Load frequency control of a multi-area system incorporating realistic high-voltage direct current and dish-Stirling solar thermal system models under deregulated scenario

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Abstract
A maiden attempt was made to demonstrate the impact of realistic high-voltage direct current (RHVDC) tie-line along with realistic dish-Stirling solar thermal system (RDSTS) models in multi-area load frequency control studies under a deregulated scenario. Area-1, area-2 and area-3 comprise thermal-RDSTS systems with relevant generation rate constraints. Each area includes two generation and two distribution companies. A new secondary controller with a cascaded combination of fractional order (FO) proportional derivative with filter coefficient (N) and FO-proportional-integral-derivative with filter coefficient (N) (FOPDN-FOPIDN) is proposed for the first time. The performance indices (peak magnitude, settling time and oscillations magnitude) of the proposed controller shows the dominance in comparison with the existing FOPI, PIDN and FOPIDN controllers in the policy schemes like poolco, bilateral and contract violation. A recent metaheuristic algorithm named the crow-search algorithm is successfully applied for simultaneous optimisation of the proposed FOPDN-FOPIDN controller gains and RDSTS parameters under the deregulated environment for the first time. Under the above policy schemes, the effect of RDSTS and RHVDC tie-line using FOPDN-FOPIDN controller is investigated, and the use of RHVDC tie-line with AC tie-line is explored. System dynamic response comparison with parallel AC-RHVDC tie-lines reveals better performance over AC tie-line and RHVDC tie-line when used alone.

1 | INTRODUCTION

Deviations in tie-line power and frequency during abnormal conditions with small perturbations in load are mitigated by load frequency control (LFC) [1]. These deviations lead to a mismatch between real power generation with the load demand and the associated losses. The day by day increase in need of real power generation by load demand through tie-lines and its economic impact tends to deregulate electricity market [2]. Market players are not included in the traditional power system (PS) market. The restructured PS consists of an independent system operator (ISO), generation companies (GENCOs), transmission companies (TRANSCOs) and distribution companies (DISCOs). ISO provides the rules and regulations for bidding between GENCOs and DISCOs using three agreements like poolco, bilateral and contract violation [3, 4]. ISO maintains the transparency in agreement policy among the companies. The DISCOs and GENCOs may interact with any GENCO or DISCO that may or may not belong to the same control area. Donde et al. [5] formulated the interaction among the DISCOs and GENCOs by a DISCO participation matrix (DPM) and each of its elements is identified as contract participation factor (cpf). Parida et al. [6] provided the commencement of a realistic deregulated PS market by accommodating the concepts of DPM and area participation factor (apf) in the multi-area hydrothermal system. Debbarama et al. [7] investigated on three-area thermal system in a restructured environment. Later, a more realistic PS model is presented by the authors in [8, 9] by integrating the thermal system with various sources like hydro, nuclear and gas.

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The increase in population and their daily needs tend to increase the amount of energy required. Moreover, fossil energy fuels are getting depleted day by day. Bevrani et al. [10] proposed the concept of accommodating renewable energy in LFC studies. The wide availability of wind and solar in nature dominates over the other renewable energy sources (RES). Das et al. [11] demonstrated the frequency control of isolated hybrid PS by integrating solar thermal plant. Rahman et al. [12] demonstrated the frequency study by incorporating the dish-Stirling solar thermal system (DSTS). The penetration level of DSTS energy into the grid is set to a constraint in avoiding instability due to the non-minimum phase characteristic of the fixed-speed-DSTS (FSDS). Transient droop compensation overcomes this problem. Li. Y et al. [13–15] developed a realistic DSTS (RDSTS) model in a single-area frequency control studies by considering the non-minimum phase and transient droop characteristics, but it is limited to isolated systems only. Moreover, the authors in [16] modelled the RDSTS system with FSDS dynamics and transient droop compensation in a three-area conventional LFC system. Some past literatures [4–8] have studied LFC under a deregulated system, but till date a system under the deregulated environment that includes RDSTS has not been found [4–15]. The system dynamic performance may change if they are included. Thus a comprehensive study is needed.

With advancements in inter-area power transfer capability, technologies such as high-voltage direct current (HVDC) links and parallel AC-HVDC links create a solution for the increase in load demand. Authors in [17–19] presented the approximate model of HVDC links and discuss the benefits in combining of DC links with AC links. The stored energy utilisation in HVDC links with power transfer capabilities was developed by Ferre et al. [20]. The addition of RES into PS reduces the inertia levels of the system because of low-level rotational inertia in RES. The idea of matching the inertial energy of a synchronous machine to the capacitive energy stored in the HVDC link through inertia emulation control (IEC) with voltage source inverters is presented by Zhu et al. [21]. Adeyui et al. [22] presented the idea of multi-terminal HVDC links. Rakhshani et al. [23] proposed an approach by considering virtual inertia of an HVDC link with derivative control of two-area LFC. Later, Pathak et al. [24] also examined the realistic HVDC (R HVDC) system with the two-area thermal system using IEC strategy with an integral controller and renamed the HVDC link model as accurate HVDC link. Authors in [16, 25] developed an RHVDC model of three-area systems, but it is limited to conventional LFC study only. In LFC, under the deregulated environment, if such RHVDC is utilised, the system dynamic performance may be different since the behaviour dynamics in the restructured scenario is completely different [20–25]. Surprisingly, such RHVDC is not studied in deregulation that leads to the necessity of a study.

Secondary controllers are required to accomplish a smooth and steady-state profile. Numerous secondary controllers like integer-order (IO) controller, a higher degree of freedom (DOF) controllers, such as 2DOF, 3DOF [12], FO-cascade controllers and intelligent controllers are available in the literature. IO controllers such as integral (I) [4, 6, 25], proportional-integral (PI) [8], integral-derivative (ID) [9], integral-double-derivative (IDD), [8, 31], proportional-integral-derivative (PID) [2,8] and PID with filter coefficient (PIDN) controllers [32] are implemented by many authors in LFC studies. Some authors have implemented intelligent controllers like fuzzy [4, 19] neural network controllers [17] in the field of LFC. Authors in [24, 26–28] worked on fractional order (FO) controllers like fractional-order proportional-integral (FOPID) [30] and fractional-order proportional-integral-derivative (FOPID) [7, 27] in LFC studies. Dash et al. [29] presented the idea of cascading of IO controllers such as PI-PD and PD-PID, but it is restricted to conventional LFC systems only. Washima et al. [30] demonstrated the cascading of two FO controllers like FOPID-FOPID in the restructured electricity market of LFC. However, the cascade combination of two FO controllers with filters co-efficient (N) such as FO proportional-derivative filter with coefficient (N) (FOPDN) and FO proportional-integral-derivative filter with coefficient (N) (FOPIDN) is not yet investigated in multi-area LFC studies under deregulated environment with RDSTS and RHVDC systems, which require intensive study.

