Comparative Performance Analysis of Deregulated Hydrothermal System With Dual Mode Controller and Diverse Source of Generation Employing Imperialistic Competition Algorithm

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ABSTRACT This paper presents an accomplishment of Load Frequency Control (LFC) under deregulated environment using Imperialistic Competition Algorithm (ICA) based Dual Mode Controller (DMC). The Capacitive Energy Storage (CES) and Static Synchronous Series Compensator (SSSC) have been successfully used to improve the performance of the system dynamics. The optimization techniques are beneficial to the design of the Dual Mode Controller and overcome the drawbacks identified by the conventional controllers. The traditional Load Frequency Control system is adapted to interpret bilateral contracts on the system. The performance index is calculated by using the integral of the square of error technique to optimize the controllers of the Load Frequency Control system. The simulation analysis reveals that due to the presence of the Imperialistic Competition Algorithm-based Dual-Mode Controller, the performance of the system improves in terms of peak time, settling time, and overshoot, and also performance index is lesser than the system without the Imperialistic Competition Algorithm based Dual Mode Controller following a load disturbance in either of the areas.

INDEX TERMS Deregulation, load frequency control, capacitive energy storage, static synchronous series compensator, imperialistic competition algorithm, dual mode controller, integral controller.

NOMENCLATURE

LFC	- Load Frequency Control.
AGC	- Automatic Generation Control.
ICA	- Imperialistic Competition Algorithm.
DPM	- Disco Participation Matrix.
cpf	- Contract Participation Factor.
apf	- ACE Participation FActor.
DMC	- Dual Mode Controller.
CES	- Capacitive Energy Storage.
SSSC	- Synchronous Series Compensator.
ISO	- Independent System Operator.
FACTS	- Flexible AC Transmission Systems.
IC	- Integral Controller.
PIC	- Proportional Integral Controller.
PID	- Proportional Integral Derivative.
TCPS	- Thyristor Controlled Phase Shifters.
WOA	- Whale Optimization Algorithm.
UC	- unit commitment.
ACE	- Area Control Error.
PI	- Performance Index.
Δf_1	- Change in Frequency in Area 1.
Δf_2	- Change in Frequency in Area 2.
$\Delta P_{tie1,2}$	- Change in Tie-Line Power.
P_D	- Real Power Demand.
Q_D	- Reactive Power Demand.
ΔP_D	- Change in Real Power Demand.
ΔQ_D	- Change in Reactive Power Demand.
$P - f$	- Real Power – Frequency.
$Q - V$	- Reactive Power - Voltage.

R	- Speed Regulation.
T_P	- Peak Time.
T_S	- Settling Time.
M_P	- Peak Overshoot.
T_R	- Rise Time.
T_t	- Time Constant of Turbine.
T_{12}	- Synchronizing Coefficient.
T_p	- Time Constant of Turbo Generator.
ΔP_{SSSC}	- Change in Power Output of SSSC.
K_{SSSC}	- Gain of the SSSC.
T_{SSSC}	- Time Constant of SSSC.
K_{CES}	- Gain of the CES.
T	- Time Constants.
K_i	- Gain of the Integral Controller.
K_p	- Gain of the Proportional Controller.
K_P	- Power System Gain.
ε	- Specified limit of the Error Signal.
$Coun_i$	- Position of the ith Country.
N_{coun}	- No. of Countries in the Imperialistic.
C_1, C_2	- Acceleration Coefficients.
Col_n^i	- Position of ith Colony of the nth Empire.
Ic_n	- Cost of nth Empire.
IC_n	- Normalized Cost.
H	- Inertia Constant.
f^o	- Initial Frequency.
I_n	- Position of nth Empire.
IP_n	- Initial Number of Colonies of the nth Empire.
n	- Number of Iterations.
N_{col}	- Remaining Countries form n^{th} Empire.
n_{coun}	- Total Number of Countries.
$newcol_n^i$	- Updated Position of Colonies of the nth Empire.
N_{imp}	- Most Powerful Countries from nth Empire.
NTP_n	- Normalized Cost of nth Empire.
TP_n	- Total Power of nth Empire.
ps_n	- Possession Probability of n_{th} Empire.
ζ	- Positive Number Less than 1.
α, β	- Weighting Factors.

I. INTRODUCTION

The effective operation of a power system has essential that its frequency is maintained constant within acceptable limits. There are two aspects to maintaining frequency as constant. One is the coordination of Generation – Load schedule, whereas the second is planned power flow in the tie-line of the system. These two are the most critical challenges in operating a hydrothermal system during the dynamic operation [1], [2]. Currently, the power sector is undergoing a deregulated market environment that affords power at controlled tariffs to a system that establishes firms demanding everyone to sell power at lesser tariffs. The Transmission Companies (TransCos), Distribution Companies (DisCos), and Generating Companies (GenCos) are the several units of such a type of system. The generation in power system control concepts under deregulation in [3]. A new framework

for implementing load following contracts in price-based operation and the execution of Independent System Operator (ISO) is a practical working of the system with balancing the economics have been deliberated in [4].

It was shown that the customized AGC scheme included agreement data and measurements, which improved the control signals to be dispatched to controllers. The above scheme included Area Control Error (ACE) as a fraction of the control error signal. It satisfied the North American Reliability Council (NERC) performance criteria. It also explained an interesting case to determine if any of the contracts were violated, and this case study results with three sets were presented in [5].

The LFC problem is simulated comprehensively and has been evaluated under the deregulated environment in [6]. The automatic generation control could be simulated and optimized after deregulation. The idea of bilateral contracts and DPM was introduced and implemented in the two-area system. The system's response to contract violations was also studied and reported [7]. The dynamic response of the CES unit with a small volume to the system encouragingly progresses been presented in [8]. Several FACTS devices have been extensively active to offer enhanced stability for the control of power systems networks. The combination of Static Synchronous Series Compensator and Capacitive Energy Storage are realized as vital devices to get better dynamic response of the system [9].

The integral of the square of error is considered in the search for optimal Automatic Generation Control (AGC) parameters. The various optimization techniques used in two areas of the hydrothermal system in the presence of Static Synchronous Series Compensator (SSSC) and Capacitive Energy Storage (CES) under deregulation are considered to exemplify the optimum parameter search. The results demonstrate the superior working of PSO over others in the tuning of AGC [10]. A detailed study of the Imperialistic Competition Algorithm for optimization techniques was presented in [11].

In the hydrothermal system, the gain of the controllers are optimized by the Imperialistic Competition Algorithm with CES and Static Synchronous Series Compensator under the deregulated scenario [12]. The continuous and discrete model of Load Frequency Control of two areas hydrothermal system with the traditional level of controllers and selection of the appropriate value of sampling period and parameters of speed regulation has investigated with generation rate constraints is given in [13]. The performance of electric governor, mechanical governor, and single-stage and two-stage reheat turbines on dynamic responses has been considered. Also, the choice of the parameter of speed regulation and sampling period has been scrutinized. The performance is examined with the controller gains of Integral Controller (IC), Proportional Integral Controller (PIC), and Proportional Integral Derivative (PID) in the interconnected Automatic Generation Control system are optimized by Bacterial Foraging (BF) technique is given in [14]. The IC gains and electric governor parameters were optimized using the ISE criterion. The concept of IC and PC

are used in the design of DMC, and the main benefit of PIC is that, it reduces the error in steady-state is nearly zero but typically gives large deviations in frequency are given in [15]. The parameters of speed governors and turbines and their transfer function models can be found in the IEEE committee report [16].

