



On design of a robust decentralized ADRC-based TCSC controller for an interconnected multi-area power system

Gomaa Haroun A. H.^{1,2,*} and Li Yin-Ya¹

¹ Nanjing University of Science and Technology, Nanjing 210094, China.

² College of Engineering Sciences, Department of Electrical and Electronics Engineering, Nyala University, South Darfur, Nyala, Sudan.

* Corresponding author: Gomaa Haroun A. H. (Email: gomaaharoun1982@yahoo.com)

Article history: Received 22 July 2019, Received in revised form 04 October 2019, Accepted 05 October 2019

ABSTRACT

In this article, a robust active disturbance rejection control (ADRC) is proposed for load frequency control (LFC) of an interconnected multi-area power system. Two widely employed test systems, namely, two-areas and four-areas hydro-thermal power utilities are concerned to validate the efficacy of the suggested method. In order to design ADRC, the extended state observer (ESO) is proposed to estimate the unknown dynamics uncertainties of the plant. Further, to enhance the performance of the system, series flexible ac transmission system (FACTS) like thyristor controlled series compensator (TCSC) and thyristor controlled phase shifter (TCPS) are considered. The simulation results indicated that the system performance is improved with the inclusion of FACTS devices. The adjustable parameters of the proposed FACTS controllers are optimized using particle swarm optimization (PSO) algorithm employing an Integral of Time multiplied Absolute Error (ITAE) criterion. The investigations showed that the proposed controller provides better dynamic performance than others from the point of view of settling time, peak over/undershoot. Finally, the sensitivity analysis of the system is inspected by varying the system parameters and operating load conditions from their pre-specified values. It is observed that the suggested controller-based optimization algorithm is robust and performs satisfactorily with the variations in operating load conditions, system parameters and load patterns.

Keywords: Load frequency control (LFC), Active disturbance rejection control (ADRC), Particle swarm optimization (PSO), FACTS controllers.

1 Introduction

The modern electrical power system consists of different power system utilities, such as hydro, thermal, nuclear and gas, these units are coherently interconnected with each other by transmission lines (tie-lines) [1, 2, 3, 4], except nuclear units. Nuclear plants are usually well-kept at base load close to their maximum output without sharing in load frequency control (LFC) [5]. The main purposes of the interconnected power system utility are: generating, transmitting, and distributing electrical power as economically and consistently as possible while maintaining a continuous supply of the power with acceptable quality to all consumers [6]. The power system

utility will be in an equilibrium point when there is a balance between generated power and the electrical power demand. In interconnected area power systems, if the load perturbation occurred in any area of the system, the frequency related to this area is affected firstly and then the other areas are also affected accordingly through transmission-lines. Thus, each area in a power system has its generation unit which is capable for its own load perturbations and power interchange between the neighboring areas [1, 6].

In addition, with the increasing size and complexity of the power system along with the increasing energy demand in recent years, it leads to the use of soft computing methods that intelligently control the power system

network. Sudden perturbations in load and unexpected fault conditions affect the system frequency and tie-line power interchange between the control areas [7, 8]. It is impossible to maintain the balances between generation and demand without control [5]. LFC in the power systems plays a most significant role in providing the power supply with good quality [9]. In view of above, the control technique is needed to cancel the effects of random load changes for maintaining the frequency at nominal value. The main purposes of LFC in an interconnected multi-area power system are to provide the desired real power output from the generator to meet the variations in load, maintain the frequency of power system close to the nominal value and maintain the tie-lines power between areas [10, 11]. Hence, a control scheme is required, that not only keeps constancy of frequency and desired output power but also to attain zero steady-state error and inadvertently scheduled power interchange.

Nowadays, researchers are annoying to develop different control algorithms to explore the best controller for power system problems. Conventional controllers such as PI and PID controllers are widely used in the power system to handle the LFC problems [12, 13, 14], but in general, have some limitations. Literature survey show that there are several advanced control strategies have been suggested by many researchers over the past decades for LFC scheme [5]. In this regard, many development and research works have been presented such as conventional [15], optimum control [16], Genetic algorithm (GA) [17], Firefly algorithm (FA) [5], Fuzzy logic controller (FLC) [18], etc. which play a vital role in LFC mechanism. GA has been widely addressed in the literature regarding LFC mechanism design. Meena and Kumar (2016) employed the intelligent Genetic algorithm to tune the parameters of fuzzy PID controller in a two-area thermal power system with generation rate constraints [17]. It has been asserted by many researchers that the application of FLC improves the transient performance of PID controller and handling the variations in the operating point by online adjusting the controller parameters [18, 19]. Fuzzy logic controller based conventional PID controllers can be successfully utilized for the nonlinear system, but there are no specific rules to discover appropriate choice of the fuzzy parameters (such as inputs, membership functions, rule base, etc.). In general, these parameters are selected by utilizing certain empirical rules and therefore may not be getting the optimal parameters. Inappropriate selection of the input-output scaling factor may considerably deteriorate the transient performance of FLC. In [10],

the authors utilized hybrid Differential Evolution (DE) and Pattern Search (PS) in multi control area power system to explore the optimum scaling factors of the fuzzy PI/PID controller, without considering the impact of nonlinearities. A novel nature-inspired technique termed as multi-verse optimizer (MVO) [20], was established in a two-area non-reheat thermal power system with high voltage direct current (HVDC) to optimize the scalar factors of Fuzzy PID.

It is obvious from past the studies that the performance of the power system depends on the controller syntheses and the techniques utilized to tune the controller parameters. Therefore, constructing and implementing a new control strategy with high-performance heuristic optimization methods to real-world problems is always welcome. Recently, a new biologically-inspired technique known as particle swarm optimization (PSO) has been highlighted by [21]. It is a population technique used to explore the search space of the stated problem. It has been efficaciously set up to handle the non-linearity and non-convex optimization problems. A new technique based on craziness particle swarm optimization (CPSO) has been presented for LFC of a two-area thermal power system with governor dead band (GDB) non-linearity [22], to optimize the scaling parameters of PI controller. A novel nature-inspired technique based on PSO algorithm has been employed in a five-area non-reheat thermal power system [23], to optimize the scaling factors of PID controller. Modern research confirmed that the PSO is so worthwhile in optimization method and gives high-performance results and could be superior to many algorithms [24, 25].

Recently, some articles have been confirmed that the active disturbance rejection control (ADRC) approach is an emerging technique, which estimates and mitigates the phenomena's of the uncertainties, and the results did not require accurate model information comparing with the other sophisticated controllers [26, 27]. Thus, it has been investigated that the ADRC approach can be employed to solve the load frequency control (LFC) successfully [26, 28]. It is demonstrated that three-order ADRC is a good candidate for LFC and good damping performance can be attained. Fast dynamic responses, robustness against parameter variations and load perturbations are obtained using ADRC technique [26, 27]. A robust ADRC technique is constructed for a two-area power system with non-reheat thermal power system [28]. The concept of employing power electronic devices for power plant control has been widely preferable and acceptable in the form of Flexible AC Transmission Sys-

tems (FACTS) devices which afford more flexibility in power plant operation and control. This additional flexibility permits the independent amendment of certain system variables such as tie-line power flows, which are not normally controllable. In [29], dynamic modelling of the Thyristor Controlled Series Compensator (TCSC) and super-conducting magnetic energy source (SMES) devices are established and equipped for a two-area with multi-sources power plant to improve the dynamic responses of the plant and enhance the stability. Zare et al. [30], proposed a new method for modelling of TCSC device based on the Taylor series expansion and applied it for a two-area with multi-sources power plant to tackle the LFC problem.

In this article, a robust hybrid ADRC-TCSC coordinated controller is developed and employed for LFC of an interconnected multi-area power system to damp effectively the tie-line power flow and area frequency fluctuations. The simulation results of the proposed controller are compared with the ADRC-TCPS and ADRC controllers. The scaling factors of the controllers and adjustable gains of the series damping controllers are tuned by PSO algorithm. The proposed controller presented in this article has more advantages such as robust against the load changes and system variations, reduced the oscillations of frequency and the tie-line power deviations for all area of the power system. The main contributions of this article can be listed as follows:

- (i) To design and perform a robust ADRC controller for LFC problem.
- (ii) To investigate the impacts of coordinated controllers ADRC-TCSC, ADRC-TCPS and ADRC on dynamic responses of the power system under load perturbation.
- (iii) Analyzing the dynamic performance of coordinated controllers on an interconnected two test systems, namely two-area hydro-thermal and four-area hydro-thermal power utilities.
- (iv) Sensitivity analysis is carried out to assess the robustness of the proposed controller by varying the system parameters and operating load conditions from their nominal values.
- (v) To analyse the impact of different load perturbation patterns on the dynamic performance of the proposed approach.

The rest sections of this article are organized as follows: The mathematical model of an interconnected multi-area power system is firstly formulated in section 2, wherein the dynamic modelling of FACTS devices are

also pointed out. Then, the essential idea of the ADRC design is outlined in section 3. The objective function is stated in section 4, followed by its optimization solution. Simulation results are presented in section 5, to show the effectiveness of the current controller, and the dynamic performance of the suggested controller compared with other controllers are also demonstrated. Finally, the conclusion of this article is elaborated in section 6.

2 Power system under study

2.1 System modeling

Mathematical model of an interconnected power system under investigation should first develop in order to perform an appropriate control approach to enhance the dynamic performance of the power utility. Initially, a two-area constitutes from hydro-thermal power utility is established and its dynamic performance is studied, as well as later the work is extended to a four-area hydro-thermal power system. The schematic model of a two-area hydro-thermal power plant under investigation is presented in Fig. 1. The two areas are interconnected through FACTS devices in series with the transmission-line in order to improve the dynamic performance of the system. Each control area of the power plant contains speed governing unit, turbine and generator systems having three inputs and two outputs. In Fig. 1, ACE_1 and ACE_2 are area control errors; u_1 and u_2 are the signal outputs from the controllers; B_1 and B_2 represent the frequency bias factors; R_1 and R_2 are the speed governor regulation parameters in p.u. Hz; T_g and T_t meant the governor and turbine time constants for thermal system in sec; K_r and T_r represents the steam turbine reheat constant and steam turbine reheat time constant; T_{hi} is hydro governor time constant in sec; T_w represents the water starting time in sec; ΔP_{L1} and ΔP_{L2} are the load perturbations; ΔP_{Tie} is the incremental change in transmission-line power in p.u.; K_{p1} and K_{p2} are the power system gains; T_{p1} and T_{p2} are the power system time constants in sec; T_{12} denotes the synchronizing coefficient; Δf_1 and Δf_2 denote the system frequency deviations in Hz.

As described in Figs. 1 and 2, each area of the interconnected power system consists of a single-speed governor, turbine and generator. Furthermore, each control area includes three inputs and two outputs. The inputs are the controls signals ΔP_r (also indicated as u), load perturbation ΔP_L and tie-line power error ΔP_{Tie} . The outputs are the incremental frequency Δf and area con-

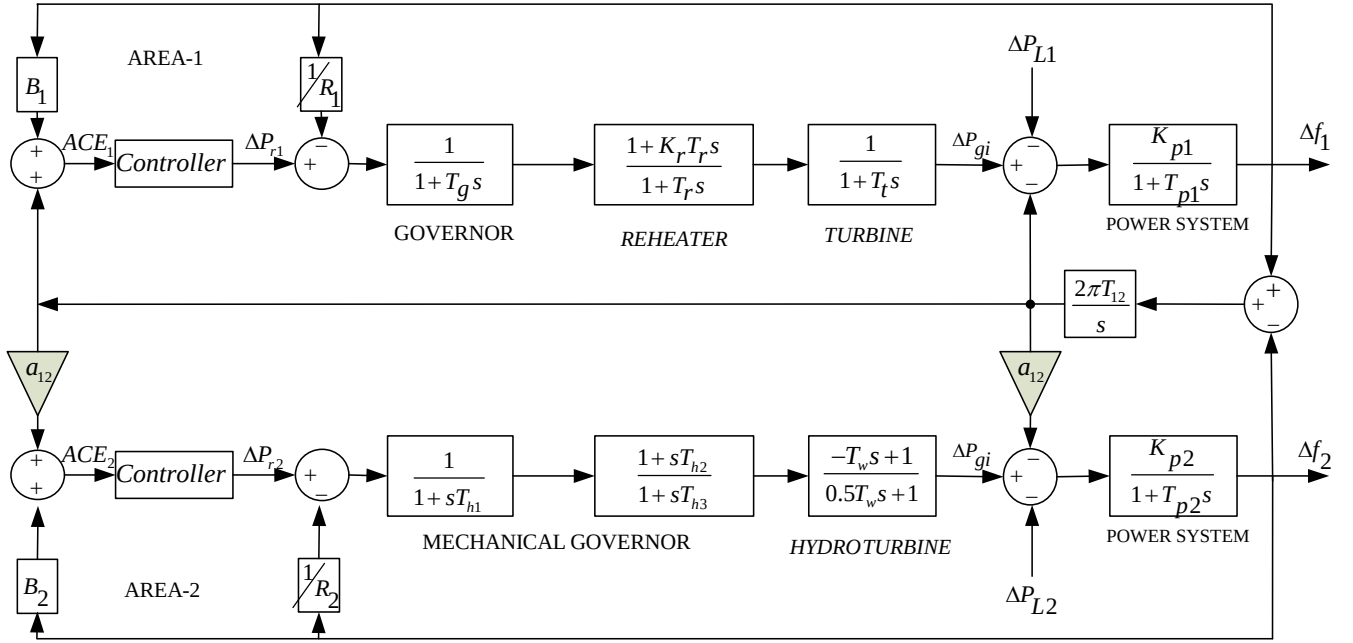


Fig. 1 Transfer function model of a two-area hydro-thermal power plant.

