag{5}$$

in this relation, Y'_{ii} and Y'_{jj} are composed of the variables, Y_{ii}, Y_{jj} which include $x_{ij} = x_{iE} + x_{Ej}$. The linearized model of the *n* machine system can be summarized as follows:

$$\begin{aligned} & \Delta\dot{\delta} = \omega_0\Delta\omega \\ & \Delta\dot{\omega} = (-\Delta T_e - D\Delta\omega)/2H \\ & \Delta\dot{E}'_q = (-\Delta E'_q - (x_d - x'_d)\Delta I_d + \Delta E_{fd})/T'_{do} \\ & \Delta\dot{E}_{fd} = (-\Delta E_{fd} - K_A\Delta V_T)/T_A \\ & \Delta T_e = \Delta I_q E'_{q0} + I_{q0}\Delta E'_q + \Delta I_q(x_q - x'_d)I_{d0} + \Delta I_d(x_q - x'_d)I_{q0} \\ & \Delta V_{Td} = x_q\Delta I_q, \Delta V_{Tq} = \Delta E'_q - x'_d\Delta I_d \end{aligned} \tag{6}$$

by combining the (6), the state space model of the power system of n machines equipped with UPFC can be obtained.

2.3. The structure of the wide area damping control system

Usually, there are two solutions for the design of the controller of damping: the decentralized approach and the centralized approach. The main advantage of the first method is that the design is implemented based on the measured local signals and there is no need to measure separate signals and transmit this information to the control location. However, it seems that this method is not suitable and effective for the stabilization of today's developed power systems. On the other hand, the damping control of the concentrated wide area provides an effective solution for the purposes of damping fluctuations. Because in this method, the information of a wide area of the system can be accessed and it will be possible to observe inter-regional modes more appropriately. Wide area controls include any controls that require measured and transmitted input-output signals. It has been shown that if the remote signals are applied to the complementary controllers, the dynamic performance of the system will improve significantly for the damping of inter-regional modes. Although this method requires the installation of telecommunications equipment to exchange information and dampen fluctuations, it is still a better strategy than installing costly controllers. The general structure of wide area damping controller (WADC) designed for FACTS devices in the power system can be shown as Figure 3. In fact, WADC is designed to stabilize inter-area oscillations by providing complementary damping control for FACTS. The time delay in remote signals caused by the use of wide area measurements or other sources such as sampling rate and control law calculations can be represented by a delay d in the feedback loop. This delay is modeled by e^{-sd}.

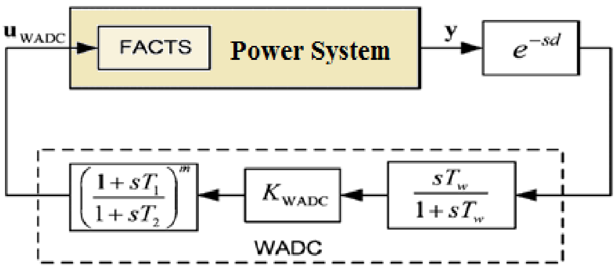

Figure 3. WADC structure for power system equipped with FACTS

According to Figure 3, the structure of WADC is as (7):

$$H_{WADC}(s) = K_{WADC}\frac{sT_W}{1+sT_W}\left(\frac{1+sT_1}{1+sT_2}\right)^m \quad (7)$$

where, T_1 and T_2 are the parameters of the phase compensator, T_w is the constant of the filter (usually 5 to 10 seconds), K_{WADC} is also the WADC gain and m is the number of pre-phase post-phase blocks, which is usually considered for two. To find the unknown values of the controller, you can use the phase compensation method presented in the topics of linear control. According to the structure of FACTS systems, it is possible to damp the fluctuations created in the power system by providing an auxiliary signal. In such a case, the auxiliary controller parameters can be obtained using the phase compensation method. Since there is a need for information transmission in large power systems, and this itself imposes a delay on the system, the effects of this delay (reducing the stability margin of the dynamic system) should be considered in the design of the controller.