Collective modeling of the reservoirs caught up in gas systems and electric power and locations of both the networks are crucial features to be well-thought-out in planning energy resources [17]. The different energy storage amenities are considered for modeling the system and system optimization to the natural gas and electric power systems. The tactic can be handled by the interdependent operation between the cascade of hydro plants, and the coordination of hydrothermal problems characterizes it. The dissimilarity of the circuit capacity and transmission line losses are also considered [18]. The studies have been conducted for models of nonlinear and linear speed governor mechanisms with the models of the turbine in hydro systems are suggested by the report of the IEEE committee [19].

The Thyristor Controlled Phase Shifters (TCPS) and CES are positioned in the tie line of the system, and their various methods of control strategy are proposed in [20]. The system has been studied with the effect of unit commitment (UC) using PIDN-FOPD for various approaches. The Whale optimization algorithm (WOA) is effectively used for concurrent optimization of various controllers mentioned above. The analysis has explored that the system dynamics are improved by using WOA [21].

The recent literature presented a critical study on the impact of AE-FC units on AGC performance of interconnected two areas non-reheat thermal system, PV-reheat thermal, and multi-source hydro-thermal system (MSHTS). Further, the effects of STG and geothermal (GT) plants are recently inspected in two and three-area deregulated systems [22]. To improve FPI performance, some researchers have implemented different optimization methods to tune the FPID controller. Hybrid harmony search-cuckoo optimization algorithms are employed efficiently to tune input/output SFs of FPID controllers for different types of systems [23]. Recently, Fractional Order (FO) controllers have been implemented in power system models, and desirable results have been observed.

A FO fuzzy PID (FOFPID) controller was tuned recently using ICA [24]. Further, the literature review indicates that the hybridization of the fuzzy controller with the FO controller shows enhanced performance compared to fuzzy hybridized with a conventional controller. A proficient frequency regulation scheme has been explored in this work for two interconnected hybrid microgrids (hμGs) comprised of multiple renewable energy sources. A new optimization algorithm has been formulated to replicate the photo-tactic swarming behavior of green leafhoppers named Green Leaf-hopper Flame optimization algorithm (GLFOA) to tune the system controllers. The superiority of GLFOA is confirmed by comparing the performance with several

popular optimization algorithms [25]. A unique interconnected hybrid microgrid (IHM) double area system is developed that includes a novel combined solar gas turbine (CSGT), biodiesel generator (BDG), wind turbine generator (WTG), and energy storage units, and DC link (DCL) using tilt-integral-derivative (TID) controller. A recently developed metaheuristic algorithm, Harris's hawk optimization (HHO) technique, is used to obtain controller gain constraints. Use of CSGT in 2- area IHM for load frequency control (LFC) is a novel work and uses the TID controller and HHO technique for tuning the controllers' parameters [26].

Automatic Generation Control maintains the balance of grid power, and also it is used to strengthen the abrupt disturbance of frequency within the system power grid. The approach is implemented to plan a system controller for the depreciation of various issues in AGC within the open market structure of the system. Under deregulation, a multi-area hydrothermal system examines countless LFC problems in the open market scenario. But all of it concerning Load Frequency Control of two area systems with the competitive market environment does not examine the existence of Dual Mode Controller and Capacitive Energy Storage and Static Synchronous Series Compensator with Imperialistic Competition Algorithm. Therefore, this paper deals with designing a Dual Mode Controller for Capacitive Energy Storage and an SSSC-based multi-area interconnected system under deregulation employing the Imperialistic Competition Algorithm.

For better understanding, the novel contributions of this work are highlighted as follows:

(i) To propose a Load Frequency Control for novel ICA tuned Dual Mode Controller for multi-area based hydrothermal system.

(ii) To exemplify the proposed technique by incorporating Capacitive Energy Storage and SSSC to damp the tie-line power oscillations.

(iii) To authenticate the strength of the proposed method, the simulation results are compared to the various intelligent control strategies in the state-of-the-art literature.

This work is organized as follows: The transfer functional block diagram of LFC of two areas of the hydrothermal system under deregulated environment is discussed in the second section. The design of Capacitive Energy Storage and its block diagram is presented in the third section. The design and accomplishment of SSSC and its transfer functional block diagram is presented in section 4. The fifth Section focused on designing and implementing the dual-mode controller's continuous and discontinuous mode of operation. The incorporation of the imperialistic competition algorithm and its implementation is presented in the sixth section. Finally, the seventh section presents the results and discussions, followed by the conclusion.

II. LOAD FREQUENCY CONTROL UNDER DEREGULATED SCENARIO
The LFC of interconnected two area systems has been examined with a reheat unit in area 1 and a hydro unit in area 2.
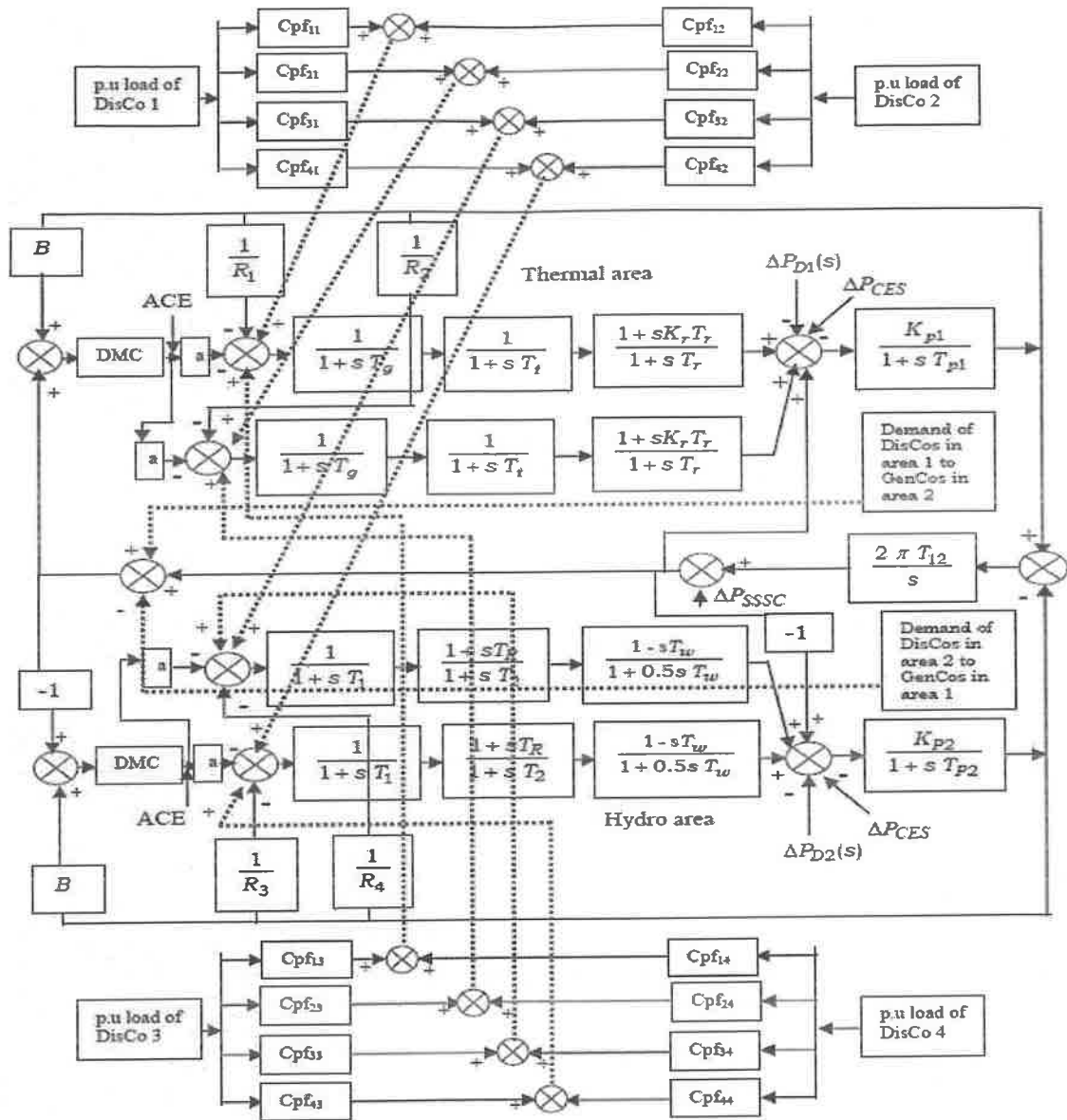
FIGURE 1. The DMC based LFC of hydrothermal system under deregulation with SSSC and CES.