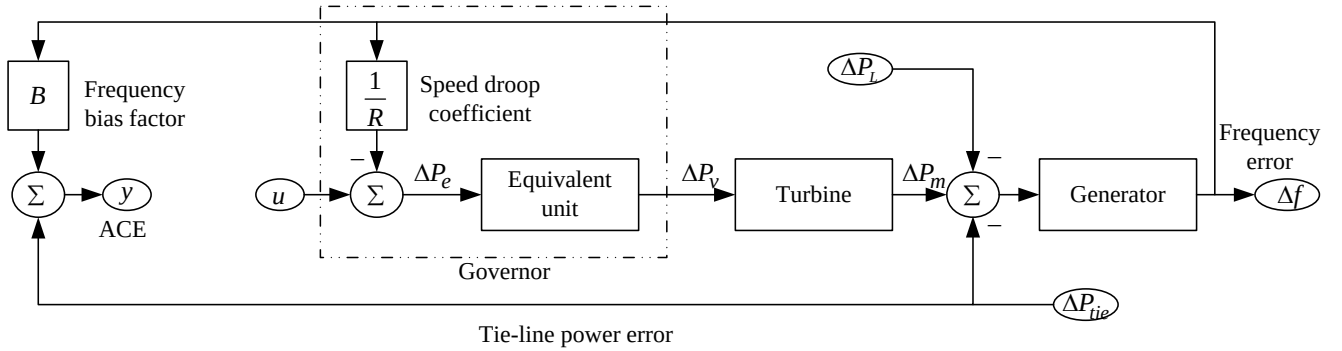


Fig. 2 Schematic diagram of the one-area generating unit.

trol error (ACE) presented by Eq. (1) [1].

$$ACE = \Delta P_{Tie} + B \Delta f. \quad (1)$$

The transfer function (TF) used to express the one-area generator unit for the sake of suitability in frequency-domain analyses. Let the TF from ΔP_e to ΔP_m be $G_{ET}(s) = \text{Num}_{ET}(s)/\text{Den}_{ET}(s)$, where $\text{Num}_{ET}(s)$ and $\text{Den}_{ET}(s)$ are the polynomials of the numerator and denominator, respectively. According to [1], the transfer function of the reheat turbine system is:

$$G_{ET}(s) = \frac{\text{Num}_{ET}(s)}{\text{Den}_{ET}(s)} = \frac{K_r T_r s + 1}{(T_g s + 1)(T_t s + 1)(T_r s + 1)} \quad (2)$$

From [1], the transfer function of the hydro turbine system is written as:

$$G_{ET}(s) = \frac{\text{Num}_{ET}(s)}{\text{Den}_{ET}(s)} = \frac{(T_{h2}s + 1)(-T_w s + 1)}{(T_{h1}s + 1)(T_{h3}s + 1)(0.5T_w s + 1)} \quad (3)$$

The TF of the generator is:

$$G_{Gen}(s) = \frac{1}{\text{Den}_M(s)} = \frac{1}{Ms + D} \quad (4)$$

The nominal parameters of the plant as demonstrated in Eqs. (2)-(3) are taken from [31, 32] and are furnished in Table 1. From Fig. 2, the output $Y(s)$ can be modelled as:

$$Y(s) = G_P(s)U(s) + G_L(s)\Delta P_L(s) + G_{Tie}(s)\Delta P_{Tie}(s) \quad (5)$$

where $G_P(s)$, $G_L(s)$, and $G_{Tie}(s)$ are the transfer functions between the three inputs ($U(s)$, ΔP_L and ΔP_{Tie}) and area control error output ACE . The three TFs in Eq. (5) are expressed as:

$$G_P(s) = \frac{RBNum_{ET}(s)}{RDden_{ET}(s)Den_M(s) + Num_{ET}(s)} \quad (6)$$

$$G_L(s) = \frac{-RBden_{ET}(s)}{RDden_{ET}(s)Den_M(s) + Num_{ET}(s)} \quad (7)$$

$$G_{Tie}(s) = \frac{Num_{ET}(s) + RDden_{ET}(s)Den_M(s) - RBden_{ET}(s)}{RDden_{ET}(s)Den_M(s) + Num_{ET}(s)} \quad (8)$$

Under a decentralized control scheme, the ADRC approach is located in each control area acting as local LFC strategy as shown in Fig. 1. Two decentralized areas are joined to each other through transmission-lines. Reheat and hydro turbine units are distributed in the two areas orderly. Substituting the values of system parameters into the $G_P(s)$ between the controller input $U(s)$ and ACE output, yields

$$G_{PR}(s) = \frac{3.3966s + 1.02}{0.24s^4 + 2.0364s^3 + 4.302s^2 + 3.9401s + 1.02} \quad (9)$$

$$G_{PH}(s) = \frac{-0.5233s^2 - 0.4967s + 1.02}{94.965s^4 + 208.6815s^3 + 38.0655s^2 + 1.679s + 1.03} \quad (10)$$

From Eq. (10), it can be observed that the TF of hydro unit has a positive zero, which can bring instability to the plant. This problem can be handled by fine optimizing the controller parameters. The system with hydro turbine system will be stabilized by the controller as well. The controller design and the parameter tuning are introduced and explained in following sections.

2.2 Mathematical modelling of TCSC in LFC

In order to improve the controllability and the power deliver quality, high voltage AC transmission systems based on the power electronics and other static controllers are utilized. These strategies are called as Flexible AC Transmission System (FACTS) devices. They are several FACTS devices controller, one of the main intrinsic of FACTS devices is Thyristor Controlled Series Compensator (TCSC) employed for frequency stabilization by fixing TCSC unit in series with transmission-line between interconnected power plants [30, 33]. Basically a TCSC is synthesis from three apparatuses: the capacitor banks, bypass inductor and the bidirectional thyristors. The reactance of a TCSC is handled by controlling the

firing angles of the thyristors in conformity with a system control approach, typically in response to some system parameter perturbations. Both the capacitive and the inductive reactance compensation devices are possible by appropriately selecting the capacitor and inductor values of the TCSC device. TCSC unit is concerned as a variable reactance, the adjustable value of which is tuned automatically to constrain the power flow across the branch to pre-specified value. The variable reactance X_{TCSC} indicates the net equivalent reactance of the TCSC when working in a two case either inductive or capacitive mode [30]. Fig. 3, describes the architecture diagram of an interconnected a two-area hydro-thermal power generation with TCSC connected in series with the transmission-line. Since the reactance to the resistance ratio is quite high ($\frac{X}{R} \geq 10$) the effect of the resistance in the dynamic performance investigation is neglected [34]. The tie-line power exchange without TCSC device is expressed by Eq. (11).

$$\Delta P_{Tie12}(s) = \frac{2\pi T_{12}^0}{s} [\Delta f_1(s) - \Delta f_2(s)] \quad (11)$$

In Eq. (11), $\Delta f_1(s)$ and $\Delta f_2(s)$ are the incremental frequency of the system; T_{12}^0 represents the synchronizing coefficient without TCSC. The line current flow from area-1 to area-2 can be modelled as in Eq. (12), when the TCSC is connected in series with the transmission-line

$$I_{12} = \frac{|V_1| \angle(\delta_1) - |V_2| \angle(\delta_2)}{j(X_{12} - X_{TCSC})} \quad (12)$$

where X_{12} represents the transmission-line reactance, X_{TCSC} is the TCSC reactance connected in series with the transmission-line, δ_1 and δ_2 are the voltage angles of area-1 and area-2 respectively. It is obvious from the Fig. 3 that, the complex transmission-line power as

$$P_{Tie12} - jQ_{Tie12} = V_1^* I_{12} = |V_1| \angle(-\delta_1) \left[\frac{|V_1| \angle(\delta_1) - |V_2| \angle(\delta_2)}{j(X_{12} - X_{TCSC})} \right] \quad (13)$$

Solving Eq. (13) as aforementioned above, and comparing the real part

$$P_{Tie12} = \frac{|V_1| |V_2|}{(X_{12} - X_{TCSC})} \sin(\delta_1 - \delta_2) \quad (14)$$

Considering the series compensation of $K_C = \frac{X_{TCSC}}{X_{12}}$, then the Eq. (14) can be written as:

$$P_{Tie12} = \frac{|V_1| |V_2|}{X_{12}(1 - K_C)} \sin(\delta_1 - \delta_2) \quad (15)$$

The Eq. (15) above can be re-formulated as

$$P_{Tie12} = \frac{|V_1| |V_2|}{X_{12}} \sin(\delta_1 - \delta_2) + \frac{K_C}{1 - K_C} \frac{|V_1| |V_2|}{X_{12}} \sin(\delta_1 - \delta_2) \quad (16)$$

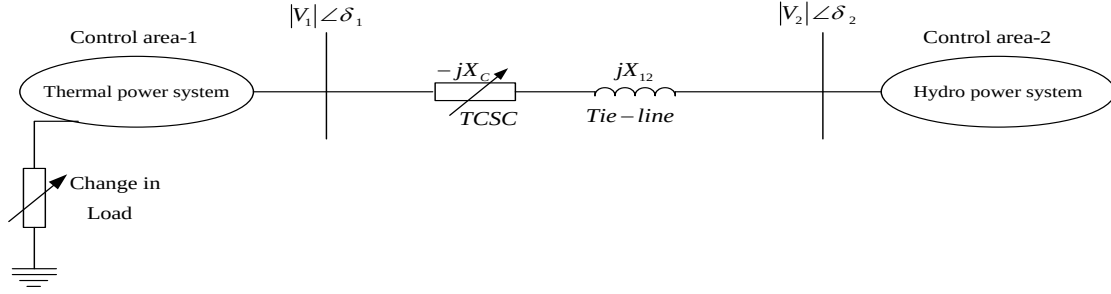


Fig. 3 Two-area interconnected hydro-thermal power system with TCSC in series with the tie-line.

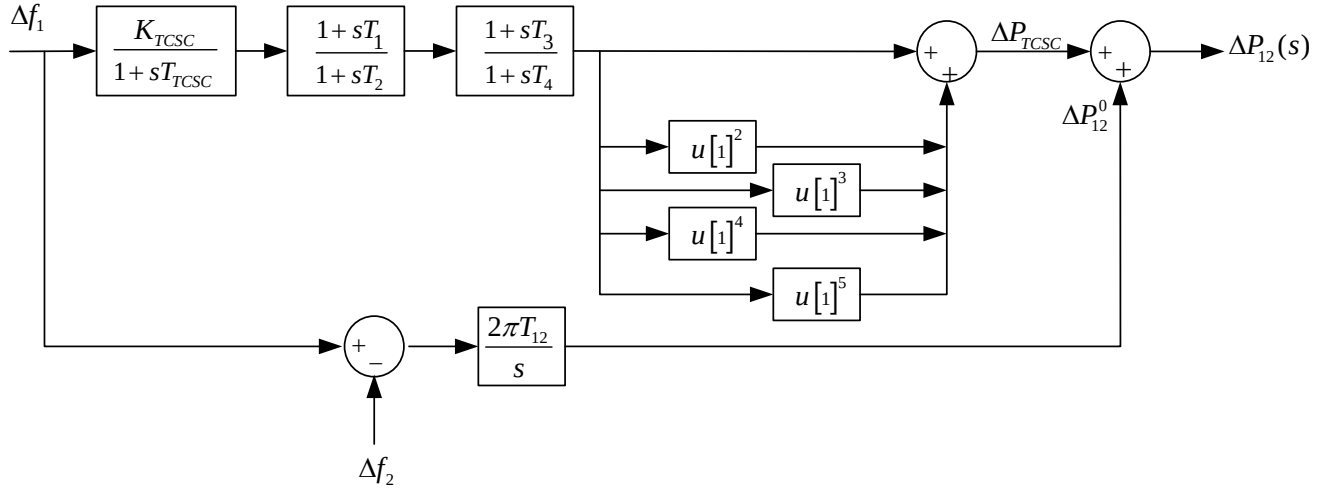


Fig. 4 Basic architecture for the proposed TCSC-based damping controller.