The secondary controller gains and other parameters are set to be optimised to obtain the desired steady-state response. Numerous heuristic techniques and optimisation algorithms are used for obtaining the optimised parameters. Various heuristic techniques like differential evolution [9], bacterial foraging algorithm [33], genetic algorithm [36] have been applied in LFC studies. Several optimisation techniques like flower pollination algorithm (FPA) [26], firefly algorithm (FA) [34], and cuckoo search algorithm (CSA) [35] provide obvious results. Askarzadeh [38] proposed a recent technique named crow-search algorithm (CA) that depends on the behaviour of crows. Crows are considered to have intelligent behaviour, ability to recognise faces, greedy nature, tools usage and sophisticated ways of communication. Authors in [16, 38] utilised CA for optimisation of controller parameters under conventional LFC studies. However, the same is not applied in the field of LFC studies under the restructured market for simultaneous optimisation of the controller and RDTS parameters, which needs further investigation.

From the above-mentioned literature, the major objectives of the proposed research work are as follows:

a. To integrate a realistic RDSTS with the multi-area thermal under the restructured power system.

b. Optimising the parameters of RDSTS and controller gains of FOPID, PIDN, FOPIDN, and FOPDN-FOPIDN controllers considering one at a time, and comparison of the dynamic performance to obtain the best.

c. To evaluate the convergence characteristics of various algorithms like FA, FPA, CSA, and CA with the best controller obtained in (b).

d. To study the effect of RDSTS, AC tie-line alone, RHVDC alone and the parallel combination of both under bilateral transactions with the best controller.
1.1 Novelty and contribution

In view of the above, the novelties of the study are as follows:

a. The evaluation of the performance of realistic models such as RDSTS and RHVDC tie-line in LFC under the deregulated scenario.
b. The design of a new cascade controller named cascade FOPDN-FOPIDN in LFC studies.
c. The implementation of parallel AC and RHVDC tie-line in LFC under the deregulated environment.
d. Application of RHVDC tie-line alone in the multi-area system for the first time in LFC under deregulation.
e. The performances evaluation of RDSTS in LFC under the deregulated scenario is carried out for the first time.
f. Use of a metaheuristic algorithm called CS algorithm in LFC under deregulation for simultaneous optimisation of the proposed FOPDN-FOPIDN controller and RDSTS parameters.

Thus, the main contributions of the present work are as follows:

a. A study has been carried out by considering the realistic models of DSTS and HVDC in LFC studies under the deregulated scenario for the first time.
b. A new cascade combination of two FO controllers called FOPDN-FOPIDN is proposed for the system incorporating RDSTS and RHVDC tie-lines. It is also proved that the performance of FOPDN-FOPIDN controller is better than normally used controllers.
c. The controller gains and RDSTS parameters are successfully optimised by a metaheuristic named CS algorithm in LFC under the deregulated scenario.
d. A maiden effort was made to study the effect of RDSTS model with the thermal system in LFC study.
e. A study using RHVDC tie-line alone and a study for the parallel combination of RHVDC and AC tie-line are incorporated in a three-area deregulated system considering RDSTS.

2 SYSTEM INVESTIGATED

The objectives depicted in Section 1 are fulfilled by considering a three unequal area thermal of a multisource system under a deregulated environment having capacity ratios of area-1:area-2:area-3 as 1:2:4. The study system model of the above is shown in Figure 1(a). The system nominal parameters of RDSTS, RHVDC and thermal are taken from [6, 12, 25]. Generation rate constraint (GRC) of 3% per minute is considered for thermal systems. The system considered for investigation is illustrated in Figure 1(a). Investigations are carried out by considering RDSTS, RHVDC tie-line alone, AC-RHVDC tie-line for the first time with a new proposed cascade controller named FOPDN-FOPIDN whose gains are optimised by CA under the deregulated LFC studies.

The investigated system is organised as follows: (i) A three unequal area thermal system, (ii) thermal system with RDSTS, (iii) system in (ii) with RHVDC tie-line alone, and (iv) system in (ii) with the parallel AC-RHVDC tie-line and is shown in Figure 1(a). The system transfer function model with the RDSTS plant and parallel AC-RHVDC tie-line is illustrated in Figure 1(b).

Various secondary controllers such as FOPI, PIDN, FOPIDN, and cascaded FOPDN-FOPIDN are considered each at a time. Four separate case studies are considered for investigation (i) integration of RDSTS to an unequal three-area thermal system under various transactions, (ii) effect of RDSTS with all transactions, (iii) replacing of AC tie-line with RHVDC tie-line under a bilateral transaction, and (iv) parallel operation of both AC and RHVDC tie-line with the thermal system under the bilateral transaction. The system is subjected to step load perturbation of 1% in area-1. The controller gains and RDSTS parameters are optimised consecutively using crow search algorithm subjected to integral squared error (ISE) given by Equation (1):

$$\eta_{ISE} = \int_{0}^{T} \left( (\Delta F_j)^2 + (\Delta P_{p-k-m})^2 \right) dt \tag{1}$$

where $j, k$ and $m$ are area number ($j, k, m = 1, 2, 3$ and $k \neq m)$. The system is modelled in Simulink with FOMCON toolbox and the optimisation technique is coded in MATLAB R2014a software. The controller gains and RDSTS parameters are optimised using various optimisation techniques such as cuckoo search, flower pollination, firefly and crow search algorithm.

3 A BRIEF DESCRIPTION OF THE SYSTEM MODEL UNDER THE DEREGULATED SCENARIO, SYSTEM COMPONENTS AND THE PROPOSED CONTROLLER

3.1 A brief of the system model under deregulated scenario

A total of six GENCOs and six DISCOS are considered one at a time for investigation. Each area comprises thermal systems (GENCO-2, GENCO-4, and GENCO-6) and RDSTS (GENCO-1, GENCO-3, and GENCO-5), respectively. Depending on their cpfs in DPM, the GENCOs and DISCOS will communicate with each other as shown in Equations (2) and (3):

$$\text{DPM} = \begin{bmatrix}
\phi f_{11} & \phi f_{12} & \phi f_{13} & \phi f_{14} & \phi f_{15} & \phi f_{16} \\
\phi f_{21} & \phi f_{22} & \phi f_{23} & \phi f_{24} & \phi f_{25} & \phi f_{26} \\
\phi f_{31} & \phi f_{32} & \phi f_{33} & \phi f_{34} & \phi f_{35} & \phi f_{36} \\
\phi f_{41} & \phi f_{42} & \phi f_{43} & \phi f_{44} & \phi f_{45} & \phi f_{46} \\
\phi f_{51} & \phi f_{52} & \phi f_{53} & \phi f_{54} & \phi f_{55} & \phi f_{56} \\
\phi f_{61} & \phi f_{62} & \phi f_{63} & \phi f_{64} & \phi f_{65} & \phi f_{66}
\end{bmatrix} \tag{2}$$
where

$$c_{fjk} = \frac{\text{contracted load demand for } j\text{th GENCO}}{\text{total load demand of the } k\text{th DISCO}}$$

The elements in a DPM matrix represent the DISCOs and GENCOs in number. The off-diagonal elements establish the relation among DISCO of one area to GENCO of other areas.