The transfer function models of the Load Frequency Control system are given in the report of the IEEE committee on system dynamic models [16], and the parameters and specifications are given in Appendix. Fig. 1 indicates the model of the block diagram of the hydrothermal system with multi-area under deregulation, and each area consists of two Discos and three GenCos. The system performance with optimization is calculated through the Integral of Square of Error (ISE) technique [8], namely, Performance Index (PI) is given in (1) is used to compare the performance of the system with several techniques. Where α and β are called weighting factors.

$$PI = \int_0^t (\alpha \cdot \Delta f_1^2 + \beta \cdot \Delta f_2^2 + \Delta P_{tie\,1,2}^2) \quad (1)$$

III. DESIGN AND IMPLEMENTATION OF CAPACITIVE ENERGY STORAGE

This exceptional ability of Capacitive Energy Source compared to the further storage of energy systems like flywheels, pumped hydro, etc., makes it a viable option to be employed in significant applications [8]. This ability of CES allows it to function as a storage entity of energy and afford stability due to disturbances and act as a spinning reserve. The capacitor plays a significant role in making the CES entity capable of damping the oscillations formed due to the abrupt rise or fall of power. The Capacitive Energy Storage unit consists of Power Conversion System (PCS) and a supercapacitor [8]. Many discrete capacitive units are connected in parallel to form the storage capacitor based on the amount of energy storage capacity required. Either frequency deviation or Area
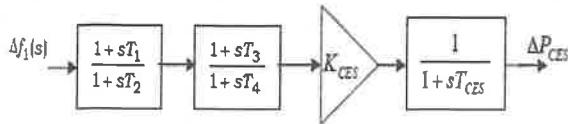
FIGURE 2. CES implemented to LFC.

Control Error (ACE) can be used as the control signal to the CES unit. Fig. 2 [8] indicates the Capacitive Energy Storage block diagram depiction of the unit to the system is given in [8]. Capacitive Energy Storage's edifice comprises gain block K_{CES}, T_{CES} is a time constant, and T_1, T_2, T_3, and T_4 are the time constants of blocks of phase compensation with two stages.

IV. DESIGN AND IMPLEMENTATION OF STATIC SYNCHRONOUS SERIES COMPENSATOR

The Static Synchronous Series Compensator influenced the tie-line power flow by emulating a capacitive or an inductive reactance. It is a voltage source switching converter with self-commutation to control a voltage in quadrature means of the line current [9]. The compensation level can be energetically controlled by altering the magnitude and polarity of the injected voltage V_S. The SSSC can also be operated together in capacitive mode or inductive mode.

Fig. 3 [9] shows the Static Synchronous Series Compensator block diagram is to be integrated into the system [9] to progress the performance. The Static Synchronous Series Compensator structure comprises gain block K_{SSSC}, T_{SSSC} is a time constant, and T_1, T_2, T_3, and T_4 are the time constants of blocks of phase compensation having two stages. The deviation of the frequency of area 1 is the input to the Static Synchronous Series Compensator.
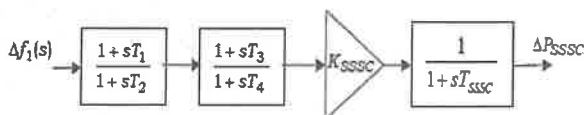

FIGURE 3. SSSC implemented to LFC.

V. DESIGN AND IMPLEMENTATION OF DUAL-MODE CONTROLLER

Integrating the Integral Controller (IC) into the system offers zero steady-state error; however, it results in abnormal settling time and the system overshoot. For the step load, small values of gain of the proportional controller results in a large steady-state error. The immense value of proportional controller gain provides improved steady-state performance except for transient response. So the gain of the proportional controller alone is not suitable for eliminating steady-state error. A general way of reducing the steady-state error is by introducing IC in the system. Suppose the gain of the integrator controller is adequately high. In that case, it gives a highly unfavorable response with a sharply rising peak

overshoot and a low value of peak overshoot due to the small value of integral controller gain. Still, the rise time of the system increases. So the above concept is called DMC, which involves both a proportional and integral controller. The DMC is beneficial for the proper design of the gain of the proportional controller and integral controller. Usually, the overshoot of the system can be abridged by employing a Proportional Controller (PC) [13], [14]. So exertions have been offered in this work to construct a Dual Mode Controller, which includes both integral controller and proportional controller, as shown in Fig. 4 [13]. Based upon the $ACE(t)$ operation of control law that can be interchanged between the different control modes i.e. continuous mode and discontinuous mode. The controller's output is in (2) and (3).

$$\text{if } |ACE(t)| > \varepsilon$$
$$\Delta P_c(t) = -K_p \cdot ACE(t), \qquad (2)$$

and,

$$\Delta P_c(t) = -K_i \int ACE(t)dt$$
$$\text{if } |ACE(t)| < \varepsilon \qquad (3)$$

where $\Delta P_c(t)$ = the output signal of the controller
K_p = proportional controller gain
ε = specified limit of the error signal
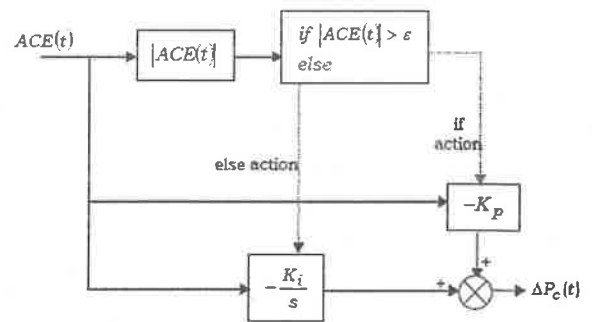K_i = integral controller gain.

FIGURE 4. Proposed DMC control scheme.

The proposed DMC is simple in configuration and easy to put into practice, as it uses the value of Area Control Error (ACE) which is already available in the system. But care should be taken that the hyper switching plane should be specified at every load change.