The first part of Eq. (16) demonstrates the power interchange in transmission-line without the TCSC and the second part represents the existence of TCSC in the transmission-line power interchange. In order to achieve the linear incremental model, the Eq. (16) can be expressed as:

$$\Delta P_{Tie12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0) \sin(\Delta\delta_1 - \Delta\delta_2) + \frac{\Delta K_C}{1 - \Delta K_C} \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^0 - \delta_2^0) \quad (17)$$

Since for the small change in real power, the variation of load angle is virtually very small, we can suppose that $\sin(\Delta\delta_1 - \Delta\delta_2) \approx (\Delta\delta_1 - \Delta\delta_2)$. Therefore Eq. (17) can be presented as

$$\Delta P_{Tie12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0) (\Delta\delta_1 - \Delta\delta_2) + \frac{\Delta K_C}{1 - \Delta K_C} \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^0 - \delta_2^0) \quad (18)$$

The Eq. (18) above can be reduced to

$$\Delta P_{Tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + \frac{\Delta K_C}{1 - \Delta K_C} K_1 \quad (19)$$

where $T_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0)$ and $K_1 = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^0 - \delta_2^0)$. Since $\Delta\delta_1 = 2\pi \int \Delta f_1 dt$ and $\Delta\delta_2 = 2\pi \int \Delta f_2 dt$. Thus, the Laplace transformation of Eq. (19) can be written as:

$$\Delta P_{Tie12}(s) = \frac{2\pi T_{12}}{s} [\Delta f_1(s) - \Delta f_2(s)] + \frac{\Delta K_C}{1 - \Delta K_C} K_1 \quad (20)$$

From the Taylor series expansion approach [34], we know that when $|x| < 1$:

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + x^4 + \dots \quad (21)$$

As the compensation ratio is bound in the range (-1, 1) i.e. $\Delta K_C < 1$ for all the inductive and the capacitive operation modes, thus, the aforementioned Taylor series expansion above can be employed to model TCSC

Table 1 System parameters.

Parameter	Value	Parameter	Value
T_t	0.3 (s)	T_{p2}	13 (s)
T_g	0.2 (s)	K_{p1}	120 Hz/p.u.MW
T_r	10 (s)	K_{p2}	80 Hz/p.u.MW
K_r	0.333 (s)	$B_1 = B_2$	0.425 p.u.MW/Hz
T_{h1}	48.7 (s)	$R_1 = R_2$	2.4 Hz/p.u.MW
T_{h2}	0.513 (s)	ΔP_{L1}	0.01 p.u.MW
T_{h3}	10 (s)	a_{ij}	-1.0
T_w	1.0 (s)	T_{ij}	0.0707 p.u.MW
T_{p1}	20 (s)		

controller as follows

$$\frac{\Delta K_C}{1 - \Delta K_C} = \Delta K_C + \Delta K_C^2 + \Delta K_C^3 + \Delta K_C^4 + \Delta K_C^5 + \dots \quad (22)$$

Hence the Eq. (20) can be formulated as:

$$\begin{aligned} \Delta P_{Tie12}(s) &= \frac{2\pi T_{12}}{s} [\Delta f_1(s) - \Delta f_2(s)] \\ &+ (\Delta K_C + \Delta K_C^2 + \Delta K_C^3 + \Delta K_C^4 + \Delta K_C^5 + \dots) K_1 \end{aligned} \quad (23)$$

From the Eq. (23) mentioned above, the tie-line power interchange can be controlled by handling ΔK_C . If the control input signal to the TCSC damping controller is supposed to be $\Delta Error(s)$ and the TF of the signal conditioning circuit is $K_C = \frac{K_{TCSC}}{1+sT_{TCSC}}$. The expression is presented by Eq. (24)

$$\Delta K_C(s) = \frac{K_{TCSC}}{1+sT_{TCSC}} \Delta Error(s) \quad (24)$$

where K_{TCSC} and T_{TCSC} is the adjustable gain and time constant of the TCSC unit respectively. The basic schematic diagram of the suggested TCSC- based controller is highlighted in Fig. 4 where the frequency deviation in area-1, i.e. Δf_1 may be appropriately employed as the control signal $\Delta Error(s)$, to the TCSC device to tackle the percentage deviation change in the system compensation level. Therefore,

$$\Delta K_C(s) = \frac{K_{TCSC}}{1+sT_{TCSC}} \Delta f_1(s) \quad (25)$$

Regarding the design objectives, only the first five parts in Eq. (23) are utilized in the TCSC controller designed as displayed in Fig. 4. In the current TCSC controller, K_1 is included in the TCSC term K_{TCSC} , i.e., $K'_{TCSC} = K_{TCSC} \cdot K_1$ in which

$$\Delta P_{TCSC} = \Delta K'_C + (\Delta K'_C)^2 + (\Delta K'_C)^3 + (\Delta K'_C)^4 + (\Delta K'_C)^5 \quad (26)$$

where

$$\Delta K'_C(s) = \frac{K'_{TCSC}}{1+sT_{TCSC}} \Delta f_1(s) \quad (27)$$

2.3 Mathematical modelling of TCPS in LFC

The schematic diagram of an interconnected two-area power system synthesis from hydro-thermal source presenting a TCPS in series with the transmission-line is highlighted in Fig. 5. TCPS is located near to area-1 [35]. The resistance of transmission-line is ignored. Without the TCPS device, the tie-line power deviation from area-1 to area-2 can be provided as

$$\Delta P_{Tie12}(s) = \frac{2\pi T_{12}^0}{s} [\Delta f_1(s) - \Delta f_2(s)] \quad (28)$$

When a TCPS is located in series with the transmission-line, the current passing from area-1 to area-2 can be written as

$$I_{12} = \frac{|V_1| \angle(\delta_1 + \varphi) - |V_2| \angle(\delta_2)}{jX_{12}} \quad (29)$$

From Fig. 5,

$$\begin{aligned} P_{Tie12} - jQ_{Tie12} &= V_1^* I_{12} \\ &= |V_1| \angle -(\delta_1 + \varphi) \left[\frac{|V_1| \angle(\delta_1 + \varphi) - |V_2| \angle(\delta_2)}{jX_{12}} \right] \end{aligned} \quad (30)$$

By formulating the Eq. (30) we obtain:

$$\begin{aligned} P_{Tie12} - jQ_{Tie12} &= \frac{|V_1| |V_2|}{X_{12}} \sin(\delta_1 - \delta_2 + \varphi) \\ &- j \times \frac{[|V_1|^2 - |V_1| |V_2| \cos(\delta_1 - \delta_2 + \varphi) - |V_2| \angle(\delta_2)]}{X_{12}} \end{aligned} \quad (31)$$

Splitting the real parts of Eq. (31), we get

$$P_{Tie12} = \frac{|V_1| |V_2|}{X_{12}} \sin(\delta_1 - \delta_2 + \varphi) \quad (32)$$

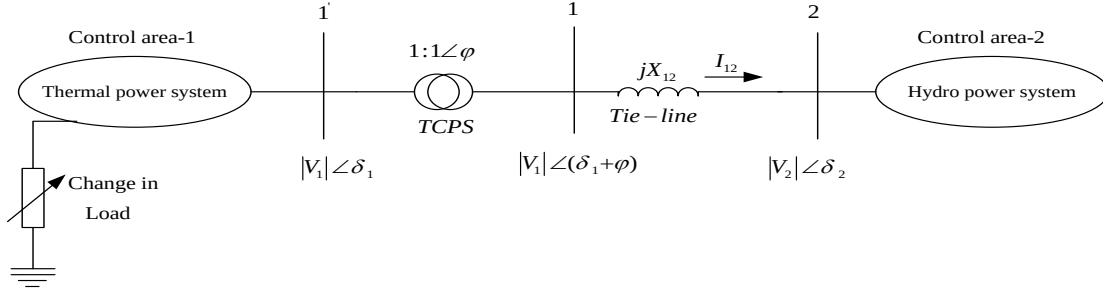


Fig. 5 Two-area interconnected hydro-thermal power system with TCPS in series with the tie-line.

In Eq. (32), perturbing δ_1, δ_2 and φ from their specified values δ_1^0, δ_2^0 and φ^0 yields:

$$\Delta P_{Tie12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0 + \varphi^0) \sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \quad (33)$$

Since $(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi)$ is extremely small, accordingly for small perturbation in real power load, the variation of the bus voltage angles, as well as the variation of TCPS phase angle are practically quite small. Hence, $\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \approx (\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi)$. Therefore

$$\Delta P_{Tie12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0 + \varphi^0) (\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \quad (34)$$

The Eq. (34) can be reduced to

$$\Delta P_{Tie12} = T_{12} (\Delta\delta_1 - \Delta\delta_2) + T_{12} \Delta\varphi \quad (35)$$

Where $T_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0 + \varphi^0)$. Since $\Delta\delta_1 = 2\pi \int \Delta f_1 dt$ and $\Delta\delta_2 = 2\pi \int \Delta f_2 dt$ [30]. Hence, the Laplace transformation of Eq. (35) can be written as:

$$\Delta P_{Tie12} = \frac{2\pi T_{12}}{s} [\Delta f_1(s) - \Delta f_2(s)] + T_{12} \Delta\varphi \quad (36)$$

The tie-line power interchange aforementioned above can be handled by adjusting the phase shifter angle $\Delta\varphi$. The phase angle $\Delta\varphi(s)$ mention above can be established as:

$$\Delta\varphi(s) = \frac{K_\varphi}{1 + sT_{TCPS}} \Delta Error(s) \quad (37)$$

Therefore, Eq. (36) demonstrated above can be expressed as

$$\Delta P_{Tie12} = \frac{2\pi T_{12}}{s} [\Delta f_1(s) - \Delta f_2(s)] + T_{12} \frac{K_\varphi}{1 + sT_{TCPS}} \Delta Error(s) \quad (38)$$

If the speed deviation Δf_1 is sensed, it can be used as the control signal (i.e. $\Delta Error(s) = \Delta f_1$) to the TCPS

device to handle the TCPS phase angle which in turn, handles the transmission-line power [35]. Thus,

$$\Delta\varphi(s) = \frac{K_\varphi}{1 + sT_{TCPS}} \Delta f_1(s) \quad (39)$$

Then, the tie-line power change in Eq. (38) becomes

$$\begin{aligned} \Delta P_{Tie12} &= \frac{2\pi T_{12}}{s} [\Delta f_1(s) - \Delta f_2(s)] \\ &+ T_{12} \frac{K_\varphi}{1 + sT_{TCPS}} \Delta f_1(s) = \Delta P_{tie12}^0(s) + \Delta P_{TCPS}(s) \end{aligned} \quad (40)$$

where $\Delta P_{TCPS}(s) = T_{12} \frac{K_\varphi}{1 + sT_{TCPS}} \Delta f_1(s)$.

Fig. 6 describes the MATLAB/SIMULINK MODEL of the TCPS controller. The incremental frequency ($\Delta f_i, i = 1, 2$), which provides the information of each mode of interest, is employed as the input signal for the controller. There are two adjustable parameters such as the gain K_φ and the time constant T_{TCPS} should be optimized to attain the optimal design of the TCPS frequency controller.

3 Design LFC controller based on ADRC technique

In this section, the basic concept of the ADRC approach is briefly derived and constructed as a decentralized LFC for an interconnected multi-area power system. The basic structure of the time-domain ADRC is introduced as in [26, 36, 37]. In this part, the transfer function (TF) representation of the ADRC will be established for a general n -th order system.

3.1 Transfer function derivation for n -th order system

Consider the system with a disturbance as presented in Eq. (41):

$$Y(s) = G_p(s) \cdot U(s) + W(s) \quad (41)$$

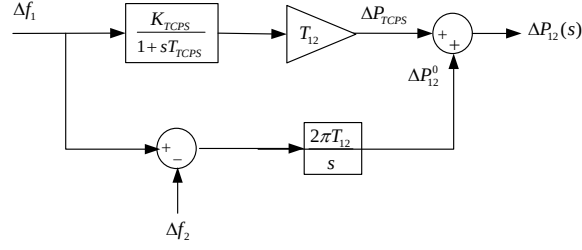


Fig. 6 Basic architecture for the proposed TCSC-based damping controller.

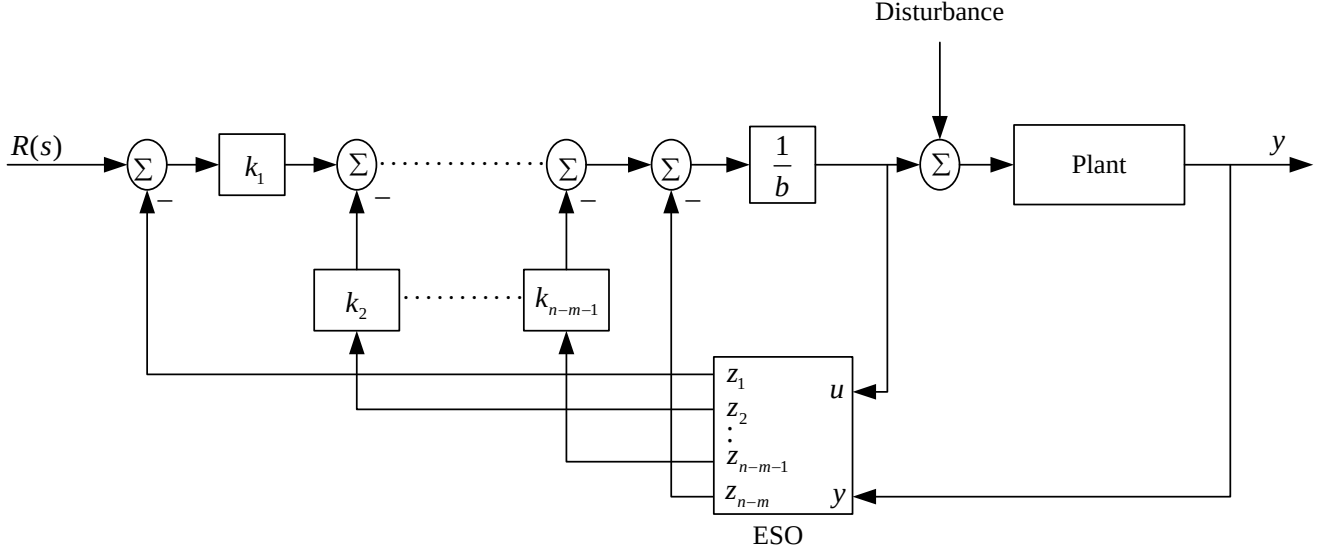


Fig. 7 General architecture for the ADRC approach.