However, the column elements sum should be unity. Based on generation capability, the apfs of GENCOs are calculated [6].

The scheduled tie power equations among the areas are given by Equation (4) and are taken from [6, 7, 30]:

$$\Delta P_{\text{tie-scheduled, }jk} = P_{\exp j} - P_{\text{imp } k}$$  (4)
where
\[ P_{\text{exp}, j} = \text{area-}j\text{'s GENCOs power demanded by the DISCOS in area-}j. \]
\[ P_{\text{exp}, k} = \text{area-}k\text{'s GENCOs power demanded by the DISCOS in area-}j. \]

The power exchange between deviations in actual tie power and error is given by Equation (5):
\[ \Delta P_{\text{error},jk} = \Delta P_{\text{tie-actual},jk} - \Delta P_{\text{tie-scheduled},jk} \]  
\[ (5) \]

The area control error (ACE) signal is the combinations of frequency change and tie-line power and is given by Equation (6):
\[ ACE_i = B_i \Delta F_i + \Delta P_{\text{error},jk} \]  
\[ (6) \]

3.2 | System components

3.2.1 | Realistic dish-Stirling solar thermal system

The DSTS system comprises a parabolic dish, a tracking device, and a receiver. The parabolic dish reflects the thermal energy collected by it and focuses on the receiver. This energy is used for heating the working liquids and it serves as an input to the Stirling engine. Stirling engine converts thermal energy to rotational energy which drives the squirrel-cage induction generator (SCIG) to generate electricity. The transfer function of DSTS with gain \((K_{\text{DSTS}})\) and time constant \((T_{\text{DSTS}})\) [12, 30] is given by Equation (7):
\[ G_{\text{DSTS}}(s) = \frac{K_{\text{DSTS}}}{1 + sT_{\text{DSTS}}} \]  
\[ (7) \]

Due to its narrow speed operation of SCIGs, SCIGs are unable to maintain frequency regulations by the speed changes in the generator [13–15]. To overcome this, SCIGs are provided with transient droop characteristics (variable speed and energy storage devices that provide necessary spinning reserve). Moreover, a constraint is to be imposed on the penetration level of solar energy to the grid in order to avoid the onset of instability due to non-minimum phase characteristics of the DSTS system forming an RDSTS system with the non-minimum phase and transient droop characteristics as shown in Figure 2(a). The transfer function model of RDSTS is given by Equation (8):
\[ \Delta P_{\text{DS}}(s) \]
\[ \Delta P_{\text{e}}(s) \]
\[ = \frac{1}{s} \times \left( \frac{K_{\text{DSTS,i}}}{1 + sT_{\text{DSTS},i}} \right) \times \left( \frac{T_{\text{e}1,i} + 1}{T_{\text{eqv},V_{\text{SC}}} + 1} \right) \times \left( \frac{-T_{\text{eqv},F} + 1}{T_{\text{eqv},F} + 1} \right) \]  
\[ (8) \]

where \(\Delta P_{\text{DS}}(s)\) and \(\Delta P_{\text{e}}(s)\) are the output and input of the RDSTS system. In this study, a maiden effort was made to study the RDSTS system dynamics under various transactions of the deregulated market.

3.2.2 | Realistic high voltage direct current tie-line

In general, the HVDC link comprises inverter and rectifier that are controlled by the firing angles. From the past literatures, the conventional model of HVDC is designed [17, 18] based on assumptions and are represented by Equation (9):
\[ \Delta P_{\text{tie,DC}} = \frac{K_{\text{DC}}}{1 + sT_{\text{DC}}} \]  
\[ (9) \]

where \(\Delta P_{\text{tie,DC}}\) is the power in the DC link. HVDC gain constant is \(K_{\text{DC}}\) and is given by 1.0; \(T_{\text{DC}}\) is settling time for a small load disturbance and is given by 0.2 s.

Parameters such as loading condition, rated voltage level and converters impudence are not considered in conventional modelling of HVDC links. Considering the parameters and drawbacks of conventional modelling led to the realistic modelling of HVDC links [24]. The tie-line power of DC link is given by Equation (10):
\[ \Delta P_{\text{tie,DC}}(\text{in}) = \left( 2\Pi T_{\text{eqv}}/\text{i} \right) \cdot \left( \Delta F_{j}(\text{i}) - \Delta F_{k}(\text{i}) \right) \]  
\[ (10) \]

where
\[ T_{\text{eqv}} = \left( \frac{T_{j,\text{DC}} \cdot T_{k,\text{DC}}}{T_{j,\text{DC}} + T_{k,\text{DC}}} \right) \quad \forall j, k = 1, 2, 3 \text{and } j \neq k \]  
\[ (11) \]

By considering the number of capacitors and capacitance-voltage, the change in DC capacitor voltage in terms of frequency can be given by Equation (12) [16, 24, 25].
\[ \Delta V_{\text{DC}}(\text{i}) = \left( \frac{2F F_{\text{VSC}}}{N_{\text{DC}} C_{\text{VSC}} F_{\text{VSC}} V_{\text{DC}}^2} \right) \Delta F_{j}(\text{i}) \]  
\[ (12) \]

where \(F_{\text{VSC}}\) is the power rating of voltage source converters (VSC) inverters. Equation (12) establishes the relation between change in frequency and voltage change of a HVDC tie-line. Therefore, the transfer function model of RHVDC tie-line, considering the above parameters for the multi-area system, is modelled, and its transfer function model is shown in Figure 2(b). In present work, the investigations are carried out by considering AC tie-line alone, RHVDC tie-line alone and parallel AC-RHVDC tie-line alone with RDSTS system for the first time in LFC under deregulated scenario.

3.3 | Proposed cascaded FOPDN-FOPIDN controller

The idea of extending integer order (IO) calculus to an arbitrary real number is accomplished by fractional order (FO) calculus.
The real order transfer function of FOPID ($P^p D^\mu$) [7, 27] with two controllable parameters differentiator ($\mu$), integrator ($\lambda$), and three gains ($K_{Pj}, K_{Dj},$ and $K_{Ij}$) is given by Equation (13):

$$G_{c,j}(s) = \frac{U_j(s)}{R_j(s)} = K_{Pj} + K_{Ij}s^{\lambda_j} + K_{Dj}s^{\mu_j} \quad (\lambda_j, \mu_j > 0) \quad (13)$$

where $j$ is area number = 1, 2 and 3. Due to the continuous operation of loads, a noise of high-frequency signals is introduced into the system by the D-parameter. A filter is to be added in order to avoid these unwanted signals. The transfer function of FOPID controller with filter coefficient ($N$) is given by Equation (14).

$$G_{c,j}(s) = K_{Pj} + \frac{K_{Ij}}{s^{\lambda_j} + K_{Dj}s^{\mu_j} + N_j}{(1 + N_j s^{\mu_j})} \quad (14)$$

The presence of a derivative and proportional term in the forward path introduces a derivative kick in the FOPIDN controller, which is undesirable in electronic circuits [33, 37]. In order to overcome this, the industrial engineers have introduced the concept of cascade controllers. This study presented the
design of a new cascade controller named FOPDN-FOPIDN controller involving two control loops. Two sequential controlling processes of cascading controller improve the system dynamics over a single sequential control system.