VI. IMPLEMENTATION OF IMPERIALISTIC COMPETITION ALGORITHM

The concept of the Imperialistic Competition Algorithm was propounded by A. Gargari and Lucas [11]. The Imperialistic Competition Algorithm is a consequence of the conception of imperialistic competitions. The Imperialistic Competition Algorithm is initiated by a preliminary population represented as countries. Imperialists represent the countries that possess the great admirable value of the objective function,

and the discarded countries fit to be the colonies of the respective imperialists. All the respective colonies were spread among the Imperialists based on power. The colonies are afterward moving towards their appropriate imperialist, and respective imperialist's places will be improved based on the certainty. In the next stage, the competition was conducted between the empires, and based on this competition, weaker empires were eliminated. This competition leads to a further increase in the power of the strong empire and diminishes the frail empire's power also; empires are eliminated if they are unable to recover their position. The competitions are conducted for all the empires for the duration of several iterations and result in the formation of only one empire. The remaining empires turn out to be the colonies of this empire. The flowchart of the proposed algorithm implemented for Load Frequency Control of multi-area hydrothermal system under deregulation is given in Fig. 5 [12]. The simulation parameters of the Imperialistic Competition Algorithm are specified in Appendix.
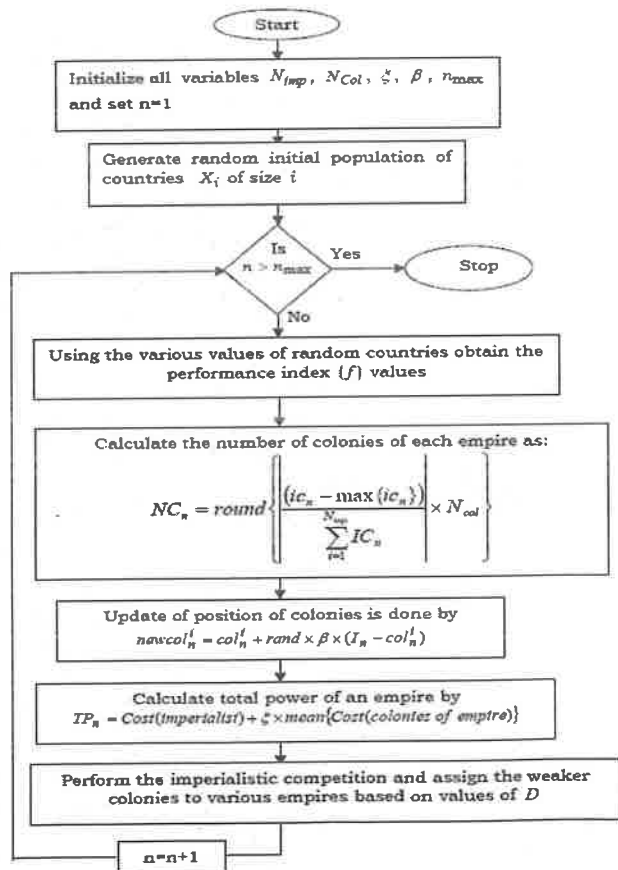
can be defined as $Coun_i = (x_i^1, x_i^2, \ldots x_i^n)$, where $i = 1, 2, 3 \ldots Ncoun$, where N_{coun} be the complete set of countries in the imperialistic.

The function of the variables can find the evaluation of the cost function of the different countries $(x_i^1, x_i^2, \ldots x_i^n)$. The individual country's cost, i.e., C_i can be computed in (4).

$$C_i = f(x_i^1, x_i^2, \ldots x_i^n) \qquad (4)$$

where C_i denoted as cost of the ith country.

The most commanding countries are preferred to formulate the empires, and it is symbolized as N_{imp}. The N_{col} denoted countries which have been leftover are preferred as colonies of these empires. Based on the value of objective function or power, the colonies are equally allocated to the imperialists. For minimization problems, the cost functions are inversely proportional to the individual imperialist's powers. So the value of the normalized costs can be evaluated for the empires in (5) as follows,

$$IC_n = ic_n - \max\{ic_i\} \qquad (5)$$

where ic_n denoted as cost of the nth imperialist and IC_n denoted as normalized cost.

The calculation of the normalized power of each imperialist in (6) is as follows,

$$IP_n = \left| \frac{IC|_n}{\sum_{i=1}^{N_{imp}} IC_n} \right| \qquad (6)$$

where IP_n is denoted as the normalized power of each imperialist. Initially, the total number of colonies of each empire is calculated in (7) as follows,

$$NC_n = round(IP_n \times N_{col}) \qquad (7)$$

where the NC_n is assumed to be the initial number of colonies of the nth empire.

FIGURE 5. Flowchart of imperialistic competition algorithm.

A. INITIAL EMPIRES GENERATION
The initializing the algorithm, countries are generated, and it is denoted as the preliminary population [12]. Generally, in the problem of optimization, the country's position

B. IMPERIALISTS AND COLONIES MOVEMENT
In this stage, the colonies are moved to the imperialists, relevant. The new positions of the colonies of nth the empire are updated in (8) as follows,

$$newcol_n^i = col_n^i + rand \times \beta \times (I_n - col_n^i) \qquad (8)$$

where col_n^i is the position of the ith-colony of nth imperialist and the rand is a random number between 0 to 1, β is a weight factor equal to 1.75, and I_n is the position of nth-imperialist.

C. POSITION OF IMPERIALIST'S UPDATION
The positions of the imperialists are updated based on the cost function or the power of the imperialists. The imperialist attained lower costs than the imperialists were interchanged, and the respective colonies were also moved to the new imperialists based on the new position.

TABLE 1. Performance evaluation of proposed ICA based DMC system.

S. No.	Proposed System	Area 1- Thermal			Area 2- Hydro		
		Peak Time in (sec)	*Overshoot in (Hz)*	*Settling time in (sec)*	*Peak Time in (sec)*	*Overshoot in (Hz)*	*Settling time in (sec)*
1	Conventional Dual Mode Controller	2.21	0.00283042	7.541	0.83	0.00583379	4.241
2	Particle Swarm Optimization	2.155	0.00314339	4.120	0.895	0.00598582	2.760
3	ICA based Integral Controller	2.24	0.0029334	4.106	0.88	0.00593382	2.655
4	ICA based Dual Mode Controller	2.25	0.00287201	4.005	0.87	0.00591586	2.585

D. COMPUTATION OF TOTAL POWER

The empire's power is evaluated by the total powers of respective colonies and the corresponding imperialist. So the whole power of an empire can be determined (9) as:

$$TP_n = Cost(imperialist) + \xi$$
$$\times mean\{Cost(colonies\ of\ empire)\} \quad (9)$$

where TP_n- is the total power of nth-empire and ξ is considered as a positive number, less than 1.

E. CONDUCTING COMPETITIONS

The imperialistic competitions are conducted for each empire, and finally, after the completion, the empires undertake the colonies of other empires. At last, the colonies with less power in the empires can be identified, and competition is conducted to acquire these weaker colonies based on the possession probability. The normalized value of the total power of each empire can be determined in (10).

$$NTP_n = TP_n - \max\{TP_i\} \quad (10)$$

where NTP_n is the normalized power of nth-empire. The possession probability of each empire is in (11).

$$ps_n = \left| \frac{NTP_n}{\sum_{i=1}^{N_{imp}} NTP_i} \right| \quad (11)$$

where ps_n is the possession probability of the nth-empire. The vector PS is subdivided into the colonies of the various empires and can be determined in (12).

$$PS = \lfloor ps_1, ps_2, \ldots ps_{N_{imp}} \rfloor \quad (12)$$

where PS is denoted as possession probability of the imperialist. A random vector employing equivalent size as that of a vector PS is formed in (13) as follows,

$$R = \lfloor r_1, r_2, \ldots r_{N_{imp}} \rfloor \quad (13)$$

$$\begin{bmatrix} 0.1 & 0.0 & 0.3 & 0.4 \\ 0.0 & 0.1 & 0.0 & 0.2 \\ 0.3 & 0.4 & 0.1 & 0.0 \\ 0.2 & 0.0 & 0.2 & 0.1 \\ 0.2 & 0.3 & 0.0 & 0.1 \\ 0.2 & 0.2 & 0.4 & 0.2 \end{bmatrix}$$

FIGURE 6. Disco participation matrix.