where $U(s)$ and $Y(s)$ denotes the system input and system output respectively, and $W(s)$ is the disturbance consisting of the unknown internal and external disturbances. In general, the TF of the system $G_p(s)$ can be expressed as

$$\frac{Y(s)}{U(s)} = G_p(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \dots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0}, \quad n \geq m \quad (42)$$

where a_i and b_i ($i = 0, 1, 2, 3, \dots, n, j = 0, 1, 2, 3, \dots, m$) denotes the coefficients of the polynomial of $G_p(s)$. Divided both sides of the Eq. (41) by $G_p(s)$, then yield:

$$(1/G_p(s))Y(s) = U(s) + W'(s) \quad (43)$$

where $W'(s) = W(s)/G_p(s)$. In Eq. (43), the TF $1/G_p(s)$ can be modeled as

$$\begin{aligned} \frac{1}{G_p(s)} &= \frac{a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0}{b_m s^m + b_{m-1} s^{m-1} + \dots + b_1 s + b_0} \\ &= c_{n-m} s^{n-m} + c_{n-m-1} s^{n-m-1} + \dots + c_1 s + c_0 + G_{rem}(s) \end{aligned} \quad (44)$$

where, c_i ($i = 0, \dots, n-m$) means the coefficients of $1/G_p(s)$, and the remainder $G_{rem}(s)$ can be written as:

$$G_{rem}(s) = \frac{d_{m-1} s^{m-1} + d_{m-2} s^{m-2} + \dots + d_1 s + d_0}{b_m s^m + b_{m-1} s^{m-1} + \dots + b_1 s + b_0} \quad (45)$$

where d_j ($j = 0, \dots, m-1$) represents coefficients of the numerator of the $G_{rem}(s)$. Substitute Eq. (44)

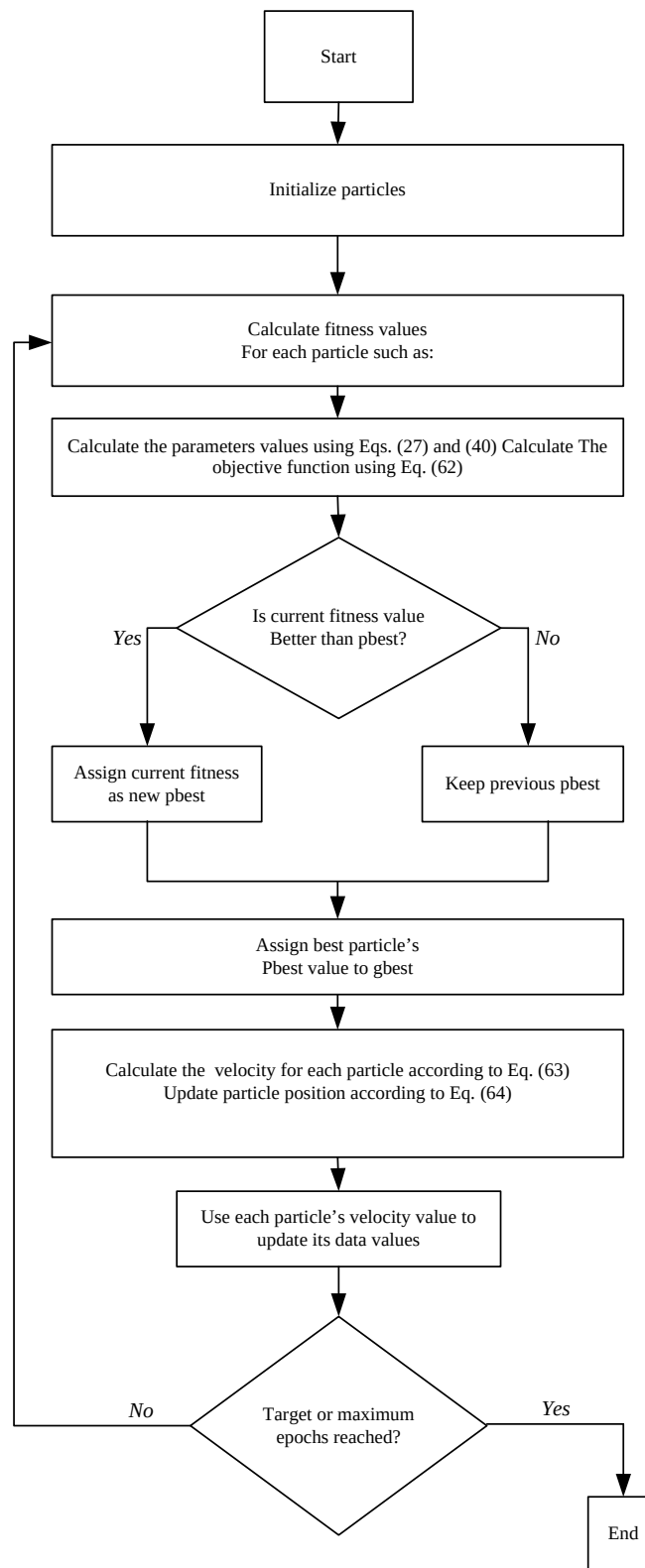


Fig. 8 Flowchart of PSO algorithm.

Table 2 ADRC parameters.

	Order of ESO	ω_c	ω_c	b
Area 1	3.0	4.0	20	14.1525
Area 2	3.0	4.0	20	551.050

into Eq. (43), and rearranged yields:

$$\begin{aligned} & c_{n-m}s^{n-m}Y(s) \\ &= U(s) - [c_{n-m-1}s^{n-m-1} + \dots + c_1s + c_0 + G_{rem}(s)]Y(s) \\ & \quad + W'(s) \end{aligned} \quad (46)$$

where $c_{n-m} = \frac{a_n}{b_m}$. Dividing the Eq. (46) by c_{n-m} , yields:

$$s^{n-m}Y(s) = bU(s) + D(s) \quad (47)$$

where $b = 1/c_{n-m}$ and

$$\begin{aligned} D(s) &= -\frac{1}{c_{n-m}}[c_{n-m-1}s^{n-m-1} + \dots + c_1s + c_0 + G_{rem}(s)]Y(s) \\ & \quad + \frac{1}{c_{n-m}}W'(s) \end{aligned} \quad (48)$$

We will using Eq. (47) later to demonstrate the system model for the controller design.

3.2 Design of the extended state observer (ESO)

The robustness of the ADRC depends on the precise estimation of the disturbance $D(s)$ [26, 36]. Thus, the ESO needs to be established to estimate the $D(s)$ in real time. This can be achieved by augmenting the state variables of the system in Eq. (47) to include $D(s)$. In order to construct the extended state observer (ESO), the system modelled in Eq. (47) can be formulated as:

$$sX(s) = AX(s) + BU(s) + E(s)D(s) \quad (49)$$

$$Y(s) = CX(s) \quad (50)$$

where

$$X(s) = \begin{bmatrix} x_1(s) \\ x_2(s) \\ \vdots \\ \vdots \\ x_{n-m}(s) \\ x_{n-m+1}(s) \end{bmatrix},$$

$$\begin{aligned} A &= \begin{bmatrix} 0 & 1 & 0 & \dots & \dots & 0 \\ 0 & 0 & 1 & \dots & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & \dots & 1 \\ 0 & 0 & 0 & \dots & \dots & 0 \end{bmatrix}_{(n-m+1) \times (n-m+1)}, \\ B &= \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ \vdots \\ 0 \\ b \\ 0 \end{bmatrix}_{(n-m+1) \times 1}, E(s) = \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ \vdots \\ 0 \\ 0 \\ 1 \end{bmatrix}_{(n-m+1) \times 1}, C = \\ & [1 \ 0 \ 0 \ \dots \ \dots \ 0]_{1 \times (n-m+1)} \end{aligned}$$

To derive the estimator, we suppose that $D(s)$ has the local Lipschitz continuity. Hence, the ESO can be modelled as:

$$sZ(s) = AZ(s) + BU(s) + L(Y(s) - \hat{Y}(s)) \quad (51)$$

$$\hat{Y}(s) = CZ(s) \quad (52)$$

where $Z(s)$ is the estimated state vector and $Z(s) = [z_1(s) \ z_2(s) \ \dots \ z_{n-m}(s) \ z_{n-m+1}(s)]^T$, and L is the observer gain vector and $L = [\beta_1 \ \beta_2 \ \dots \ \beta_{n-m} \ \beta_{n-m+1}]^T$. To set all the eigenvalues of the extended state observer to $(-\omega_0)$, the observer gains are selected as

$$\beta_i = \binom{n-m+1}{i} \cdot \omega_0^i, \quad i = 1, 2, \dots, n-m+1 \quad (53)$$

Thus, we can adjust and change the observer terms by tuning the parameter ω_0 , which signifies the bandwidth of the observer. With a suitable tuned ESO, $z_i(s)$ can be able to approximate the value of $x_i(s)$ relatively ($i = 1, \dots, n-m+1$), then we can write:

$$z_{n-m+1}(s) = \hat{D}(s) \approx D(s) \quad (54)$$

where $\hat{D}(s)$ represents the estimation of $D(s)$. The disturbance $D(s)$ can be removed, if the control input $U(s)$ is designed as:

$$U(s) = (U_0(s) - z_{n-m+1}(s))/b \quad (55)$$

The original system depicted in Eq. (47), it will be reduced to a pure integral plant. This manner can be illustrated by Eq. (56), where $U_0(s)$ denotes the control law for adjusting the ACE output $Y(s)$.

$$\begin{aligned} s^{n-m}Y(s) &= b \cdot [(U_0(s) - z_{n-m+1}(s))/b] + D(s) \\ &= U_0(s) - \hat{D}(s) + D(s) \approx U_0(s) \end{aligned} \quad (56)$$

The aim of LFC is to regulate the ACE to zero. A standard PD controller can achieve this goal. So, the control law $U_0(s)$ is selected as

$$U_0(s) = k_1(R(s) - z_1(s)) - k_2z_2(s) - \dots - k_{n-m-1}z_{n-m-1}(s) \quad (57)$$

where $R(s)$ represent the reference input. To simplify the tuning procedure, all the closed-loop poles of the PD controller are set to $(-\omega_c)$. Then the controller gains in Eq. (57), have to be designed as

$$k_i = \binom{n-m}{i} \cdot \omega_c^{n-m-i}, \quad i = 1, 2, \dots, n-m-1 \quad (58)$$

where ω_c denotes the bandwidth of the controller. Generally, ω_c varies from 3 ~ 10 rad/s [28]. The general structure of the ADRC is described in Fig. 7.

According to the detailed illustrative above, the ADRC approach for area-1 of the power system can be designed and represented by the following equations.

$$sZ(s) = (A - LC)Z(s) + BU(s) + LY(s) \quad (59)$$

$$U_0(s) = k_1(R(s) - z_1(s)) - k_2z_2(s) - k_3z_3(s) \quad (60)$$

$$U(s) = (U_0(s) - z_4(s))/b \quad (61)$$

$$\text{where, } Z(s) = \begin{bmatrix} z_1(s) \\ z_2(s) \\ z_3(s) \\ z_4(s) \end{bmatrix}, A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ b \\ 0 \end{bmatrix}, L = \begin{bmatrix} 4\omega_0 \\ 6\omega_0^2 \\ 4\omega_0^3 \\ \omega_0^4 \end{bmatrix},$$

$$C = [1 \ 0 \ 0 \ 0], k_1 = \omega_c^3, k_2 = 3\omega_c^2, k_3 = 3\omega_c.$$

The ADRC for the second areas has similar architecture to area 1. The tuned parameters of the ADRCs approaches in two areas are presented in Table 2. According to Ref. [26], the observer bandwidth (ω_0) is selected as five times controller bandwidth (ω_c). The controller gain b for area-2 is relatively large compared to the gain for the area-1. This is for compensating the effects of the positive zero in area-2. As observed

in Table 2, there are only two adjusting parameters for designing of the ADRC approach, namely the controller bandwidth (ω_c) and controller gain (b).