The transfer function of FOPDN and FOPIDN are given by Equations (15) and (16):

\[
G_i,j(t) = \frac{K_{pi,j} + K_{pi,j}d_{i,j}N_{i,j}}{1 + \frac{N_{i,j}}{\mu_{i,j}}} \quad (15)
\]

\[
G_o,j(t) = \frac{K_{pj} + K_{pi,j}d_{i,j}N_{i,j}}{1 + \frac{N_{i,j}}{\mu_{i,j}}} \quad (16)
\]

The schematic diagram of the proposed cascaded controller with two loops is displayed in Figure 2(d). The system is set to a disturbance \(d_i(t)\) and its output is \(Y(t)\). The outer loop equation of the system is given by Equation (17):

\[
Y(t) = G_1(t)U_1(t) + d_i(t) \quad (17)
\]

where \(U_1(t)\) is the input of the outer loop. Form Figure 2(d), the inner process output is the input of the outer process (i.e. \(U_1(t) = y_2(t)\)).

The reference signal \(R(t)\) controls the outer process \(G_1(t)\), and inner process equations are given by Equation (18).

\[
y_2(t) = G_2(t)U_2(t) \quad (18)
\]

where \(U_2(t)\) is the input for the inner process. In this study, FOPDN is the outer controller \(G_1(t)\) and FOPIDN is the inner controller \(G_2(t)\), and its corresponding equations are in Equations (15) and (16), respectively.

The transfer function of the cascaded FOPDN-FOPIDN controller is given by Equation (19):

\[
Y_j(t) = \left( \frac{G_i(t)G_j(t)G_j(t)}{1+G_i(t)G_j(t)+G_i(t)G_j(t)G_j(t)} \right) R_j(t) + \left( \frac{G_i(t)}{1+G_j(t)+G_i(t)G_j(t)} \right) d_j(t) \quad (19)
\]

Based on the properties of FOPIDN controllers, the cascaded FOPDN-FOPIDN controller is applicable for higher-order non-linear systems and system responses are distinguished with conventional controllers. The ACE signal acts as an input to the cascaded FOPDN-FOPIDN controller, that is, the combinations of deviations in frequency, and parallel AC-RHVDC tie-lines. The constrained set of controller gains and parameters are optimised by CA as shown in Expression (20).

\[
\begin{align*}
K_{p1,j} & \leq K_{p1,j} \leq K_{p1,j} \text{ max} & N_{i,j} & \leq N_{i,j} \text{ max} \\
K_{p1,j} & \leq K_{p1,j} \leq K_{p1,j} \text{ max} & \mu_{i,j} & \leq \mu_{i,j} \text{ max} \\
K_{p2,j} & \leq K_{p2,j} \leq K_{p2,j} \text{ max} & N_{i,j} & \leq N_{i,j} \text{ max} \\
K_{p2,j} & \leq K_{p2,j} \leq K_{p2,j} \text{ max} & \mu_{i,j} & \leq \mu_{i,j} \text{ max} \\
K_{i,j} & \leq K_{i,j} \leq K_{i,j} \text{ max} & \lambda_{i,j} & \leq \lambda_{i,j} \text{ max} \\
K_{i,j} & \leq K_{i,j} \leq K_{i,j} \text{ max} & \mu_{i,j} & \leq \mu_{i,j} \text{ max} \\
K_{D1,j} & \leq K_{D1,j} \leq K_{D1,j} \text{ max} & \lambda_{D1,j} & \leq \lambda_{D1,j} \text{ max} \\
K_{D1,j} & \leq K_{D1,j} \leq K_{D1,j} \text{ max} & \mu_{D1,j} & \leq \mu_{D1,j} \text{ max} \\
K_{D2,j} & \leq K_{D2,j} \leq K_{D2,j} \text{ max} & \lambda_{D2,j} & \leq \lambda_{D2,j} \text{ max} \\
K_{D2,j} & \leq K_{D2,j} \leq K_{D2,j} \text{ max} & \mu_{D2,j} & \leq \mu_{D2,j} \text{ max}
\end{align*}
\] (20)

where \(K_{p1,j}, K_{D1,j}, K_{p2,j}, K_{D2,j}, \) and \(K_{i,j}\) are the controllable parameters ranging from minimum ‘0’ to maximum ‘1’, controller gains \(\mu_{i,j}, \lambda_{i,j}\) and \(\mu_{2,j}\) ranging from ‘0’ to ‘1’ and the filter coefficients \(N_{i,j}, N_{2,j}\) ranging from ‘0’ to ‘100’.

4 | CROW-SEARCH ALGORITHM

CA is a metaheuristic population-based approach proposed by Askarzadeh [38]. It depends upon the smart behaviour of crows (crow family or group of crows). It is mainly based on the storing of excess food and retrieves it from their hiding place when needed. Pieces of evidence like self-awareness, tool-making ability, remembering faces, communicating themselves, signalling each other when a stranger approaches, remembering its food hiding place up to several months and observing food hiding place of other birds and stealing it when the owner leaves shows the cleverness of a crow. After committing thievery, crows will take extra precautions in moving the hiding places of food in order to avoid the future victim.

A d-dimensional space search agent with crow’s position ‘p’ and flock size ‘n’ in the iteration is represented by a vector in Equation (21).

\[
[X^{\text{iter}}] = [X_1^{\text{iter}}, X_2^{\text{iter}}, ..., X_d^{\text{iter}}] \quad (21)
\]

where maxiter is iterations up to a maximum number, iter = 1, 2, ..., maxiter, and \(p = 1, 2, ..., n\). The search agent in iteration tracks and stores all the optimum positions of a crow-p. In iteration-\(p\), the optimum position of crow-\(p\)’s food hiding place is given by \(AP^{\text{iter}}\). In iteration, if a crow-\(q\) wish to visit its food storing place \((m_q)\) and crow-\(q\) wishes to follow crow-\(p\), two possibilities are available. The flowchart of CA is depicted in Figure 2(b).

Possibility 1: Crow-\(q\) does not know that crow-\(p\) is following while it is approaching for its food hiding place by obtaining a new position and is given by Equation (22).

\[
X^{\text{iter}+1} = X^{\text{iter}} + r_p \times FL^{\text{iter}} \times (AP^{\text{iter}} - X^{\text{iter}})
\]

\[
r_q \geq AP^{\text{iter}} \quad (22)
\]

where \(FL\) is crow-\(p\)’s flight length, random number \(r_p\) varies from ‘0’ to ‘1’. Local optimum is achieved by a lower value of \(FL\), and higher values of \(FL\) leads to global optima. The parameters of intensification and diversification are achieved by awareness probability \((AP)\). The best solution of CA is obtained with a decrease in AP value. Intensification is increased with a small value of AP.