3. RESULTS AND DISCUSSION

As mentioned, by using supplementary controllers in the power system equipped with FACTS devices, it will be possible to dampen local and interregional fluctuations. In the previous section, the structure of this controller was explained. In the following, the design of the damping controller for the power system equipped with UPFC along with the delay block in sending information will be discussed, and the simulation results will be presented both for the single-machine system and for the multi-machine system with multiple areas. It should be noted that the UPFC system is a multi-input system that includes the modulation angle and index of series and parallel converters. It is mentioned in references [38] that for the purpose of stabilizing the power system, the best option for applying the damping signal can be the phase angle of the parallel converter. Therefore, in this research, attenuating signals will be applied to this input. In addition, for the amount of delay in the system, the values considered for the delay constant i.e., d, will be d=0 ms, 180 ms. In the simulation results, it will be observed that the use of a supplementary controller in UPFC can improve the stability of the power system.

3.1. Single machine power system equipped with UPFC and supplementary controller

In this case, two light and heavy working points according to Table 1 are considered for simulating the power system (all values are given in terms of pu). Damping controller is designed by phase compensation and using MATLAB software in heavy working conditions and delay d=180 ms. The input of this controller is the rotor speed changes and the output is the phase angle related to the UPFC parallel converter. This controller has a transformation function in the form of $G(s) = \frac{1+0.2s}{1+s}\frac{1+5s}{1+3.25s}$. The disturbance considered in the mechanical power change system in the turbine-generator system is $\Delta P=0.01$ pu. The response of the system for heavy working conditions is given in Figures 4 and 5. Figure 4 shows the rotor speed changes. It can be seen that the response of the system is completely unstable without the use of a controller, and with the passage of time, the amplitude of its fluctuations increases. At the same time, the response of the system is stable in both modes, d=0 ms, 180 ms, in exchange for using the damping controller. It means that the oscillations are dampened with the passage of time, especially in the case of longer delay, for which the phase compensation controller is designed in these conditions. In case of d=180 ms, rotor speed fluctuations are almost stopped at time t=3.5 ms. But for d=0 ms, it can be seen that the fluctuations continued during the simulation. The reason for this was the design of the supplementary controller for long delay conditions. In any case, the damping controller has well dampened the fluctuations of the rotor speed or the frequency of the system, which is caused by the entry of mechanical power disturbances into the turbine-generator system. Figure 5 shows the changes in rotor load angle. It can be seen that the response of the load angle or $\Delta\delta$ without using the controller is completely unstable (blue line) and its fluctuation range increases with the passage of time. At the same time, the response of the system is stable in both modes, d=0 ms, 180 ms, by using the damping controller. It means that the oscillations are dampened with the passage of time, especially in the case of longer delay, for which the phase compensation controller is designed in these conditions.

The response of the system for light working conditions is given in Figures 6 and 7. Figure 6 shows the rotor speed changes and Figure 7 shows the load angle changes. Although the system seems stable in this case, the damping of fluctuations in the system without a damping controller is slow. By installing the damping controllers and also considering the delay, it can be seen that the oscillations are damped well. Damping is done in the delay mode of d=180 ms at the time of t=3.5 s and for the delay mode of d=0 ms at the time of t=6.5 ms. In this case, the disturbance of mechanical power in the turbine-generator system has been used to investigate the performance of additional controllers.

Table 1. Working points of the machine

V_t	P_e	Q_e	Working points
1	1.2	0.4	Light working conditions λ_2
1	0.9	0.015	Heavy working conditions λ_1

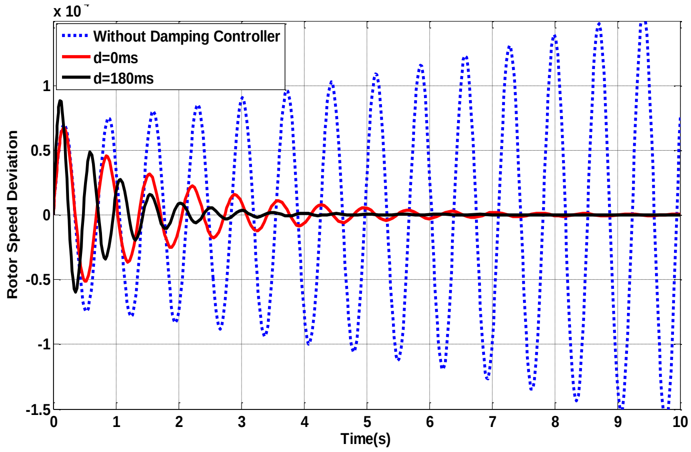

Figure 4. Rotor speed changes in single machine system and for λ1 working conditions