4 The objective function and its solution

4.1 Objective function for controller design

The aim of LFC in an interconnected control-area is to re-establish the essential frequency regulation capacity, return the frequency to its specified value as rapidly as possible and reduce the interchange power oscillations between interconnected control areas. In order to satisfy the above requirements, considering a suitable objective function is very important to explore the controller parameters. The general indices that usually concerned for a controller design are Integral of Time multiplied Absolute Error (ITAE), ISE, ITSE and IAE [24, 34, 38]. In this article, ITAE is considered as an objective function to optimize the parameters of the controllers. The expression for the ITAE is presented in Eq. (62).

$$J = ITAE = \int_0^{T_{sim}} t \cdot (|\Delta F_i| + |\Delta P_{tie,ij}|) dt \quad (62)$$

where, T_{sim} represents the simulation time. An optimization issue is handled by employing a PSO algorithm introduced in [24] to minimize the ITAE criterion to attain the optimal parameters of the controllers, subject to the following constraints:

$$\left. \begin{aligned} K_{TCSC}^{\min} &\leq K_{TCSC} \leq K_{TCSC}^{\max} \\ T_{TCSC}^{\min} &\leq T_{TCSC} \leq T_{TCSC}^{\max} \\ T_1^{\min} &\leq T_1 \leq T_1^{\max} \\ T_3^{\min} &\leq T_3 \leq T_3^{\max} \\ K_{TCPS}^{\min} &\leq K_{TCPS} \leq K_{TCPS}^{\max} \\ T_{TCPS}^{\min} &\leq T_{TCPS} \leq T_{TCPS}^{\max} \end{aligned} \right\} \quad (63)$$

4.2 Particle swarm optimization (PSO)

PSO is part of a wide category of swarm intelligence techniques for handling optimization issues [2, 24]. It is a population technique employed to explore the search space of the stated problem in order to tune the parameters that required optimizing the objective function. It can be achieved high-quality solutions within less time and stable convergence than the other stochastic algorithms such as GA. Every particle in the PSO flies

Table 3 Optimal value of controllers gains for Test 1.

Evolutionary algorithm	ADRC-TCSC controller gains				ADRC-TCPS controller gains	
	K_{FACTS}	T_{FACTS}	T_1	T_3	K_{FACTS}	T_{FACTS}
PSO	0.1102	0.0641	0.4200	0.3045	0.9672	0.8936

Table 4 Comparative system analysis for Test 1 in terms of settling time and peak over/undershoot.

Controller	Settling time (s)			Peak overshoot			Peak undershoot ($-ve$)		
	Δf_1	Δf_2	$\Delta P_{Tieth-hy}\Delta f_1$	Δf_2	$\Delta P_{Tieth-hy}\Delta f_1$	Δf_2	$\Delta P_{Tieth-hy}\Delta f_1$	Δf_2	$\Delta P_{Tieth-hy}\Delta f_1$
ADRC	10.35	17.27	9.89	0.0031	0.0087	0.0027	0.0095	0.0096	0.0020
ADRC-TCPS	14.97	19.50	8.68	0.0029	0.0083	0.0019	0.0071	0.0082	0.0016
ADRC-TCSC	6.73	10.01	4.16	0.0015	0.0036	0.0010	0.0066	0.0057	0.0014

Table 5 Optimal value of controllers gains for test 2.

Evolutionary algorithm	ADRC-TCSC controller gains				ADRC-TCPS controller gains	
	K_{FACTS}	T_{FACTS}	T_1	T_3	K_{FACTS}	T_{FACTS}
PSO	0.1354	0.0870	0.7120	0.4312	1.3050	0.8765

Table 6 Comparative system analysis for Test 2 in term of settling time.

Controller	Settling time (s)					
	Δf_1	Δf_2	Δf_3	Δf_4	$\Delta P_{Tieth-th}$	$\Delta P_{Tieth-hy}$
ADRC	5.70	11.33	7.65	7.65	10.70	7.00
ADRC-TCPS	5.30	13.54	8.80	8.80	10.70	8.30
ADRC-TCSC	4.67	4.87	4.63	4.63	10.20	4.10

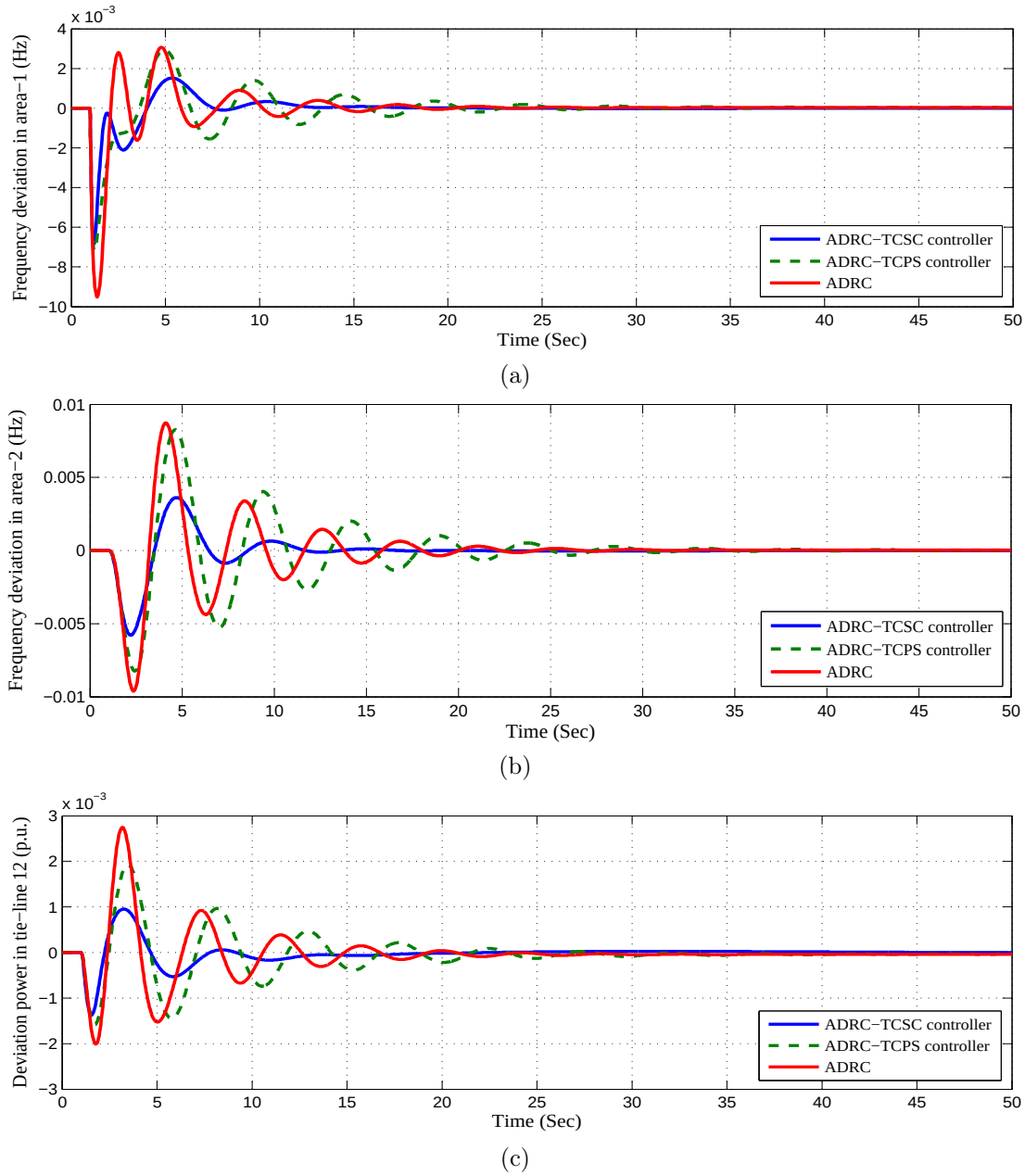


Fig. 9 System responses for Test 1: (a) and (b) represents the frequency deviation in two areas, and (c) represents the deviation power in tie-line 12.

over the space by a certain velocity that is dynamically adjusted according to its individual flying experience. In PSO algorithm each individual particle tries to enhance themselves by imitating characteristics to their successful rivals. Furthermore, every particle has a memory and then it is capable of reminding the preferable position in the search space ever visited by it. The corresponding position for the best fitness is called as $pbest$ and the overall best out of all the individuals in the population

is called $gbest$.

The modified position and velocity of every particle can be calculated according to current velocity and the distances from the $pbest_{k,d}$ to $pbest_g$ as represented by the following equations:

$$v_{k,d}^{t+1} = \omega \cdot v_{k,d}^t + c_1 \cdot r_1 (pbest_{k,d} - x_{k,d}^t) + c_2 \cdot r_2 (gbest_d - x_{k,d}^t) \quad (64)$$

$$x_{k,d}^{t+1} = x_{k,d}^t + v_{k,d}^{t+1} \quad (65)$$

where:

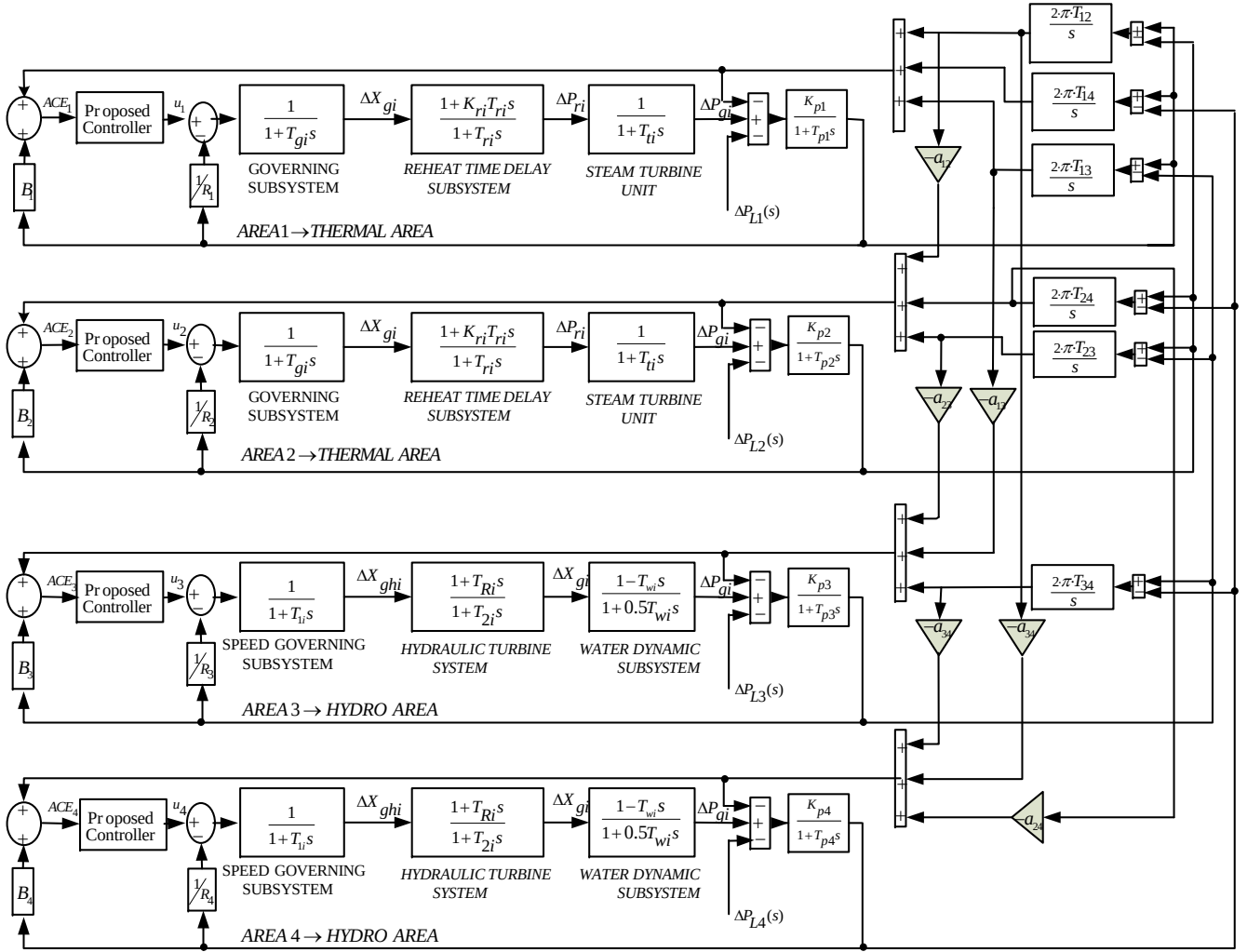


Fig. 10 Transfer function model of four-area hydro-thermal power plant.

n number of particles in the swarm.

m number of members for the vectors v_k and x_k .

t number of iterations (generations).

$v_{k,d}^t$ the velocity of particle k at iteration t .

ω inertia weight constant.

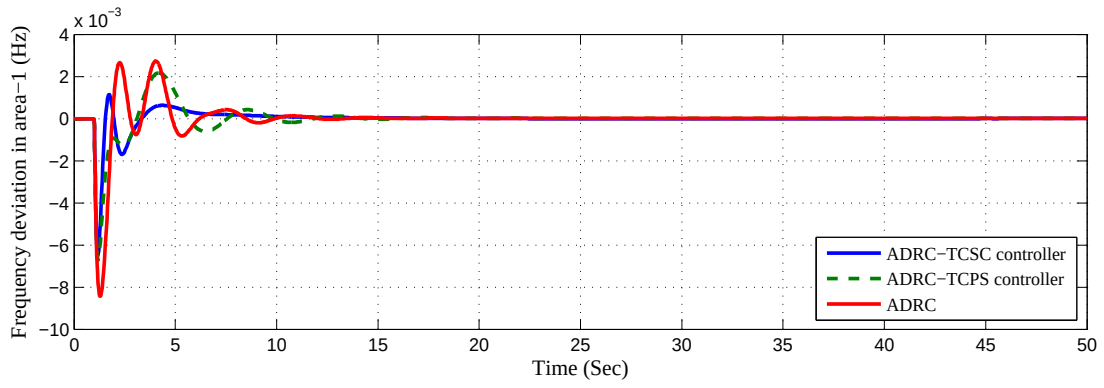
c_1, c_2 acceleration constants.

r_1, r_2 uniformly random numbers distributed in the range (0, 1).