Possibility 2: By noticing that crow-\(p\) is following crow-\(q\), crow-\(q\) ends up in a random position in a search space instead of going to its food hiding place and is given by Equation (23).

\[
X^{\text{iter}+1} = \text{randomposition} \quad (23)
\]
The parameters of CA are shown in Appendix B. In the present research work, the gains and parameters of the controllers (i.e. \( K_{p1} \), \( K_{d1} \), \( \mu_1 \), \( N_1 \), \( K_{p2} \), \( K_{d2} \), \( \lambda_2 \), \( K_{d2} \), \( \mu_2 \), and \( N_2 \) for FOPI, PIDN, FOPIDN and cascaded FOPDN-FOPIDN controllers) are simultaneously optimised using CA for the first time under the deregulated environment with cost function \( ISE \) in Equation (1). Furthermore, parameters of RDSTS like time constants of transient droop compensation (\( T_{d1} \), \( T_{d2} \)) and FSDS dynamics (\( T_{d1}^f \), \( T_{d2}^f \)) are simultaneously optimised using CA and are given by Equation (24):

\[
0 \leq T_{d1} \leq 11 \leq T_{d2} \leq 4
\]

\[
0 \leq T_{d1}^f \leq 11 \leq T_{d2}^f \leq 10
\]  

(24)

5  | RESULTS AND ANALYSIS

5.1  | System dynamic responses of the three-area thermal system considering with and without RDSTS

In the present study, a maiden effort was made to study the effect of RDSTS system on system dynamics by considering with and without RDSTS system under various transactions like poolco, bilateral and contract violations for the first time. Moreover, a new controller is designed and its performance is evaluated with well-known controllers like FOPI, PIDN and FOPIDN. Further, the controller and RDSTS parameters are optimised by CA. Figures 1 (a-i) and (a-ii) show the investigated system considering with and without RDSTS system.

5.1.1  | Poolco-based transactions in the three-area thermal system with RDSTS

Figure 1 (a-ii) shows the investigated three-area thermal system with RDSTS system. In this poolco case, the GENCOs of one area interact with their respective DISCOs of the same area only. This clearly shows that DISCOs in area-1 demands load from GENCOs in area-1 only, whereas DISCOs of area-2 and area-3 does not demand load from GENCOs in area-1. The demand of 0.01 p.u. MW is considered for the DISCOs in area-1. The DPM matrix for the poolco case is given by Equation (25) and their respective apfs are calculated to be 0.5:

\[
\text{DPM}_{\text{poolco}} = \begin{bmatrix}
0.5 & 0.5 & 0 & 0 & 0 & 0 \\
0.5 & 0.5 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]  

(25)

The steady-state output values of the GENCOs in the poolco transactions are calculated using Equation (25) and are given by Equations (26)–(31).

\[
\begin{align*}
\text{GENCO-1} &= (1/2 + 1/2 + 0 + 0 + 0 + 0) \times 0.01 = 0.01 \text{ p.u. MW} \\
\text{GENCO-2} &= (1/2 + 1/2 + 0 + 0 + 0 + 0) \times 0.01 = 0.01 \text{ p.u. MW} \\
\text{GENCO-3} &= (0 + 0 + 0 + 0 + 0 + 0) \times 0.01 = 0 \text{ p.u. MW} \\
\text{GENCO-4} &= (0 + 0 + 0 + 0 + 0 + 0) \times 0.01 = 0 \text{ p.u. MW} \\
\text{GENCO-5} &= (0 + 0 + 0 + 0 + 0 + 0) \times 0.01 = 0 \text{ p.u. MW} \\
\text{GENCO-6} &= (0 + 0 + 0 + 0 + 0 + 0) \times 0.01 = 0 \text{ p.u. MW}
\end{align*}
\]  

(26–31)

Various secondary controllers like FOPI, PIDN, FOPIDN, and cascaded FOPDN-FOPIDN are examined at a time, and every time the gains and parameters of the controller are optimised using CA simultaneously. Along with controller parameters, RDSTS parameters like transient droop compensation and FSDS dynamics are also optimised using CA. The optimum values of the controller, RDSTS with CA are given in Table 1, and its respective dynamic responses of deviations in frequency and tie-power are illustrated in Figures 3 (a) and (b), respectively, which clearly illustrates the dominance of FOPDN-FOPIDN controller (with two sequential control loops) over others in terms of oscillations magnitude and settling time.

To compare the convergence characteristics of CA, the FOPDN-FOPIDN controller with various computational techniques like cuckoo search, firefly and flower pollination are considered and optimised separately. The tuned parameters of these techniques are shown in Appendix B. The comparison of system dynamic responses and convergence characteristics of the optimisation techniques are shown in Figures 3 (c) and (d). It is seen from Figures 3(c) and (d) that the responses corresponding to CA have less settling time as compared to others. Also, CA converges faster than other algorithms. Hence, the CA is considered for optimisation in the rest of the studies. The respective tuned parameters with these computational techniques are not shown.
TABLE 1 The optimum value of controller gains and other parameters with realistic dish-Stirling solar thermal system (RDSTS) and AC tie-line under the poolco transaction

| Fractional-order proportional-integral (FPI) controller | Computational time = 310 s |
|-------------------------------------------------------|---------------------------|
| $K_{P1} = 0.9038$, $K_{I1} = 0.2522$, $\lambda_1 = 0.8801$, $T_{I1} = 0.6741$, $T_{I12} = 2.2713$, $T_{dI1} = 0.1418$, $T_{dI12} = 4.2707$ |
| $K_{P2} = 0.8334$, $K_{I2} = 1.55342$, $\lambda_2 = 0.1296$, $T_{I2} = 0.5476$, $T_{I22} = 2.1151$, $T_{dI2} = 0.5002$, $T_{dI22} = 7.6067$ |
| $K_{P3} = 1.2332$, $K_{I3} = 1.28519$, $\lambda_3 = 0.8308$, $T_{I3} = 0.9569$, $T_{I32} = 3.6067$, $T_{dI3} = 0.7466$, $T_{dI32} = 8.3953$ |

| Proportional-integral-derivative filter with coefficient (N) (PIDN) controller | Computational time = 325 s |
|---------------------------------------------------------------------------|---------------------------|
| $K_{P1} = 0.9900$, $K_{I1} = 0.5141$, $K_{D1} = 0.5472$, $N_{I1} = 23.7905$, $T_{I1} = 0.6113$, $T_{dI1} = 3.1552$ |
| $K_{P2} = 1.5799$, $K_{I2} = 1.5943$, $K_{D2} = 0.1983$, $N_{I2} = 34.6003$, $T_{I2} = 0.1299$, $T_{dI2} = 2.4222$ |
| $K_{P3} = 0.6227$, $K_{I3} = 0.5373$, $K_{D3} = 0.2442$, $N_{I3} = 22.6644$, $T_{I3} = 0.4766$, $T_{dI3} = 1.2300$ |
| $T_{dI1} = 0.3745$, $T_{dI2} = 6.5952$, $T_{dI3} = 0.4907$, $T_{dI32} = 0.4907$, $T_{dI3} = 2.5746$, $T_{dI32} = 8.8233$ |