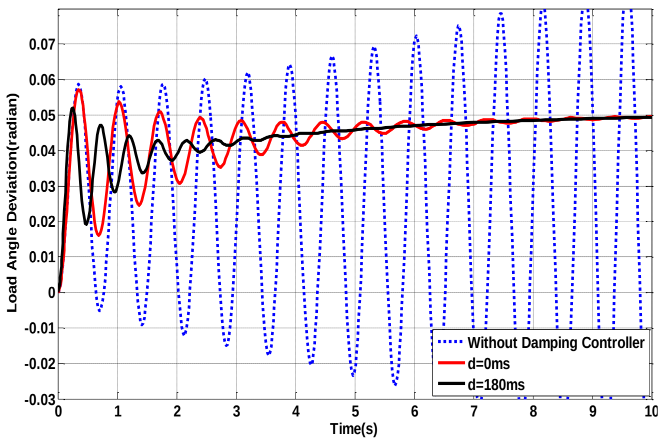

Figure 5. Variations of the rotor load angle in the single machine system and for the working conditions of λ_1

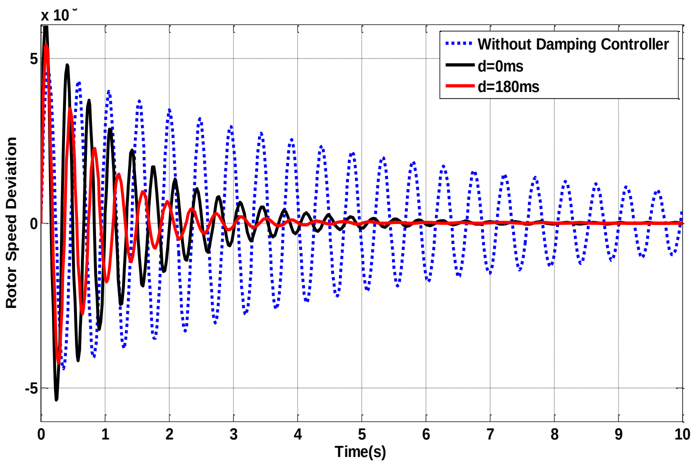

Figure 6. Rotor speed changes in single machine system and for λ_2 working conditions

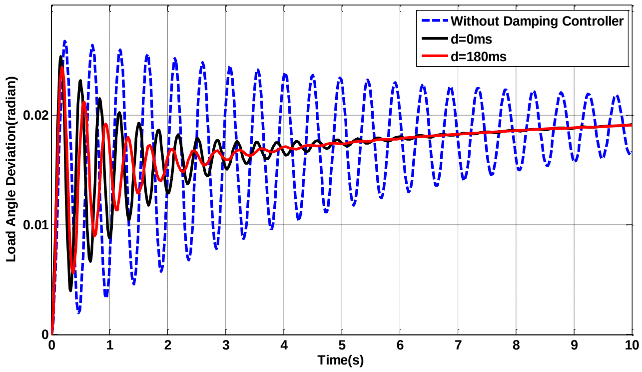

Figure 7. Variations of rotor load angle in single machine system and for λ_2 working conditions

3.2. Multi-machine power system equipped with UPFC and supplementary controller

In this section, the simulation of a two-zone power system that is connected by UPFC, along with damping complementary controller, is performed by considering the delay effect similar to the previous section. The working conditions are similar to the previous section for the machines of each section. The block diagram of this power system is as shown in Figure 8. A parallel converter will be used for the purposes of damping fluctuations. The damping controller is designed based on the classic phase compensation method. It should be noted that in the above system, it is assumed that the set of generators of a region are displayed with an average inertia and damping coefficient. The controller designed for this mode is in the form of $G(s) = \frac{-5999s^2-1702.86s-868.96}{1s^2+7.885s+14.57}$. Active power changes in the generators of a region as much as ΔP=0.05 pu have been used as a disturbance to the system. Figure 9 shows the fluctuations of the speed changes of the rotors of the generators of the two regions in heavy working conditions relative to each other. The magnification of this figure is shown in Figure 10 for better analysis. It can be seen that the oscillations of the changes in the rotor speed (or the oscillation created in the frequency) of the system are slowly damped in the absence of the damping controller. But with the use of the damping controller and despite the delay in the transmission of system information, the system has been well damped.