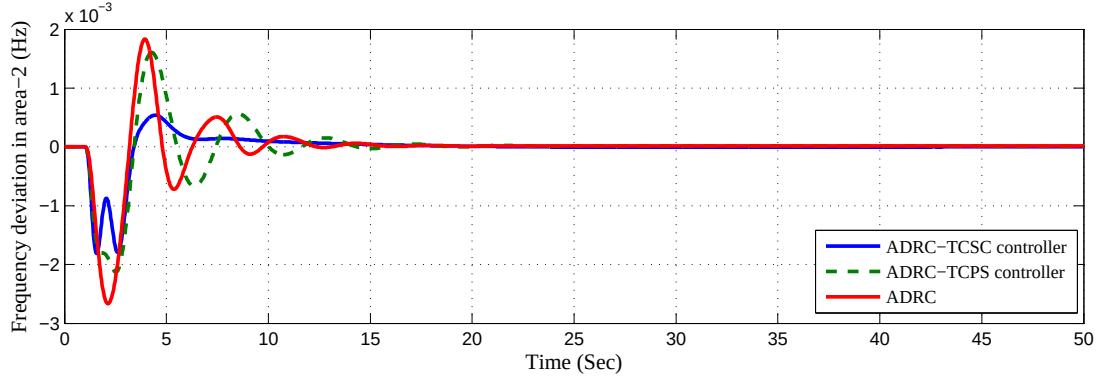
$x_{k,d}^t$ the position of particle k at iteration t .

The i th individual in the swarm is denoted by a m -

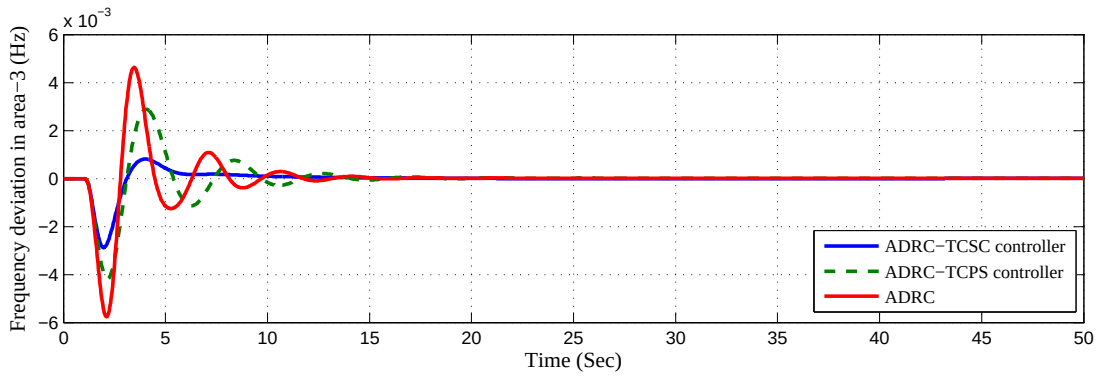
dimensional space $x_j = (x_{j,1}, x_{j,2}, \dots, x_{j,m})$, ($j = 1, 2, \dots, n, d = 1, 2, \dots, m$) and its rate of position change (velocity) is represented by another m -dimensional space $v_j = (v_{j,1}, v_{j,2}, \dots, v_{j,m})$. The best previous position of the j th individual is indicated as $pbest_j = (pbest_{j,1}, pbest_{j,2}, \dots, pbest_{j,m})$. The index of better particle overall of the particles in the swarm is denoted by $gbest_g$. The scaling parameters c_1 and c_2 regulate the relative pull of $pbest$, and $gbest$ and their best values are chosen as $c_1 = c_2 = 2$, and the parameters r_1 and r_2 assist in stochastically varying these pulls. The best chosen value of ω is $\omega_{\max} = 0.9$, $\omega_{\min} = 0.4$. The flowchart of PSO used in this article to optimize the parameters of the proposed controller is highlighted in Fig. 8.



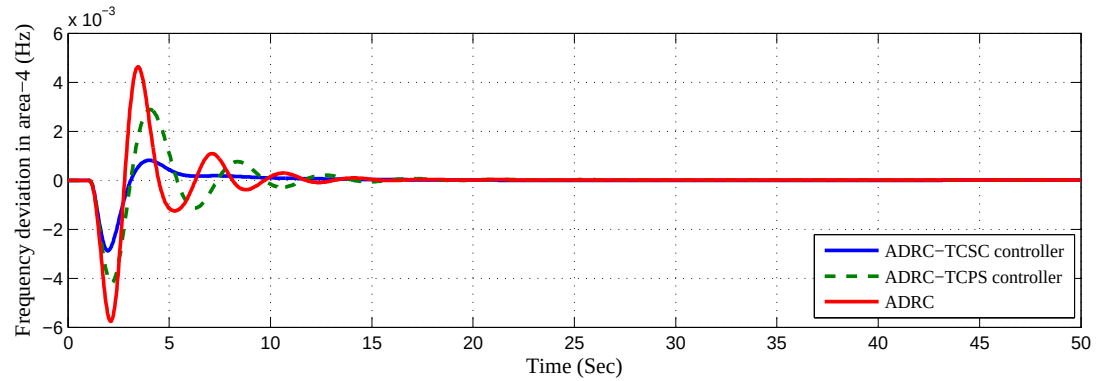
(a)



(b)



(c)



(d)

Fig. 11 System responses for Test 2: (a), (b), (c) and (d) represents the frequency deviation in four areas respectively.

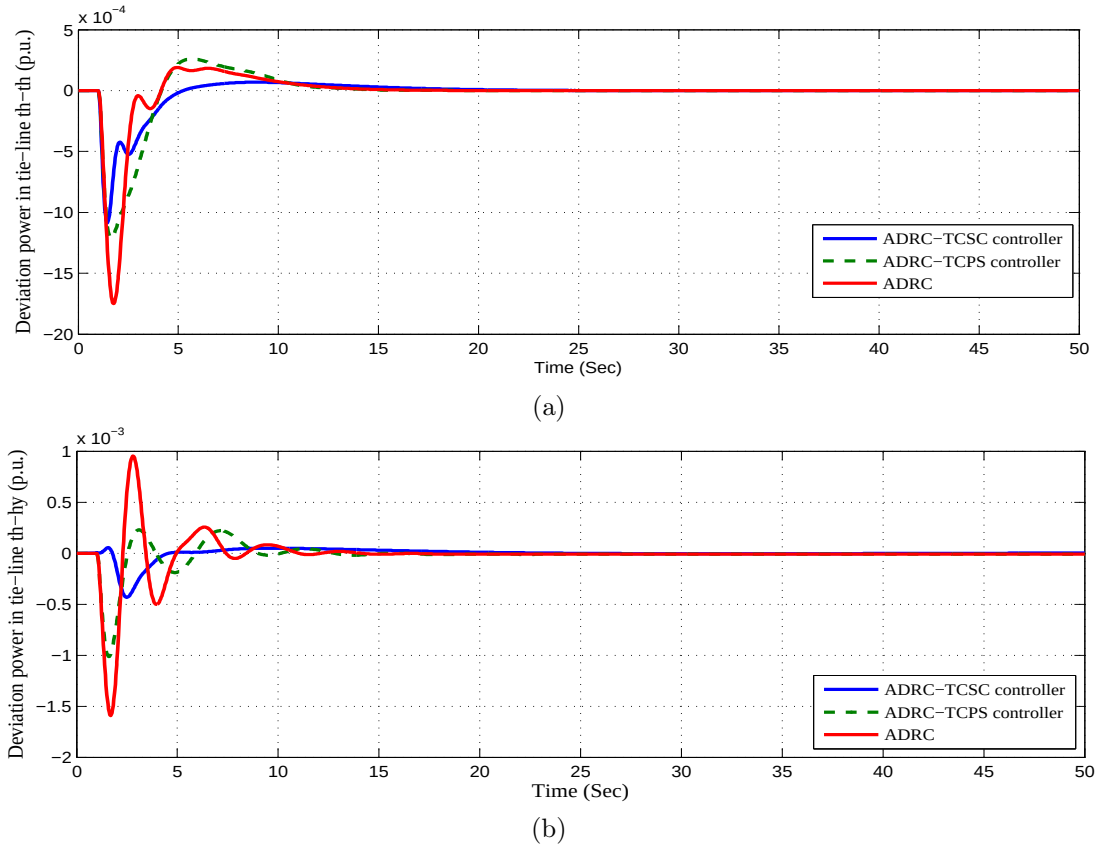


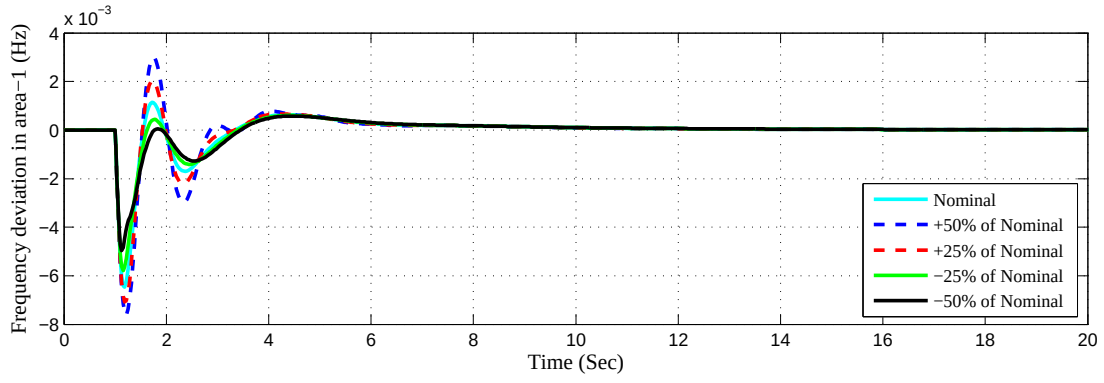
Fig. 12 System responses for Test 2: (a) and (b) represents the deviation power in thermal-thermal tie-line and thermal-hydro tie-line respectively.

5 Results and discussion

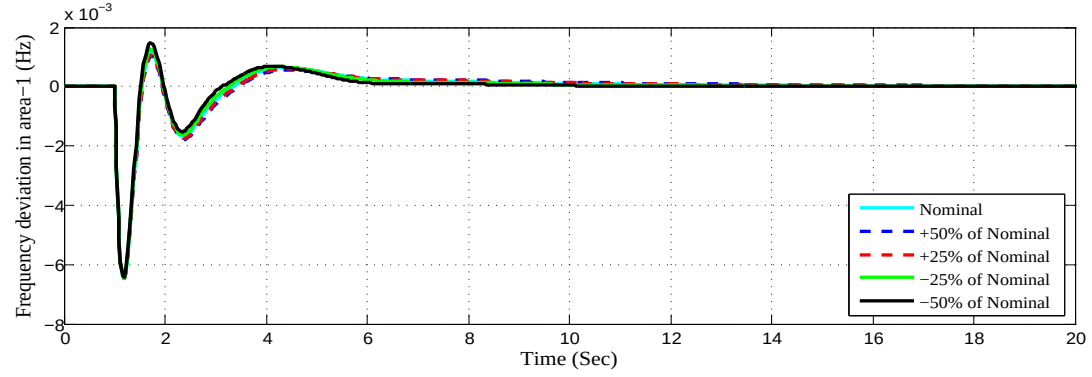
The objective function of LFC in the power system is to diminish the frequency oscillation of the individual area as well as the deviation of the power interchange between the relative control areas caused by unexpected load change. Therefore, the main purpose of this simulation study is to test the efficacy and capability of the proposed controller to solve the aforementioned problems above of LFC in the power system. The controller is equipped on two test systems, namely, two-area and four-area hydro-thermal power plants and the dynamic presentations are assessed under normal and perturbed conditions. Dynamic models of the investigated systems are developed in MATLAB/SIMULINK environment, while the MATLAB code of the suggested optimization method is written separately in the *.m file*. The proposed controller is designed separately for each control area using PSO algorithm employing ITAE criterion based objective function. The proposed PSO algorithm as demonstrated above is employed to explore the ADRC-TCSC, ADRC-TCSP controller's gains for the testing

two cases of the system, namely, two-area and four-area hydro-thermal power plants. The system parameters are obtained from [31, 32], and are listed in Table 1. In an interconnected multi-area power system the load perturbation can occur at any place in the power system, either in one area or in a few areas or in all areas simultaneously. Hence, in this study, the simulations have been performed for the system under applied 1% step load perturbations in area-1. The optimization technique was repeated 100 times and the best parameters of the controllers obtained corresponding to the minimum objective function are listed in associated sections. Before presenting the simulation results, it is helpful to list briefly what simulation procedures we are going to perform in continue of this article to demonstrate the effectiveness of the proposed technique. The simulation process can be performed as follows:

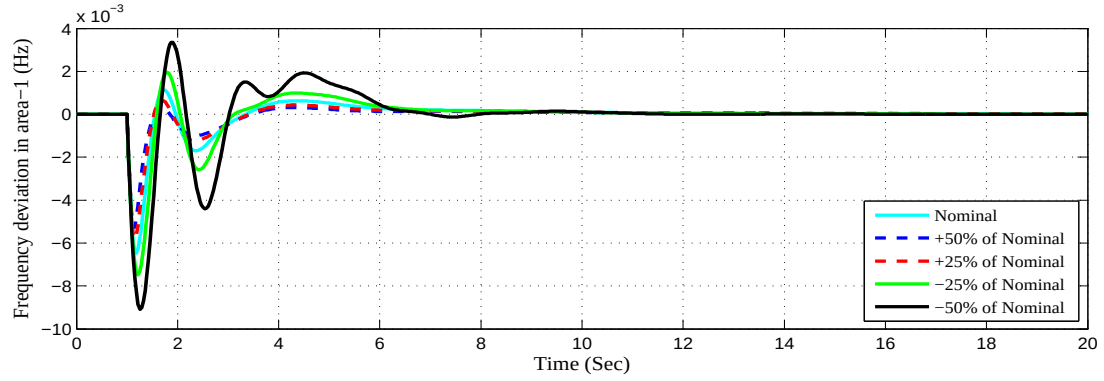
- (i) Performance evaluation of ADRC-TCSC controller with ADRC-TCPS and ADRC controllers under step load change in area-1;
- (ii) Sensitivity analysis to appraise robustness of the



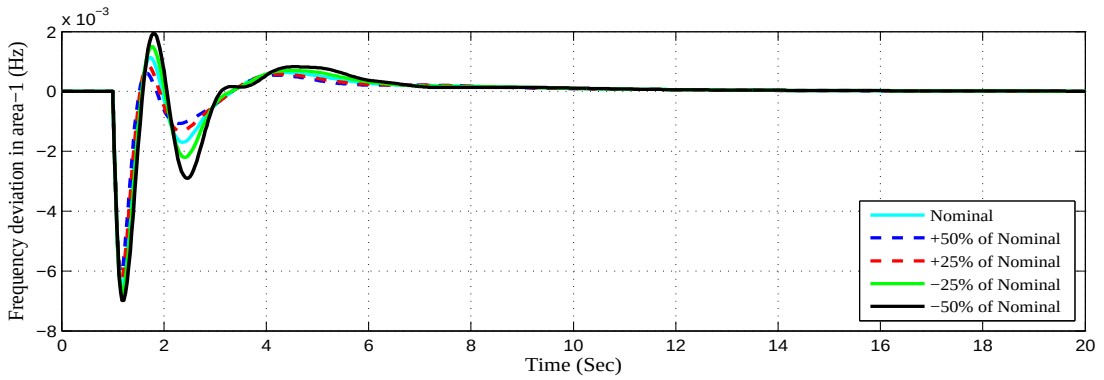
(a)



(b)



(c)



(d)

Fig. 13 Sensitivity analysis of the plant (Frequency deviation of area-1 after 1% step load perturbation): (a) Variation of T_g , (b) Variation of T_r , (c) Variation of K_r and (d) Variation of B .

current controllers against uncertainty in system parameters and loading condition in a range of -50% to +50% in steps of 25% from their nominal values.

- (iii) Performance evaluation for different load perturbation patterns:
 1. Pulse load perturbation.
 2. Sinusoidal load perturbation.

5.1 Test 1: Two-area hydro-thermal power system

Initially, a two-area hydro-thermal power system equipped with ADRC-TCSC, ADRC-TCPS, and ADRC controllers, as shown in Fig. 1, is considered and 1% step load change is subjected to area-1 for investigating the dynamic performance of the concerned power system. PSO algorithm is stated to explore optimal values of ADRC-TCSC controller employing ITAE based objective function. The optimization technique was repeated 100 times and at the end of optimization the best controller gains corresponding to the minimum objective function are furnished in Table 3. The comparative performances in terms of frequency in two areas and tie-line power flow deviations of the considered test system after load change are plotted in Figs. 9(a)-(c). To show the superiority of proposed controller, the numerical simulation results obtained are compared with those obtained by other intelligent controllers, namely ADRC-TCPS, and ADRC controllers which are recently reported in the literature and the comparative results are furnished in Table 3 and Figs. 9(a)-(c). It can be observed from Figs. 9(a)-(c) and Table 4 that the suggested PSO algorithm based ADRC-TCSC controller outperforms than other intelligent controllers.

5.2 Test 2: Extention to multi-area power system

To investigate the numerical computational effectiveness of the proposed controller, the study is extended to an intricate system, namely four-area hydro-thermal power plant. Area-1 and area-2 comprise of reheat type thermal power plants while area-3 and area-4 comprise of hydro-power plants. The TF model of test 2, is described in Fig. 10 and the nominal system parameters are presented in Table 1. PSO algorithm is established to explore optimal values of the proposed controller employing ITAE based objective function. The optimal parameters attained by the proposed algorithm regarding the minimum objective function is tabulated in Table 5. The comparative

transient responses of proposed system in terms of the frequency deviation in areas 1-4, and tie-line power deviation after 1% step load perturbation are depicted in Figs. 11(a)-(d) and 12(a)-(b). Typical transient specifications in terms of settling time and peak over/undershoot of system oscillations are observed from Figs. 11(a)-(d) and 12(a)-(b) and presented in Tables 6 and 7. To show the superiority of proposed PSO tuned ADRC-TCSC controller, simulation results are compared with those results obtained by other controllers like ADRC-TCPS controller, and ADRC approach for the similar test system and comparative results are given in Table 6 and 7 and Figs. 11(a)-(d) and 12(a)-(b). It can be seen from Tables 6 and 7 and Figs. 11(a)-(d) and 12(a)-(b) that proposed controller outperforms and appears to be more advantageous than the other controllers and satisfying the demand for LFC problem.

5.3 Sensitivity analysis

In order to investigate the potentiality and robustness of the proposed controller, sensitivity analysis is performed for Test 2; under a wide change in system parameters and loading conditions [2, 5, 39]. Sensitivity is defined as the ability of the system to perform effectively while its variables are changed within a certain tolerable range [2, 5, 39]. Taking one at a time, the operating load conditions, governor time constant of thermal plants (T_g), steam turbine reheat time constant (T_r), steam turbine reheat constant (K_r), and the synchronizing coefficient (B) are changed in the range of -50% to +50% in steps of 25% from their nominal values, individually. The quantitative analysis in terms of settling times, and peak/undershoots with these changed conditions for 0.01 p.u step load perturbation in area-1 are summarized in Table 8. The dynamic responses with aforementioned uncertainties are depicted in Figs. 13(a)-(d). It is inferred that from Table 8, and Figs. 13(a)-(d), there is insignificant impact of the changes in the system loading condition and parameters on the obtained results in that the frequencies and transmission-line power fluctuations are suppressed as well. Thus, the sensitivity analysis show that proposed ADRC-TCSC coordinated controller is quite robust; since, the optimized ADRC-TCSC controller at the nominal loading condition with nominal parameters performs satisfactorily under the uncertainty scenarios. Thereby, the optimal parameters of the controller once set for nominal condition need not to be set again for $\pm 50\%$ variations in the system parameters and loading condition.

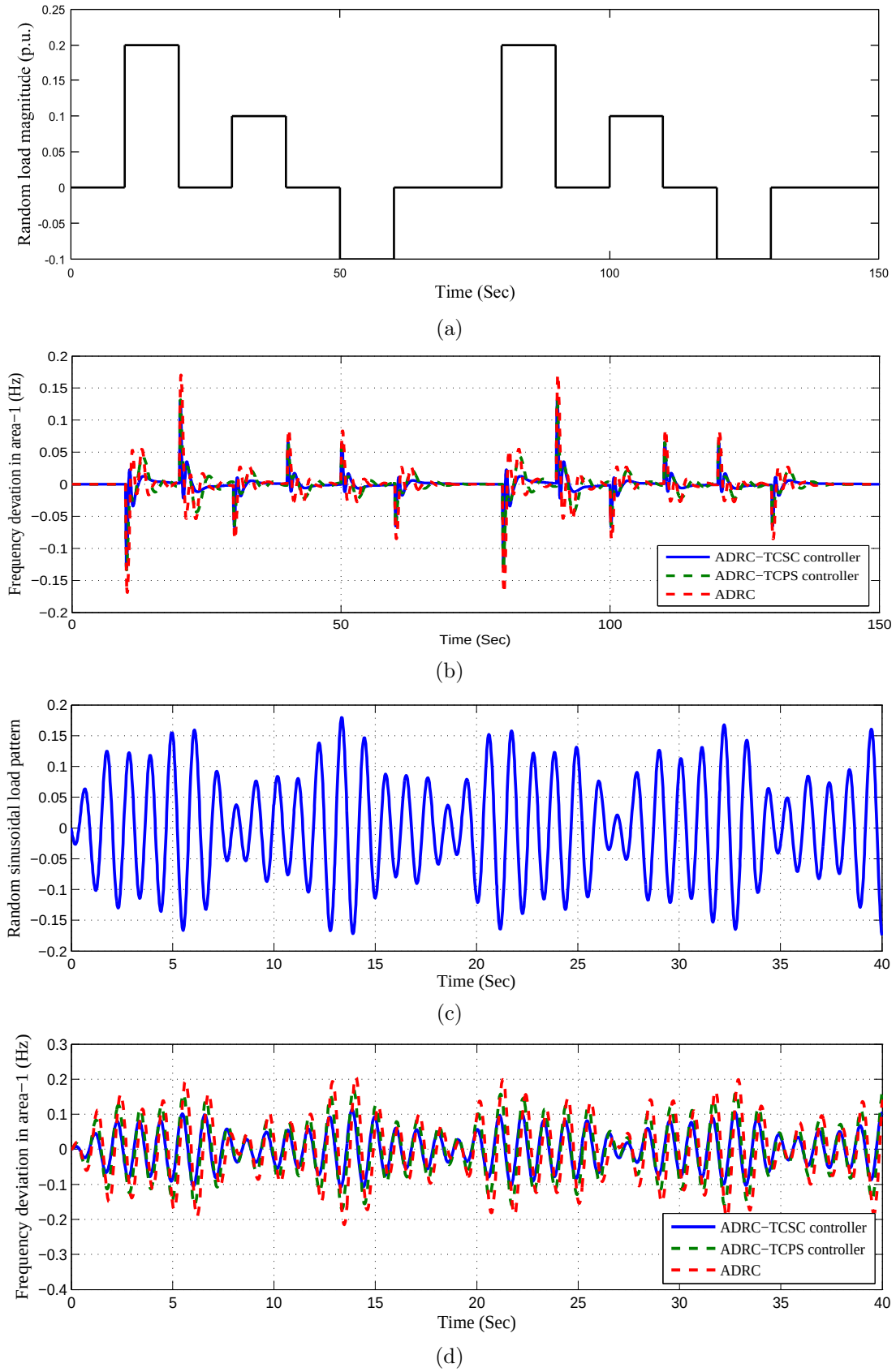


Fig. 14 (a) Random step load perturbations, (b) change in frequency in area-1 for varying step load applied to area-1; (c) Sinusoidal load perturbation, (d) change in frequency in area-1 for sinusoidal load perturbation.

Table 7 Comparative system analysis for Test 2 in terms of peak over/undershoot.

Controller	Peak overshoot						Peak undershoot ($-ve$)					
	Δf_1	Δf_2	Δf_3	Δf_4	$\Delta P_{Tieth-th}$	$\Delta P_{Tieth-hy}$	Δf_1	Δf_2	Δf_3	Δf_4	$\Delta P_{Tieth-th}$	$\Delta P_{Tieth-hy}$
ADRC	0.0027	0.0018	0.0046	0.0046	0.00020	0.00090	0.0084	0.0027	0.0057	0.0057	0.0017	0.0016
ADRC-TCPS	0.0021	0.0016	0.0028	0.0028	0.00030	0.00020	0.0065	0.0021	0.0041	0.0041	0.0012	0.0010
ADRC-TCSC	0.0011	0.0006	0.0008	0.0008	0.00007	0.00005	0.0063	0.0018	0.0028	0.0028	0.0011	0.0004

Table 8 Sensitivity analysis of Test 2:(Four-area hydro-thermal) with the proposed controller.