| FOPIDN controller | Computational time = 340 s |
|-------------------|---------------------------|
| $K_{P1} = 1.0523$, $K_{I1} = 1.3700$, $\lambda_1 = 0.1591$, $K_{D1} = 1.1020$, $\mu_1 = 0.9987$, $N_{I1} = 79.7015$ |
| $K_{P2} = 1.4733$, $K_{I2} = 0.4903$, $\lambda_2 = 0.3838$, $K_{D2} = 0.2017$, $\mu_2 = 0.9865$, $N_{I2} = 90.0534$ |
| $K_{P3} = 0.7845$, $K_{I3} = 0.1204$, $\lambda_3 = 0.3522$, $K_{D3} = 0.0231$, $\mu_3 = 0.9735$, $N_{I3} = 67.7639$ |
| $T_{I1} = 0.5813$, $T_{I2} = 3.3533$, $T_{I3} = 0.5524$, $T_{I22} = 1.4357$, $T_{I32} = 0.9215$, $T_{dI22} = 2.4334$ |
| $T_{dI1} = 0.9425$, $T_{dI2} = 4.5640$, $T_{dI3} = 0.8566$, $T_{dI32} = 6.7997$, $T_{dI32} = 0.5280$, $T_{dI3} = 8.5985$ |

| Cascaded FOPDN-FOPIDN controller | Computational time = 355 s |
|----------------------------------|---------------------------|
| $K_{P11} = 0.5576$, $K_{P21} = 0.3140$, $\mu_{11} = 0.5479$, $N_{I1} = 48.2025$, $T_{I1} = 0.2890$, $T_{dI1} = 2.3096$, $T_{dI1} = 0.3718$ |
| $K_{P12} = 0.6945$, $K_{I12} = 0.3530$, $\lambda_{12} = 0.9898$, $K_{D12} = 1.6201$, $\mu_{12} = 0.3753$, $N_{I2} = 45.415$, $T_{dI2} = 5.2338$ |
| $K_{P13} = 0.5431$, $K_{I13} = 1.3861$, $\mu_{13} = 0.4935$, $N_{I3} = 83.4213$, $T_{I3} = 0.3115$, $T_{dI3} = 3.8774$, $T_{dI3} = 0.3422$ |
| $K_{P14} = 0.9814$, $K_{I14} = 0.6597$, $\mu_{14} = 0.9798$, $K_{D14} = 1.7223$, $\mu_{14} = 0.6830$, $N_{I2} = 75.615$, $T_{dI2} = 7.1491$ |
| $K_{P13} = 0.6052$, $K_{I13} = 1.4933$, $\mu_{13} = 0.7299$, $N_{I3} = 91.343$, $T_{I3} = 0.9318$, $T_{dI3} = 1.1306$, $T_{dI3} = 0.1957$ |
| $K_{P12} = 0.3499$, $K_{I12} = 0.5282$, $\lambda_{12} = 0.9188$, $K_{D12} = 1.6700$, $\mu_{12} = 0.1989$, $N_{I3} = 94.132$, $T_{dI3} = 4.2370$ |

5.1.2 Bilateral-based transactions in the three-area thermal system with RDSTS

Figure 1(a-ii) is considered for investigation. In this bilateral case, the DISCOs of one area are free to interact with any other GENCOs of same or another area:

| DPM\_Bilateral = |
|------------------|
| 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 |
| 0.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 |
| 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |
| 0.2 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |
| 0.2 | 0.2 | 0.2 | 0.1 | 0.2 | 0.1 |

The DPM considered in bilateral transactions is given by Equation (32). The steady-state output values of the GENCOs under bilateral transactions are calculated using Equation (32) and are given by Equations (33–38):

GENCO-1 = \((0.2 + 0.2 + 0.1 + 0.2 + 0.2) \times 0.01\) \(= 0.011\) p.u. MW

GENCO-2 = \((0.2 + 0.2 + 0.1 + 0.2 + 0.1) \times 0.01\) \(= 0.009\) p.u. MW

Using the procedure given by [6], the apfs are calculated for GENCOs and is given by $apf_{I1} = 0.55$, $apf_{I2} = 0.45$, $apf_{I3} = 0.5$, $apf_{I4} = 0.45$, $apf_{I1} = 0.5$ and $apf_{I2} = 0.5$, respectively. The power demand of 0.01p.u. MW is considered by all the DISCOs.

Secondary controllers like FOP1, PIDN, FOPIDN, and cascaded FOPDN-FOPIDN are selected one at a time and
are optimised using CA. The optimised gains and parameters of controller and RDTS are shown in Table 2. The system dynamic responses with deviations in frequency, tie-power, the power generated by GENCO-1 and GENCO-2 are shown in Figures 4(a)–(d). From the responses, it is clear that the proposed cascaded FOPDN-FOPIDN controller has less settling time, oscillations magnitude over other controllers. Deviations in scheduled tie-power are calculated using Equations (4) and (5) and are found to be \( \Delta P_{\text{tie scheduled 1–2}} = \Delta P_{\text{tie scheduled 2–3}} = \Delta P_{\text{tie scheduled 3–1}} = 0 \).

5.1.3 Contract violation-based transactions in the three-area thermal system with RDSTS

The system considered for investigation is shown in Figure 1(a-ii). In contract violation, an additional uncontracted load of 0.01 p.u. MW is demanded by the DISCO-1 of area-1, which is to be supplied by GENCO-1 and GENCO-2 of area-1 only. The total load \( \Delta P_{Ld1} \) of area-1 is given by

\[
\Delta P_{Ld1} = (0.01 + 0.01) + 0.01 = 0.03 \text{ p.u. MW (40)}
\]