TABLE 2. Assessment of PI values.

| S. No.	Proposed Systems	Normal Case	Contract Violation
1	Conventional DMC	2.593×10^{-5}	4.685×10^{-5}
2	Particle Swarm Optimization	1.910×10^{-5}	3.854×10^{-5}
3	ICA based IC	1.897×10^{-5}	3.557×10^{-5}
4	ICA based DMC	1.808×10^{-5}	3.358×10^{-5}

where $r_1, r_2, r_3, \ldots r_{N_{imp}}$ are numbers generated randomly between 0 and 1. The D vector is determined in (14) as follows,

$$D = PS - R = \lfloor ps_1 - r_1, ps_2 - r_2, \ldots ps_{N_{imp}} - r_{N_{imp}} \rfloor \quad (14)$$
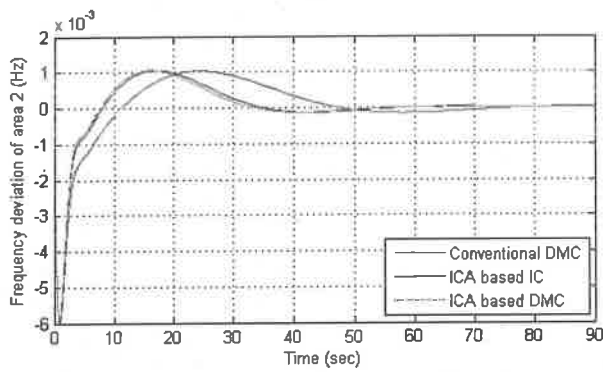
All the colonies of the empire will be shifted to the empires with a high value in the D vector.

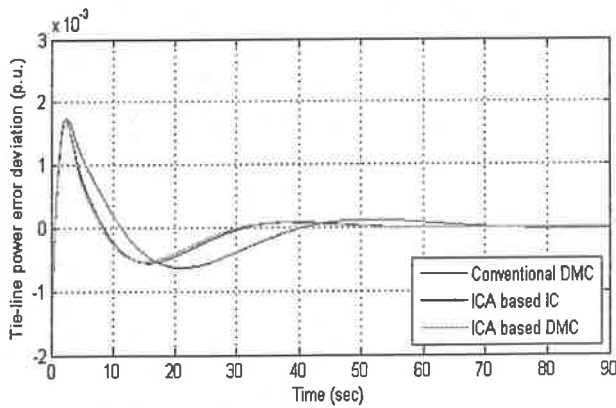### F. POWERLESS EMPIRES AND THEIR ELIMINATION

The empires which have the least power collapsed in the imperialistic competition. Typically, the empire is declared collapsed if all colonies are lost.
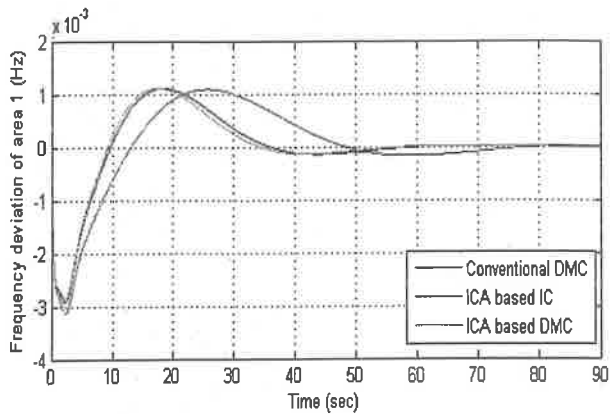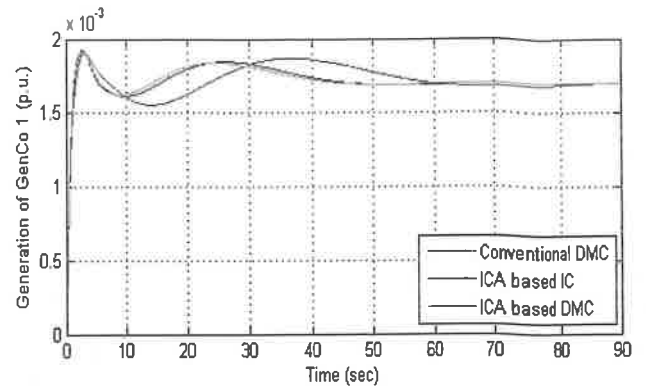
FIGURE 7. a. Deviations of area frequency in area 1 during normal condition. b. Deviations of area frequency in area 2 during normal condition. c. Tie line power error during normal condition.
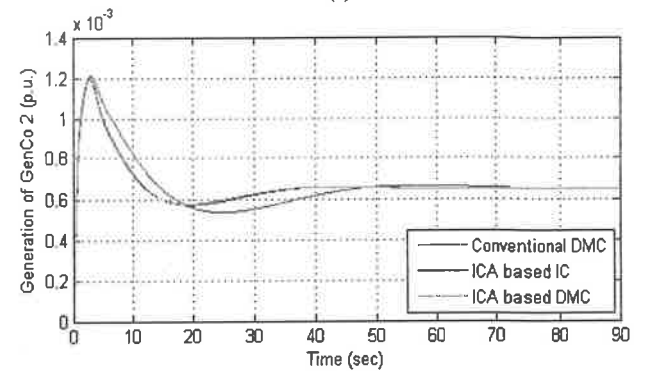

FIGURE 8. a. Generation of GenCo 1 in thermal area during normal condition. b. Generation of GenCo 2 in thermal area during normal condition. c. Generation of GenCo 3 in thermal area during normal condition.

G. CONVERGENCE

Finally, the most powerful empire is declared based on the maximum number of colonies under it. Further, there was no change in the colonies and empire after the declaration of the winner.
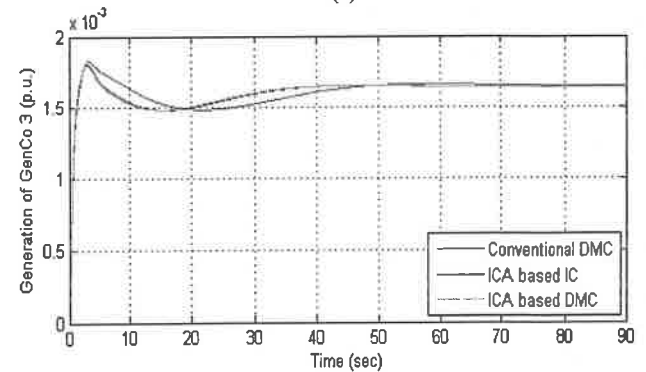
VII. RESULTS AND DISCUSSIONS

In this work, CES and Static Synchronous Series Compensator with the multi-area hydrothermal system are considered under deregulation. The participation of each and every

GenCos in the system of Automatic Generation Control as per the mentioned participation factors: $apf_1 = apf_4 = 0.5$, $apf_2 = apf_3 =$, $apf_5 = apf_6 = 0.25$. A 0.4% step load disturbance is considered in each area. The DPM is considered in this work is given in Fig. 6.