Parameter variation	%Change	Settling time (s)						Peak undershoot ($-ve$)					
		Δf_1	Δf_2	Δf_3	Δf_4	$\Delta P_{Tieth-th}$	$\Delta P_{Tieth-hy}$	Δf_1	Δf_2	Δf_3	Δf_4	$\Delta P_{Tieth-th}$	$\Delta P_{Tieth-hy}$
Nominal	No change	4.67	4.87	4.63	4.63	10.20	4.10	0.0063	0.0018	0.0028	0.0028	0.00110	0.00040
T_g	+50	4.71	4.89	4.92	4.92	10.35	4.15	0.0076	0.0024	0.0032	0.0032	0.00130	0.00053
	+25	4.69	4.70	4.70	4.70	10.30	4.12	0.0070	0.0021	0.0031	0.0031	0.00120	0.00047
	-25	4.53	4.10	4.50	4.50	10.10	4.00	0.0056	0.0015	0.0027	0.0027	0.00100	0.00041
	-50	4.53	4.00	4.50	4.50	10.10	4.00	0.0050	0.0015	0.0026	0.0026	0.00100	0.00039
T_r	+50	4.92	4.80	4.69	4.69	10.40	4.15	0.0065	0.0019	0.0029	0.0029	0.00110	0.00044
	+25	4.91	4.69	4.68	4.68	10.30	4.13	0.0064	0.0018	0.0029	0.0029	0.00110	0.00043
	-25	4.90	4.65	4.62	4.62	10.10	4.05	0.0064	0.0018	0.0028	0.0028	0.00110	0.00042
	-50	4.90	4.65	4.62	4.62	10.10	4.05	0.0063	0.0017	0.0027	0.0027	0.00110	0.00041
K_r	+50	4.72	3.99	4.17	4.17	10.00	4.21	0.0056	0.0011	0.0019	0.0019	0.00070	0.00030
	+25	4.69	4.03	4.57	4.57	10.00	4.23	0.0056	0.0014	0.0023	0.0023	0.00090	0.00035
	-25	5.22	5.57	4.60	4.60	10.91	4.92	0.0076	0.0024	0.0037	0.0037	0.00013	0.00056
	-50	4.74	5.58	5.76	5.76	10.99	5.53	0.0090	0.0037	0.0051	0.0051	0.00018	0.00080
B	+50	4.68	4.57	4.41	4.41	10.20	4.09	0.0061	0.0013	0.0024	0.0024	0.00090	0.00039
	+25	4.78	4.54	4.63	4.63	10.20	4.10	0.0062	0.0015	0.0026	0.0026	0.00010	0.00041
	-25	4.96	5.22	5.28	5.28	10.20	4.15	0.0066	0.0021	0.0032	0.0032	0.00012	0.00046
	-50	5.42	5.22	5.46	5.46	10.20	4.30	0.0069	0.0026	0.0035	0.0035	0.00013	0.00051

5.4 Comparative performance evaluation under different load perturbation patterns

To analyze the effectiveness of the suggested controller via other controllers, the analysis is performed for different load perturbation such as step load and sinusoidal load. Fig. 14(a) depicts a step load perturbation of varying amplitude with a period of 150 (s) and width of 10 (s) is subjected to area-1 without changing the optimal values of the proposed controller gains [2, 5, 34]. The change in frequency is highlighted in Fig. 14(b). It is observed from Fig. 14(b) that the oscillation is significantly reduced by employing ADRC with TCSC device in series with the transmission-line compared to ADRC-TCPS and ADRC controllers.

Further, in order to assess the effectiveness of the current approach, a sinusoidal load change represented by Eq. (66) varying the amplitude is utilized to area-1 [2, 5]. The expression for sinusoidal load change is as follows:

$$\Delta P_L = 0.03 \sin(4.36t) + 0.05 \sin(5.3t) - 0.1 \sin(6t) \quad (66)$$

Fig. 14(c) exhibits the performance of the sinusoidal load perturbation. The incremental frequency regarding area-1 is displayed in Fig. 14(d). It is cleared that from Fig. 14(d), the frequency oscillations are reduced when used TCSC coordinated ADRC controller compared with ADRC-TCPS controller and ADRC alone.

On the whole, the coordinated application of ADRC-TCSC shows sufficient robustness to random load change. Thus, it can conclude that the proposed approach could be applied to power system where the major uncertainty exists like variation in system parameters and change in load patterns.

6 Conclusion

In this article, an attempt has been made to develop a robust ADRC controller for LFC of interconnected multi-area power systems. To enhance the system responses further, FACTS devices like TCSC controller is included in the system model. The superiority of the proposed controller is demonstrated by comparing the results with ADRC-TCPS and ADRC controllers. The suggested approach is further extended and subjected to four-area hydro-thermal power plants. The parameters of the TCSC and TCPS coordinated with ADRC controllers are optimized by using particle swarm optimization (PSO) algorithm employing an ITAE criterion. From the simulation results, it is observed that significant improvements in the dynamic responses are attained with coordinated application of proposed controller. Furthermore, the sensitivity analysis is carried out to assess the robustness of the system to wide change in the operating conditions and system parameters. Finally the effectiveness of suggested approach is appraised at differ-

ent load perturbation like step load and sinusoidal load. It is observed that the developed controller is robust and performs satisfactorily with variations in operating conditions, system parameters and load perturbation.

Declaration of conflicting interest:

The authors declare that there is no conflict of interest.

Funding:

This work was supported by the National Natural Science Foundation of China under the grants (No. 61871221, 61273076) and Chinese governmental scholarship (CSC No. 2015GXZT30).

References

- [1] P. Kundur, N. J. Balu, and M. G. Lauby, *Power system stability and control*, vol. 7. McGraw-hill New York, 1994.
- [2] R. K. Sahu, S. Panda, and G. C. Sekhar, "A novel hybrid pso-ps optimized fuzzy pi controller for agc in multi area interconnected power systems," *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 880–893, 2015.
- [3] K. Vrdoljak, N. Perić, and I. Petrović, "Sliding mode based load-frequency control in power systems," *Electric Power Systems Research*, vol. 80, no. 5, pp. 514–527, 2010.
- [4] A. Gomaa Haroun and Y.-Y. Li, "Ant lion optimized fractional order fuzzy pre-compensated intelligent pid controller for frequency stabilization of interconnected multi-area power systems," *Applied System Innovation*, vol. 2, no. 2, p. 17, 2019.
- [5] P. C. Pradhan, R. K. Sahu, and S. Panda, "Firefly algorithm optimized fuzzy pid controller for agc of multi-area multi-source power systems with upfc and smes," *Engineering Science and Technology, an International Journal*, vol. 19, no. 1, pp. 338–354, 2016.
- [6] Y. Arya, N. Kumar, and S. Sinha, "Fuzzy logic based load frequency control of multi-area electrical power system considering non-linearities and boiler dynamics," *International Energy Journal*, vol. 13, no. 2, 2012.
- [7] N. V. Kumar and M. M. T. Ansari, "A new design of dual-mode type-ii fuzzy logic load frequency controller for interconnected power systems with parallel ac–dc tie-lines and superconducting magnetic energy storage unit," *Energy*, vol. 89, pp. 118–137, 2015.
- [8] A. Gomaa Haroun and L. Yin-Ya, "A novel optimized fractional-order hybrid fuzzy intelligent pid controller for interconnected realistic power systems," *Transactions of the Institute of Measurement and Control*, vol. 41, no. 11, pp. 3065–3080, 2019.
- [9] E. Çam and I. Kocaarslan, "Load frequency control in two area power systems using fuzzy logic controller," *Energy conversion and Management*, vol. 46, no. 2, pp. 233–243, 2005.
- [10] R. K. Sahu, S. Panda, and N. K. Yegireddy, "A novel hybrid debs optimized fuzzy pi/pid controller for load frequency control of multi-area interconnected power systems," *Journal of Process Control*, vol. 24, no. 10, pp. 1596–1608, 2014.
- [11] Ş. Sönmez and S. Ayasun, "Gain and phase margins based delay-dependent stability analysis of single-area load frequency control system with constant communication time delay," *Transactions of the Institute of Measurement and Control*, vol. 40, no. 5, pp. 1701–1710, 2018.
- [12] H. Bevrani and T. Hiyama, "Robust decentralised pi based lfc design for time delay power systems," *Energy Conversion and Management*, vol. 49, no. 2, pp. 193–204, 2008.
- [13] W. Tan, "Unified tuning of pid load frequency controller for power systems via imc," *IEEE Transactions on power systems*, vol. 25, no. 1, pp. 341–350, 2009.
- [14] V. Çelik, M. T. Özdemir, and G. Bayrak, "The effects on stability region of the fractional-order pi controller for one-area time-delayed load–frequency control systems," *Transactions of the Institute of Measurement and Control*, vol. 39, no. 10, pp. 1509–1521, 2017.
- [15] J. Nanda, A. Mangla, and S. Suri, "Some new findings on automatic generation control of an interconnected hydrothermal system with conventional controllers," *IEEE Transactions on energy conversion*, vol. 21, no. 1, pp. 187–194, 2006.

- [16] K. S. Parmar, S. Majhi, and D. Kothari, "Load frequency control of a realistic power system with multi-source power generation," *International Journal of Electrical Power & Energy Systems*, vol. 42, no. 1, pp. 426–433, 2012.
- [17] A. R. Meena and S. S. Kumar, "Genetically tuned fuzzy pid controller in two area reheat thermal power system," *Russian Electrical Engineering*, vol. 87, no. 10, pp. 579–587, 2016.
- [18] R. K. Mudi and N. R. Pal, "A robust self-tuning scheme for pi-and pd-type fuzzy controllers," *IEEE Transactions on fuzzy systems*, vol. 7, no. 1, pp. 2–16, 1999.
- [19] R. K. Mudi and N. R. Pal, "A self-tuning fuzzy pi controller," *Fuzzy sets and systems*, vol. 115, no. 2, pp. 327–338, 2000.
- [20] N. E. Y. Kouba, M. Menaa, M. Hasni, K. Tehrani, and M. Boudour, "A novel optimized fuzzy-pid controller in two-area power system with hvdc link connection," in *2016 International Conference on Control, Decision and Information Technologies (CoDIT)*, pp. 204–209, IEEE, 2016.
- [21] R. Poli, J. Kennedy, and T. Blackwell, "Particle swarm optimization," *Swarm intelligence*, vol. 1, no. 1, pp. 33–57, 2007.
- [22] H. Gozde and M. C. Taplamacioglu, "Automatic generation control application with craziness based particle swarm optimization in a thermal power system," *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 1, pp. 8–16, 2011.
- [23] S. S. Dhillon, J. S. Lather, and S. Marwaha, "Multi area load frequency control using particle swarm optimization and fuzzy rules," *Procedia Computer Science*, vol. 57, pp. 460–472, 2015.
- [24] A. Gomaa Haroun and Y.-y. Li, "A novel optimized hybrid fuzzy logic intelligent pid controller for an interconnected multi-area power system with physical constraints and boiler dynamics," *ISA transactions*, vol. 71, pp. 364–379, 2017.
- [25] S. S. Dhillon, J. Lather, and S. Marwaha, "Multi objective load frequency control using hybrid bacterial foraging and particle swarm optimized pi controller," *International Journal of Electrical Power & Energy Systems*, vol. 79, pp. 196–209, 2016.
- [26] L. Dong, Y. Zhang, and Z. Gao, "A robust decentralized load frequency controller for interconnected power systems," *ISA transactions*, vol. 51, no. 3, pp. 410–419, 2012.
- [27] L. Dong and Y. Zhang, "On design of a robust load frequency controller for interconnected power systems," in *Proceedings of the 2010 American Control Conference*, pp. 1731–1736, IEEE, 2010.
- [28] K. Nagarjuna and M. Krishnarayalu, "Adrc for two area-lfc," *International Journal of Engineering Research & Technology (IJERT) Vol*, vol. 3, pp. 141–146, 2014.
- [29] S. Padhan, R. K. Sahu, and S. Panda, "Automatic generation control with thyristor controlled series compensator including superconducting magnetic energy storage units," *Ain Shams Engineering Journal*, vol. 5, no. 3, pp. 759–774, 2014.
- [30] K. Zare, M. T. Hagh, and J. Morsali, "Effective oscillation damping of an interconnected multi-source power system with automatic generation control and tcsc," *International Journal of Electrical Power & Energy Systems*, vol. 65, pp. 220–230, 2015.
- [31] M. Elsis, M. Soliman, M. Aboelela, and W. Mansour, "Bat inspired algorithm based optimal design of model predictive load frequency control," *International Journal of Electrical Power & Energy Systems*, vol. 83, pp. 426–433, 2016.
- [32] B. An and Z. E. Jeyakumar, "Fuzzy logic based load frequency control of hydro-thermal system with nonlinearities," *International Journal of Electrical and Power Engineering*, vol. 3, no. 2, pp. 112–118, 2009.
- [33] J. Morsali, K. Zare, and M. T. Hagh, "Performance comparison of tcsc with tcps and sssc controllers in agc of realistic interconnected multi-source power system," *Ain Shams Engineering Journal*, vol. 7, no. 1, pp. 143–158, 2016.
- [34] R. K. Sahu, S. Panda, A. Biswal, and G. C. Sekhar, "Design and analysis of tilt integral derivative controller with filter for load frequency control of multi-area interconnected power systems," *ISA transactions*, vol. 61, pp. 251–264, 2016.
- [35] P. Bhatt, R. Roy, and S. Ghoshal, "Comparative performance evaluation of smes–smes, tcps–smes and sssc–smes controllers in automatic generation

- control for a two-area hydro-hydro system,” *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 10, pp. 1585–1597, 2011.
- [36] B. Sun and Z. Gao, “A dsp-based active disturbance rejection control design for a 1-kw h-bridge dc-dc power converter,” *IEEE Transactions on Industrial Electronics*, vol. 52, no. 5, pp. 1271–1277, 2005.
- [37] C. Huang, J. Li, S. Mu, and H. Yan, “Linear active disturbance rejection control approach for load frequency control of two-area interconnected power system,” *Transactions of the Institute of Measurement and Control*, vol. 41, no. 6, pp. 1562–1570, 2019.
- [38] R. K. Sahu, S. Panda, and S. Padhan, “Optimal gravitational search algorithm for automatic generation control of interconnected power systems,” *Ain Shams Engineering Journal*, vol. 5, no. 3, pp. 721–733, 2014.
- [39] R. K. Sahu, S. Panda, and U. K. Rout, “De optimized parallel 2-dof pid controller for load frequency control of power system with governor dead-band nonlinearity,” *International Journal of Electrical Power & Energy Systems*, vol. 49, pp. 19–33, 2013.