Based on the apf calculation mentioned in [6], the apfs are as follows \( \text{apf}_{11} = 0.4736 \), \( \text{apf}_{12} = 0.5263 \), \( \text{apf}_{21} = 0.5714 \), \( \text{apf}_{22} = 0.4285 \), \( \text{apf}_{31} = 0.45 \) and \( \text{apf}_{32} = 0.55 \), respectively. The steady-state output values of the GENCOs under contract violation transactions are calculated using Equation (39) and are given by (41–46):

\[
\text{GENCO-1} = \{(0.2 + 0.1 + 0.2 + 0.2 + 0.1 + 0.1) \times 0.01\}
+ (0.4736 \times 0.01) = 0.013736 \text{ p.u. MW (41)}
\]

\[
\text{GENCO-2} = \{(0.2 + 0.1 + 0.2 + 0.1 + 0.2 + 0.2) \times 0.01\}
+ (0.5263 \times 0.01) = 0.015263 \text{ p.u. MW (42)}
\]

\[
\text{GENCO-3} = \{(0.2 + 0.2 + 0.2 + 0.2 + 0.2) \times 0.01\}
+ (0.5714 \times 0.01) = 0.017714 \text{ p.u. MW (43)}
\]

\[
\text{GENCO-4} = \{(0.2 + 0.2 + 0.1 + 0.1 + 0.2 + 0.1) \times 0.01\}
+ (0.4285 \times 0.01) = 0.013285 \text{ p.u. MW (44)}
\]
TABLE 2  Optimum values of controller gains and other parameters in the system considering RDSTS and AC tie-line in the bilateral transaction

| Controller  | Computational time = 312 s | Computational time = 327 s | Computational time = 335 s |
|-------------|-----------------------------|-----------------------------|-----------------------------|
| FOPI controller | $K_{P1} = 0.6124, K_{I1} = 1.1311, \lambda_1 = 0.2202, T_{11} = 0.7820, T_{12} = 1.4507, \delta_{011} = 0.1095, \delta_{012} = 7.5181,$ | $K_{P1} = 1.0330, K_{I1} = 0.8780, K_{D1} = 0.7340, N_3 = 64.9210, T_{11} = 0.7556, T_{12} = 1.3289,$ | $K_{P1} = 0.0372, K_{I1} = 0.0468, \lambda_1 = 0.6366, K_{D1} = 0.9146, \mu_1 = 0.9886, N_1 = 80.4464, T_{11} = 3.0221, T_{021} = 0.3038,$ |
| PIDN controller | $K_{P2} = 0.2712, K_{I2} = 0.6836, \lambda_2 = 0.8547, T_{22} = 1.0264, \delta_{021} = 0.8087, \delta_{022} = 6.2130,$ | $K_{P2} = 0.2946, K_{I2} = 1.4795, K_{D2} = 1.8843, N_3 = 10.9108, T_{31} = 0.9770, T_{32} = 1.2378,$ | $K_{P2} = 0.5992, K_{I2} = 0.4854, \lambda_2 = 0.2711, K_{D2} = 0.1259, K_{P2} = 0.9678, N_2 = 78.65860, T_{32} = 3.9473,$ |
| FOPIDN controller | $K_{P3} = 1.1824, K_{I3} = 0.8629, \lambda_3 = 0.9905, T_{32} = 2.8758, \delta_{031} = 0.2660, T_{32} = 5.1777,$ | $T_{031} = 9.0850, T_{032} = 0.8635, T_{033} = 9.8961, \delta_{031} = 0.7275, T_{032} = 6.7080,$ | $T_{031} = 4.6870, T_{032} = 0.3975, T_{033} = 4.0663, \delta_{031} = 0.1506, T_{032} = 9.3997,$ |
| Cascaded FOPDN-FOPIDN controller | $K_{P31} = 1.0721, K_{I31} = 1.4216, \mu_{31} = 0.8586, N_{31} = 49.7815, T_{12} = 0.4412, T_{12} = 3.0221, T_{021} = 0.3038,$ | $K_{P32} = 0.9232, \lambda_{32} = 0.9899, K_{D32} = 0.5125, \mu_{32} = 0.8927, N_{32} = 22.762, T_{12} = 8.0095,$ | $K_{P31} = 1.7201, K_{I31} = 0.4388, \mu_{31} = 0.7625, N_{31} = 50.4506, T_{12} = 0.1750, T_{12} = 1.1815, T_{021} = 0.2354,$ |
| | + $(0.4500 \times 0.01) = 0.013500 \text{ p.u. MW}$ | + $(0.1000 \times 0.01) = 0.010000 \text{ p.u. MW}$ | + $(0.05500 \times 0.01) = 0.016500 \text{ p.u. MW}$ |

5.1.4  System dynamic response comparison considering with and without RDSTS

DPM in Equations (25), (32) and (39) are considered for various transactions like poolco, bilateral and contract violation is considered with and without RDSTS model using cascaded FOPDN-FOPIDN controller and CA algorithm. CA is used for optimization of the controller and RDSTS parameters. The comparison of corresponding dynamic responses and the system with and without RDSTS for all transactions in the deregulated scenario are shown in Figures 6(a)–(c). It is clearly seen that with the introduction of RDSTS systems in three-area thermal systems, system dynamics responses are improved a lot with faster settling time, rise time and fewer oscillations.

5.2  System dynamics with realistic HVDC tie-lines

Here, the RHVDC tie-lines that are developed using Equations (10)–(12) are utilised for the study under bilateral transactions for the first time. The effect of RHVDC tie-line is studied by considering RHVDC tie-line alone
and parallel AC-RHVDC tie-line along with RDSTS system, the proposed cascaded FOPDN-FOPIDN controller and CA as its optimisation technique. The investigated system with RHVDC is shown in Figures 1(a-iii) and (a-iv), respectively.

5.2.1  Realistic dynamics of a three-area thermal system with RDSTS in a combination of RHVDC tie-line alone

To study the effect of RHVDC tie-lines using bilateral transactions, the AC tie-lines of the considered system in Section 5.1.2 (thermal and RDSTS models in all the three areas) is replaced with RHVDC tie-line developed using Equations (10)–(12). The gains of the secondary controller (FOPDN-FOPIDN) and RDSTS parameters are optimised simultaneously using CA and are given in Table 4. The dynamic responses of deviations in tie-power and frequency are shown in Figures 7(a)–(d) and are compared with the system having AC tie-lines. The dynamic responses with RHVDC tie-lines show better responses in terms of oscillations magnitude, settling time, and deviations in peak.

5.2.2  Dynamics of the three-area thermal system using parallel AC tie-line and RHVDC tie-lines

The system in Section 5.1.2 is considered for investigation under bilateral transactions. To achieve the optimal power flow in the

### TABLE 3  Optimised controller gains and parameters in the system considering RDSTS and AC tie-line in contract violation transaction

| Controller | KP1 | KI1 | Td1 | L1 | KP2 | KI2 | Td2 | L2 | KP3 | KI3 | Td3 | L3 | KP4 | KI4 | Td4 | L4 |
|------------|-----|-----|-----|----|-----|-----|-----|----|-----|-----|-----|----|-----|-----|-----|----|
| FOPIDN     | 1.4181 | 0.4518 | 0.2258 | 0.1982 | 2.7539 | 0.0025 | 4.3467 |
|            | 0.8378 | 0.9815 | 0.8060 | 0.4777 | 3.6346 | 0.3266 | 7.5380 |
|            | 0.5325 | 0.2638 | 0.9364 | 0.9825 | 3.3555 | 0.1080 | 9.6211 |