The value of 0.5 is the nominal value of the gain setting considered for the conventional dual-mode controller in each area. So the optimized gain of the integral controllers for the Particle Swarm Optimization technique [10] is 0.3578, and 0.9335 has been attained for areas 1 and 2. The gain settings of 0.8454 and 0.91 have been attained through the
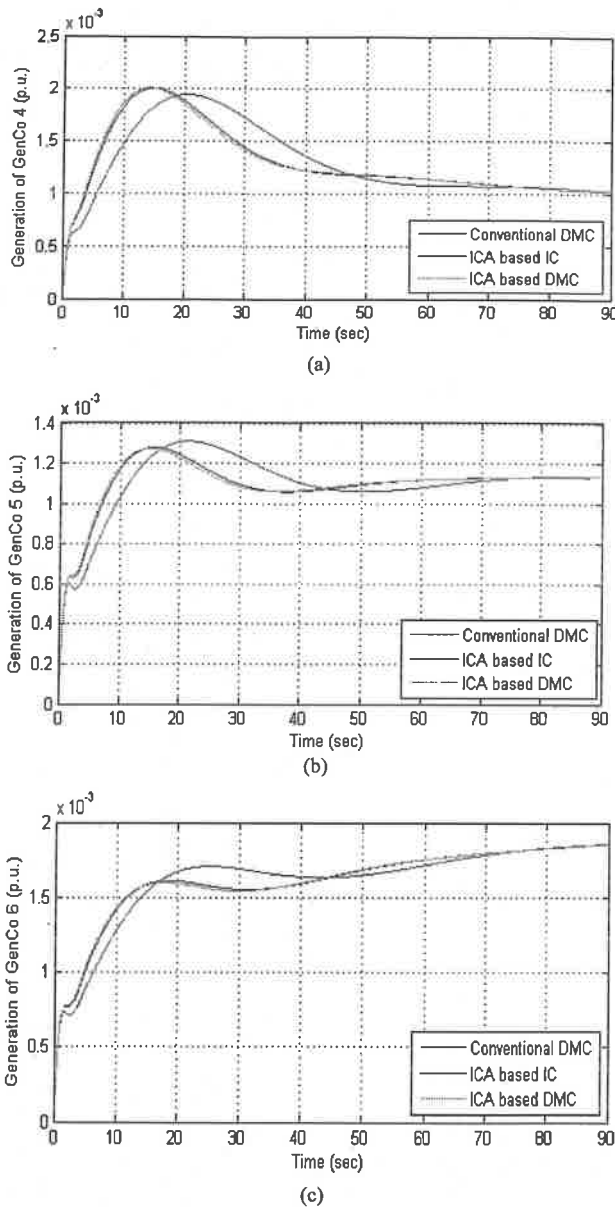
(a)

(b)

(c)

FIGURE 9. a. Generation of GenCo 4 in hydro area during normal condition. b. Generation of GenCo 5 in hydro area during normal condition. c. Generation of GenCo 6 in hydro area during normal condition.

FIGURE 10. Comparison of PI values during normal condition.

Imperialistic Competition Algorithm [12] corresponding to areas 1 and 2. The optimal values of the proportional controller and integral controller gain setting of Dual Mode Controller in both the areas are $K_{i1} = K_{i2} = 0.987$ and $K_{p1} = kp2 = 0.95$ are found by the Imperialistic Competition Algorithm. The value of the proportional gain K_p determines how fast the system responds, whereas the value of the integral gain K_i determines how fast the steady-state error is eliminated. When the value of these gains are more considerable for better control performance. The specified limit of the error signal of $\varepsilon_1 = \varepsilon_2 = 0.02$ has been deliberated to design this work's Dual Mode Controller (DMC). It is also to be
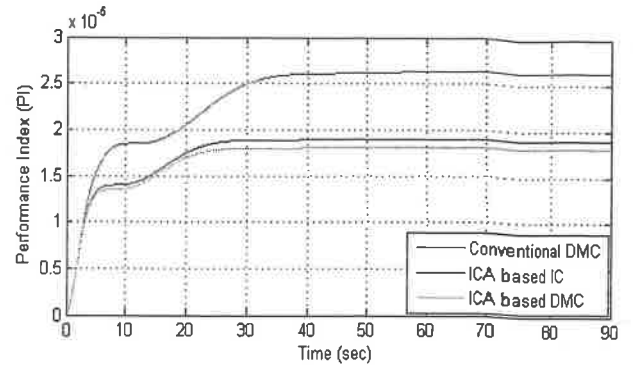
considered that the values of ε_1 and ε_2 might look arbitrary. Still, the values have been selected after carefully studying the system performance under various conditions. The comparison of system performance shown in Table-1 with the conventional dual-mode controller, imperialistic competition algorithm-based integral controller, and imperialistic competition algorithm-based dual-mode controller by frequency deviations in both areas are taken as reference. The overshoot of the system in the thermal area is 0.00287201 Hz, and the hydro area is 0.00591586 Hz for the imperialistic competition algorithm-based dual-mode controller. The settling time of the thermal area is 4.005 sec, and the hydro area is 2.585 sec is less compared with all other methods. The proposed controller gives a lower ripple in the output voltage, reduces the settling time, and keeps the output stable in case of step input. The overshoot of the output voltage during transient time is minimized using the pole-zero cancellation technique. For the system to be stable, the rise time must be less so that the speed of response is increased, and the maximum peak overshoot should also be less. The enhancement of overall system performance with imperialistic competition algorithm-based dual-mode controller can be perceived from Table-1; the dynamic system performance of both areas is improved.

The proposed system Performance Index (PI) value is shown in Table 2 with conventional Dual Mode Controller, Imperialistic Competition Algorithm based Integral Controller (IC), and Imperialistic Competition Algorithm based Dual Mode Controller. It is observed from Table 2 that the performance index of the Imperialistic Competition Algorithm-based Dual Mode Controller for the standard case is 1.08×10^{-5}, and the contract violation case is 3.358×10^{-5}. So the Imperialistic Competition Algorithm-based Dual Mode Controller has a lesser performance index value than all other techniques, which designates that the Imperialistic Competition Algorithm-based Dual Mode Controller has more improved control performance than all other techniques.