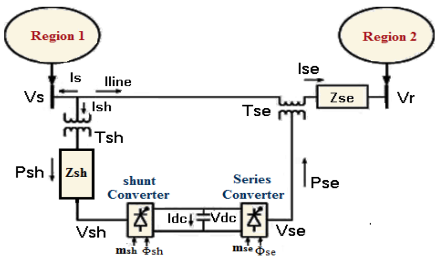

Figure 8. Two-area power system with UPFC

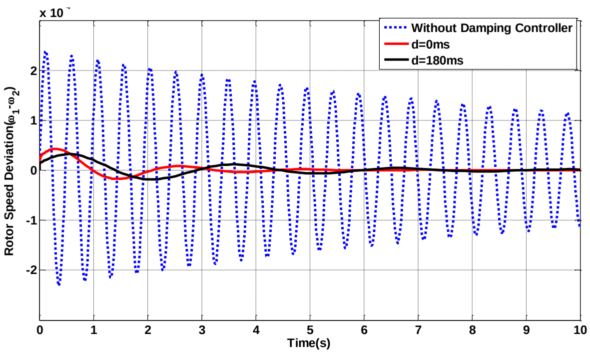

Figure 9. Fluctuations related to speed changes of rotors of two generators relative to each other in working conditions λ1

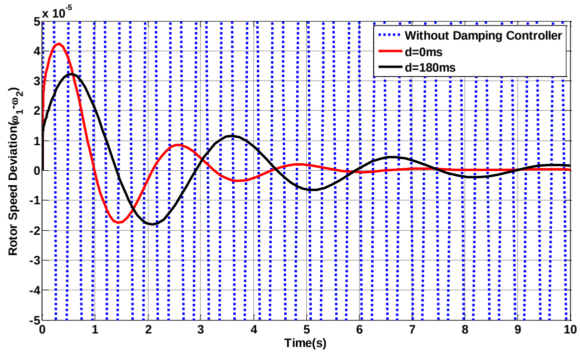

Figure 10. Magnification of the fluctuations related to the speed changes of the rotors of the two generators relative to each other in the working conditions λ_1

Figure 11 shows the fluctuations of the load angle changes of the rotors of the generators of the two regions relative to each other. It can be seen that the fluctuations of the load angle of the rotors of the generators in the two regions are slowly damped in the absence of the damping controller. But with the use of the damping controller and despite the delay in the transmission of system information, the system has been well damped. If there is no delay in sending the information, it can be seen that the fluctuations of the rotor load angle are dampened at time t=5.5 s. This is while taking into account a delay of about 180 milliseconds, the damping time of the oscillations will reach t=9 s. The power system under study will also be simulated for light working conditions. The goal is to investigate the flexibility of the designed controller for different working points. That is, by changing the working point as usual, the supplementary attenuator controller can handle the disturbances and the fluctuations created in the frequency and power of the system. Figure 12 shows the rotor speed changes for light working conditions of the power system.

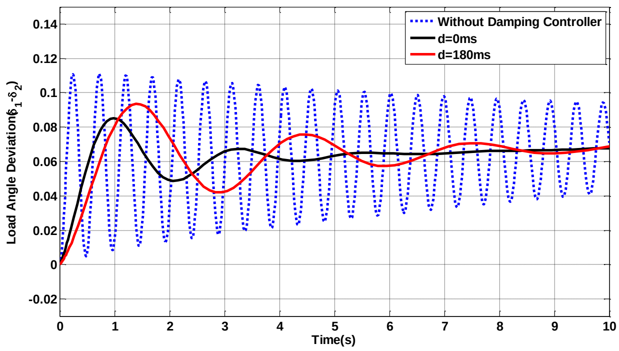

Figure 11. Fluctuations related to changes in the load angle of the rotors of the two generators relative to each other in the working conditions of λ_1