The frequency deviation of both the areas under the usual case is depicted in Fig. 7a and 7b. The error deviations in
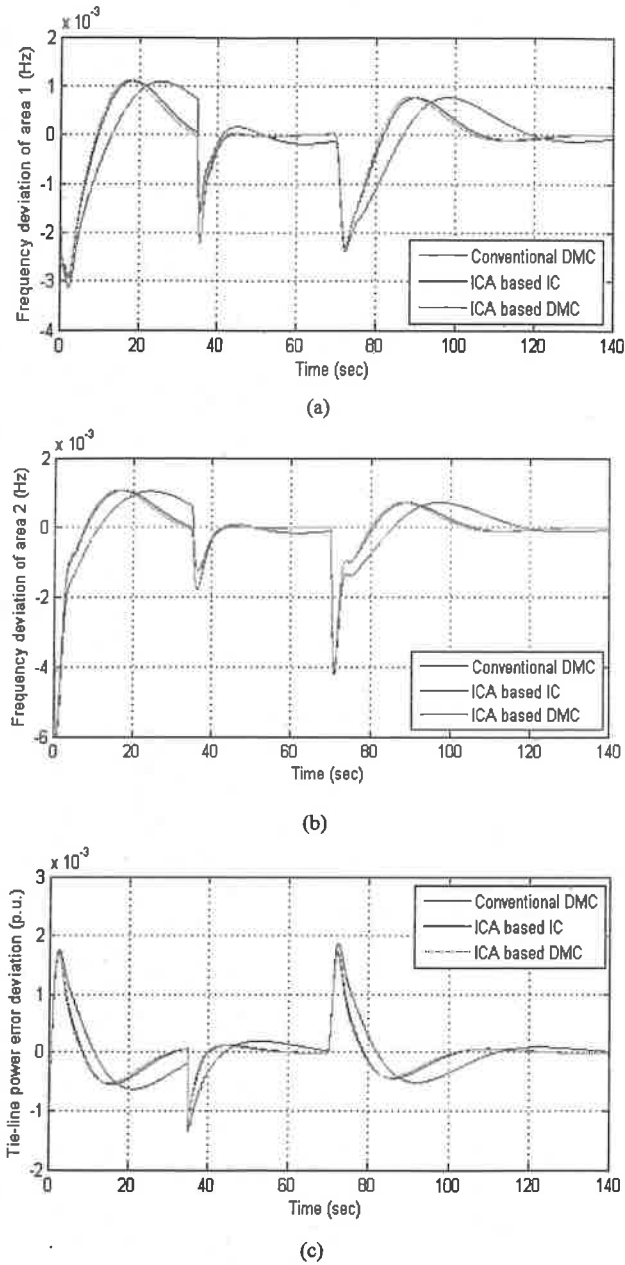
(a)

(b)

(c)

FIGURE 11. a. Deviations in area Frequency in area 1 during contract violation condition. **b.** Deviations in area Frequency in area 2 during contract violation condition. **c.** Tie line power error during contract violation condition.

(a)

(b)

(c)

FIGURE 12. a. Generation of GenCo 1 in Thermal area during Contract violation condition. **b.** Generation of GenCo 2 in Thermal area during Contract violation condition. **c.** Generation of GenCo 3 in Thermal area during Contract violation condition.

the tie-line power in the standard case are shown in Fig. 7c. It can be perceived that the lessening of frequency deviation of the system and error of oscillations in the tie-line power is achieved due to the existence of the Imperialistic Competition Algorithm-based Dual Mode Controller. The power generations of GenCo 1, Genco 2, and Genco 3 in the thermal area under the standard case are depicted in Fig. 8a, 8b, and 8c. The power generations of GenCo 4, Genco 5, and Genco 6 in the hydro area under the usual case are depicted in Fig. 9a, 9b, and 9c. The settling time of a
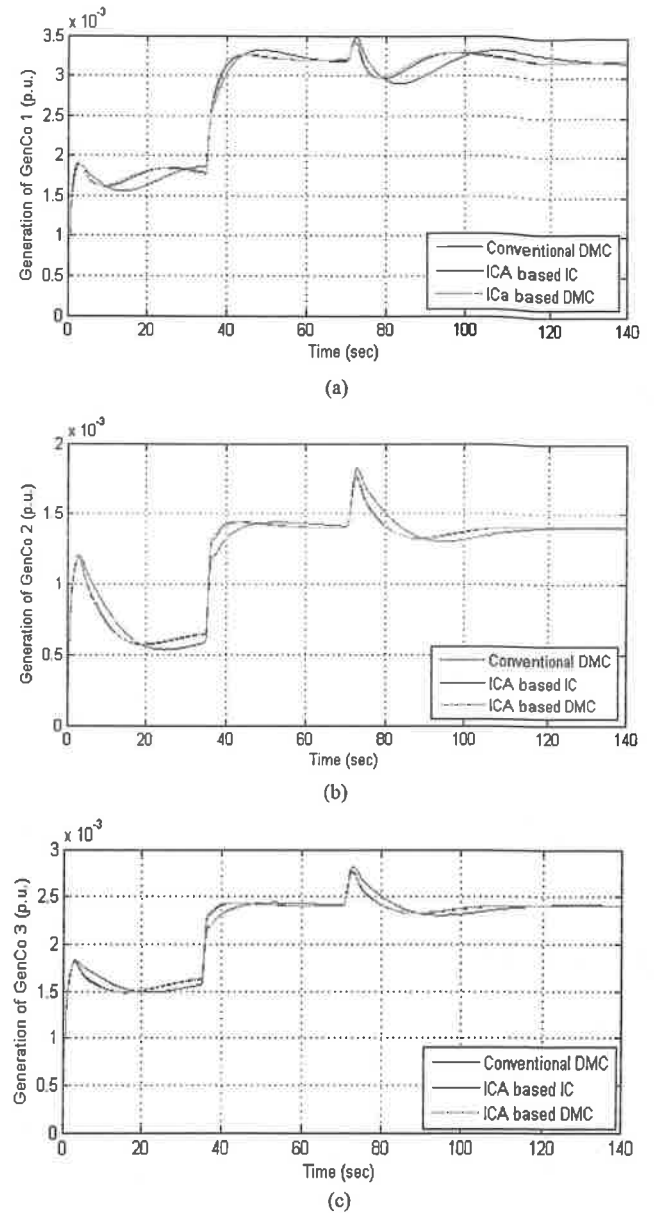
dynamical system is the time elapsed from applying an ideal step input to the time the dynamic system output entered and remained with a steady-state value of the system. It is realized that the oscillations of power are restricted due to the existence of the Imperialistic Competition Algorithm-based Dual Mode Controller. Fig. 10 indicates the assessment of the PI value of the hydrothermal system during normal conditions. The lesser value of PI indicates that the system acquires improved performance due to the existence of the Imperialistic Competition Algorithm based on the Dual Mode Controller.
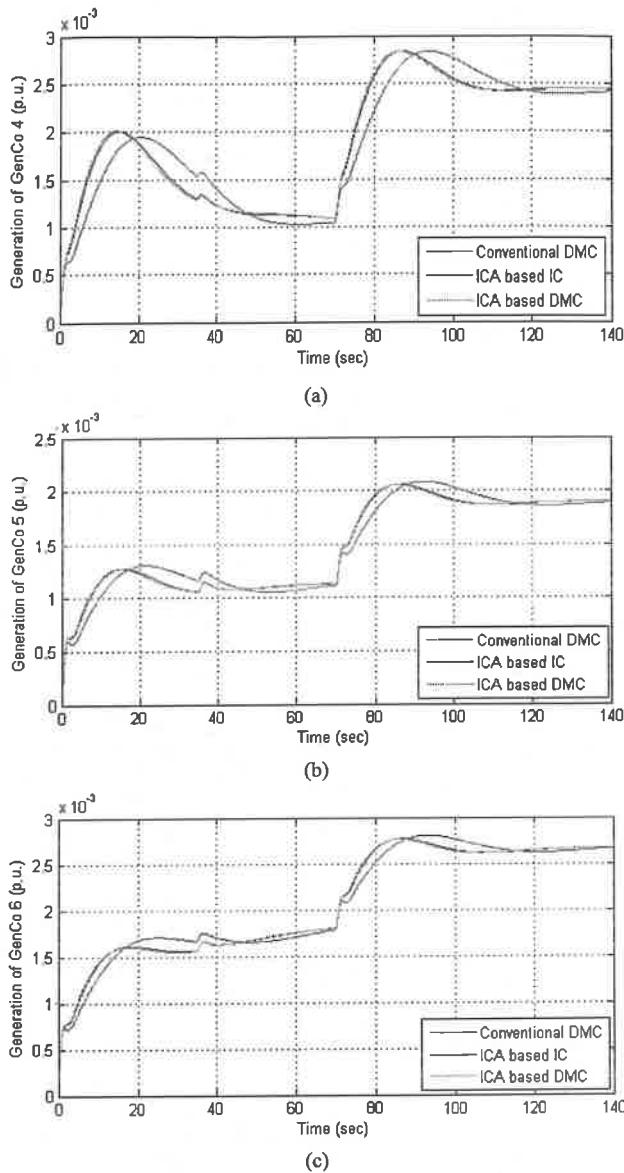
(a)

(b)

(c)

FIGURE 13. a. Generation of GenCo 4 in Hydro area during Contract violation condition. b. Generation of GenCo 5 in Hydro area during Contract violation condition. c. Generation of GenCo 6 in Hydro area during Contract violation condition.

A. CONTRACT VIOLATION

The step load increase in power demand in an LFC is supplied either from the kinetic energy of the rotating machine or increased generation. Further, following a step change in load demand in the interconnected system, the primary ALFC (Automatic Load Frequency Control) loop responds first within seconds. In contrast, the secondary ALFC loop responds rather slowly (within minutes) to compensate for the static frequency drop. During this period, undesirable perturbation oscillation may occur in the dynamic response. Incorporating SSSC and CES in the ALFC makes zero in the open loop transfer function, as the results two poles are situated at the left half of the s plane with absolute values
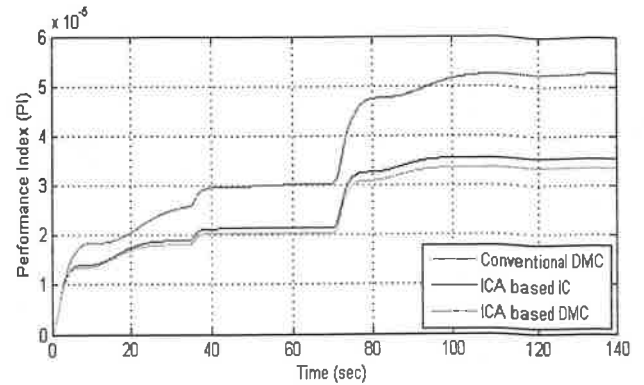

FIGURE 14. Comparison of PI values under contract violation.

improve the response. Hence, dissimilarity is occurred in the response between without and with SSSC and CES during the initial response (within 10 sec) and the response at contract violation (35 sec and 70 sec).

It possibly will arise that the DisCos are demanding more than indicated in the contract, and it may break up a contract. In this case, 0.3% of the additional step load demanded by DisCo1 after 35 sec and DisCo4 after 70 sec are considered in both areas. The add-on load is engaged by all the GenCos, which is in the same area in which defilement of agreement has arisen. The frequency deviation of both the areas under the contract violation case is depicted in Fig. 11a and 11b. The error deviations in the tie-line power in the course of contract violation are shown in Fig. 11c. It depicts that the reduction in deviation of frequency and oscillations of error in tie-line power is achieved due to the imperialistic competition algorithm-based dual-mode control.

The power generations of GenCo 1, Genco 2, and Genco 3 in the thermal area under contract violation are depicted in Fig. 12a, 12b, and 12c. The power generations of GenCo 4, Genco 5, and Genco 6 in the hydro area under contract violation are depicted in Fig. 13a, 13b, and 13c. It can be observed from the Figures the power oscillations are restricted due to the existence of the Imperialistic Competition Algorithm-based Dual Mode Controller.

The assessment of the PI values of both the systems in the course of the contract violation situation is shown in Fig. 14. It is realized that the PI value of the system acquires additionally abridged due to the existence of the Imperialistic Competition Algorithm-based Dual Mode Controller. The Performance Index value of the ICA-based integral controller and ICA-based dual-mode control under the contract violation cases are 3.557×10^{-5} and 3.358×10^{-5}. The result indicates that the Performance Index of the system with a dual-mode control-based imperialistic competition algorithm has superiority compared to all other methods.

VIII. CONCLUSION

The Imperialistic Competition Algorithm has been efficiently implemented to adjust the gain settings of the Dual Mode

Controller. A multi-area-based hydrothermal system in the competitive market environment of Capacitive Energy Storage and Static Synchronous Series Compensator has been employed to validate the system performance. The Integral Square of Error (ISE) technique has been used to evaluate the performance index for the different techniques. The system's performance was analyzed for conventional Dual-Mode Controller, Imperialistic Competition Algorithm-based integral controller, and Imperialistic Competition Algorithm based Dual Mode Controller in a two-area hydrothermal with Capacitive Energy Storage and Static Synchronous Series Compensator based system in open market scenario has been investigated. The settling time of thermal and hydro areas for conventional Dual Mode Controller is 7.541 sec and 4.241 sec; Particle Swarm Optimization technique is 4.12 sec and 2.7 sec, Imperialistic Competition Algorithm based Integral Controller is 4.106 sec and 2.655 sec. But the Imperialistic Competition Algorithm-based Dual Mode Controller is 4.005 sec and 2.585 sec. The Performance Index value for standard and Contract violation case is 1.808×10^{-5} and 3.358×10^{-5}. The simulation result indicates that the suggested Imperialistic Competition Algorithm-based Dual Mode Controller technique successfully diminishes the oscillations of frequency and tie-line power of the system. It can be understood that the Performance Index of the system with Dual Mode Controller based Imperialistic Competition Algorithm has superiority as compared to other methods.

APPENDIX

A. HYDROTHERMAL SYSTEM DATA

$$P_{r1}, P_{r2} = 1200 \text{Mw}; \quad K_{p1}, K_{p2} = 120 \text{Hz/p.u.}$$
$$\text{Mw}; \quad T_{p1}, T_{p2} = 20\text{s} \quad \text{and Tg} = 0.08\text{s}; \quad T_t = 0.3\text{s};$$
$$T_w = 1\text{s}; \quad T_r = 5\text{s}, \quad T_1 = 41.6\text{s} \quad \text{and}$$
$$T_2 = 0.513\text{s}; \quad B_1, B_2 = 0.4249 \text{p.u}$$
$$\text{Mw/Hz}; \quad R_1, R_2 = 2.4 \text{Hz/p.u.} \quad \text{Mw}; \quad T_{12} = 0.0866\text{s};$$

B. CES DATA

$$K_{CES} = 0.3; \quad T_{CES} = 0.0352\text{s}; \quad T_1 = 0.279\text{s};$$
$$T_2 = 0.026\text{s}; \quad T_3 = 0.411\text{s} \quad \text{and } T_4 = 0.1\text{s};$$

C. SSSC DATA

$$K_{SSSC} = 0.292; \quad T_{SSSC} = 0.03\text{s}; \quad T_1 = 0.188\text{s};$$
$$T_2 = 0.039\text{s}; \quad T_3 = 0.542\text{s} \quad \text{and } T_4 = 0.14\text{s};$$

D. PARAMETERS OF ICA

$$N_{imp} = 20; \quad N_{col} = 100; \quad \xi = 0.2; \quad \beta = 1.75$$

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