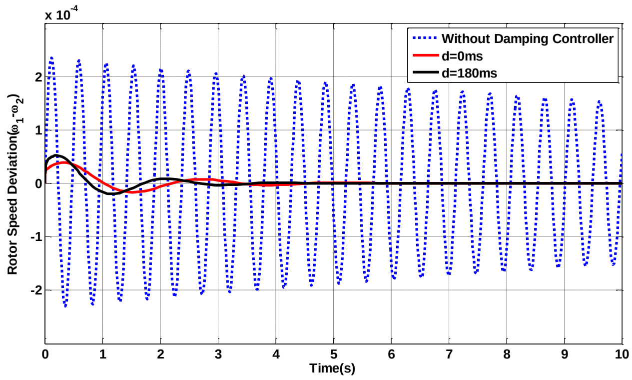

Figure 12. Fluctuations related to speed changes of rotors of two generators relative to each other in λ_2 working conditions

The magnification of this figure is shown in Figure 13. It can be seen that the damping controllers have been able to dampen the frequency fluctuations and rotor speed changes despite the delay. Figure 14 shows the fluctuations of the load angle changes of the rotors of the generators of the two regions relative to each other. It can be seen that the fluctuations of the load angle of the rotors of the generators in the two regions are slowly damped in the absence of the damping controller. But with the use of the damping controller and despite the delay in the transmission of system information, the system has been well damped.

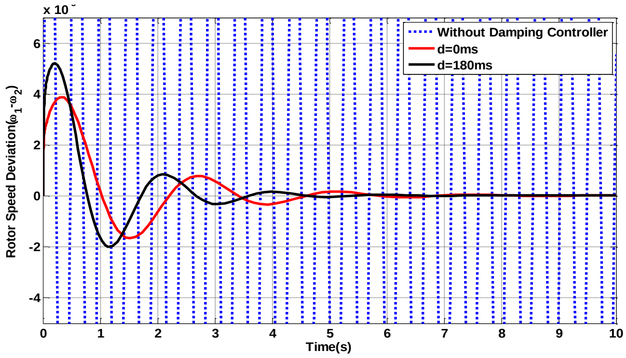

Figure13. Magnification of the fluctuations related to the speed changes of the two generator rotors relative to each other in the working conditions of λ_2

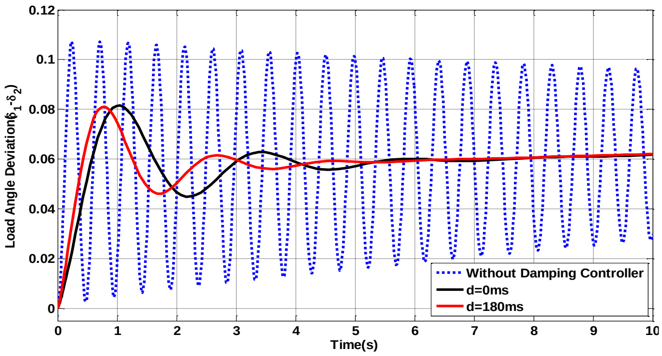

Figure 14. Fluctuations related to changes in the load angle of the rotors of the two generators relative to each other in the working conditions of λ_2

4. CONCLUSION

As previously stated, inter-regional fluctuations have emerged as a common issue in interconnected power systems in the modern era. These fluctuations are caused by the fluctuation of one or more generators against a group of generators, and if they do not subside in a timely manner, the most important goals of electric power producers, namely maximum use of the capacity of existing systems (close to their stability limit) and safe operation of power systems, will be jeopardized. The effect of FACTS tools on improving the damping of fluctuations between regions was investigated in this paper. Facts devices are based on converter circuits and are capable of controlling the amplitude and phase of the voltage injected into the power system and, as a result, the power flow in the transmission lines independently of network parameters with high flexibility. As a result, when an error occurs, they continue to dampen and ensure the safe operation of power systems by damping low-frequency fluctuations on time. They also allow for the use of the maximum load-carrying capacity of the transmission lines close to their thermal limit, improving system stability. As a result, in this article, power systems equipped with UPFC were used with the goal of utilizing its inputs to improve the dynamic performance of the power system. In this regard, the damping controller was designed with the potential delay in sending and communicating information between control units in the power system in mind. It was demonstrated that, despite the delay, the auxiliary controller designed for the UPFC system easily mitigated power system disturbances, and the frequency and load angle fluctuations of the generators in the power system were mitigated in the shortest possible time.

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