### TABLE 4  Optimum values of controller gains and parameters with RDSTS and considering realistic high-voltage direct current (RHVDC) tie-line alone

| Parameter | Value |
|-----------|-------|
| KP1       | 1.3906 |
| KI1       | 1.3779 |
| Td1       | 0.6984 |
| Td2       | 3.7858 |
| N11       | 29.0831 |
| T11       | 0.4296 |
| T12       | 2.2647 |
| T21       | 28.1710 |
| T22       | 7.9056 |
| N22       | 65.6565 |
| T31       | 0.6527 |
| T32       | 38.7534 |
| N32       | 38.7534 |
| T41       | 4.5279 |
| T42       | 4.3467 |
| N42       | 4.3467 |
| T51       | 8.4243 |
| T52       | 8.4243 |
| N52       | 8.4243 |
| T61       | 3.7858 |
| T62       | 3.7858 |
| N62       | 3.7858 |
| T71       | 0.1998 |
| T72       | 0.1998 |
| N72       | 0.1998 |
| T81       | 0.1998 |
| T82       | 0.1998 |
| N82       | 0.1998 |

### Computational time

- FOPIDN controller: 320 s
- CA optimised FOPDN-FOPIDN: 351 s

Notes: The gains of the secondary controller (FOPDN-FOPIDN) and CA optimised FOPDN-FOPIDN are given in Table 4.
FIGURE 4  System dynamic response comparison versus time (a) deviation of frequency in area-1, (b) deviation of tie power among area-2 and area-3, (c) generation companies-1 (GENCO-1) power generation deviation, and (d) GENCO-2’s power generation deviation

FIGURE 5  System dynamic response comparison versus time (a) frequency deviation in area-1, (b) deviation in tie power among area-1 and area-2, (c) deviation in tie power of actual, scheduled and error between area-1 and area-2, and (d) GENCO-1 power generation deviation
power system, the AC tie-lines in Section 5.1.2 and RHVDC tie-lines in Section 5.2.1 are replaced by the combination of AC and RHVDC tie-lines. The optimum gains and parameters of cascaded FOPDN-FOPIDN controller and RDTS are optimised using CA, and optimum values are shown in Table 5. Figures 8 (a)–(d) show the responses with AC and RHVDC tie-lines. It is clearly seen that the responses parallel combination of both RHVDC and AC tie-lines show better performance than for with RHVDC tie-line alone in terms of oscillations magnitude, settling time, and deviations in peak.

FIGURE 6 System dynamic responses versus time with and without considering RDSTS in all three-areas (a) deviation of frequency in area-1 of poolco transactions, (b) deviation in tie-power among area-1 and area-2 of bilateral transactions, and (c) deviation in tie-power among area-2 and area-3 of contract violation transactions

FIGURE 7 System dynamic responses versus time with and without RHVDC tie-line under bilateral transactions (a) deviation in frequency of area-1, (b) deviation in frequency of area-2, (c) deviation in tie-power among area-2 and area-3, and (d) deviation in tie-power among area-3 and area-1
FIGURE 8 System dynamic responses with RHVDC tie-line and combinations of both (AC and RHVDC tie-line) under bilateral transactions (a) deviation in frequency of area-2 versus time, (b) deviation in frequency of area-3 versus time, (c) deviation in tie-power among area-1 and area-2 versus time, and (d) tie-power deviation between area-3 and area-1 versus time.

TABLE 5 Crow-search algorithm optimised FOPDN-FOPIDN controller gains and parameters with considering RDSTS, the parallel combination of RHVDC tie-line and AC tie-line

| Controller Gain/Parameter | Area 1 | Area 2 | Area 3 |
|---------------------------|--------|--------|--------|
| $K_{P11}$                 | 0.7128 | 1.2210 | 1.5596 |
| $K_{D11}$                 | 0.3889 | 0.9989 | 0.8827 |
| $K_{I11}$                 | 0.7109 | 0.6733 | 1.0831 |
| $N_{11}$                  | 30.6273| 0.0131 | 55.3241|
| $T_{dS11}$                | 0.4278 | 0.0131 | 5.2067 |
| $K_{P21}$                 | 1.221  | 1.8729 | 1.8073 |
| $K_{I21}$                 | 1.2210 | 1.3792 | 0.3116 |
| $N_{21}$                  | 30.6273| 0.0131 | 55.3241|
| $T_{dS21}$                | 0.4278 | 0.0131 | 5.2067 |
| $K_{P31}$                 | 0.7128 | 1.8729 | 1.8073 |
| $K_{I31}$                 | 0.7109 | 1.3792 | 0.3116 |
| $N_{31}$                  | 30.6273| 0.0131 | 55.3241|
| $T_{dS31}$                | 0.4278 | 0.0131 | 5.2067 |
| $K_{P32}$                 | 0.7128 | 1.8729 | 1.8073 |
| $K_{I32}$                 | 0.7109 | 1.3792 | 0.3116 |
| $N_{32}$                  | 30.6273| 0.0131 | 55.3241|
| $T_{dS32}$                | 0.4278 | 0.0131 | 5.2067 |

6 CONCLUSION

In this study, a maiden attempt has been made to investigate the effect of RDSTS and RHVDC tie-line models on system dynamics in LFC of the three-area system under deregulated scenario and result reveals that use of realistic models improves system responses. Also, the use of the proposed cascaded FOPDN-FOPIDN controller improves the system performance over other controllers like FOPI, PIDN, and FOPIDN with better peak magnitude, settling time and oscillations magnitude under the various policy schemes like poolco, bilateral and contract violation. The gains and other parameters of the proposed FOPDN-FOPIDN controller and RDSTS system considering lead-lead compensation and transient droop compensation are successfully optimised by the use of crow-search algorithm. The realistic model of HVDC tie-line with capacitance, rated voltage level and power electronic converters with inertia emulation control strategy is modelled. The study on various combinations of tie-lines under bilateral transactions reveals that parallel combinations of AC-RHVDC tie-lines improve system dynamics over AC tie-line and RHVDC tie-line. Thus, this study recommends (1) the new cascade controller called cascaded FOPDN-FOPIDN controller for LFC of multi-area power system, (2) the RDSTS and RHVDC tie-line models for LFC study, (3) parallel AC-RHVDVC line for LFC in deregulated scenario, and (4) the CS algorithm can be used for any LFC under deregulated environment.

NOMENCLATURE

| Symbol | Definition |
|--------|------------|
| $a_{jk}$ | $(P_{gj}/P_{tk})$ |
| apf    | area participation factor |
| $B_j$  | area-j’s frequency response (pu MW/Hz) |
| CA     | crow-search algorithm |
| cpf    | contract participation factor |
| CSA    | cuckoo search algorithm |
| DISCO  | distribution companies |
| $D_j$  | $\Delta P_{Dj}/\Delta F_j$ (pu MW/Hz) |
| DOF    | degree of freedom |
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APPENDIX A

a. Nominal thermal system parameters are:
Nominal frequency $F = 60$ Hz, $T_{jk, AC} = 0.086$pu MW/rad, step load perturbation (SLP) = 1%, loading = 50%, $P_{r1} = 1000$ MW, $P_{r2} = 2000$ MW, $P_{r3} = 4000$ MW, $D_j = 8.33 \times 10^{-3}$ p.u. MW/Hz, $H_j = 5s$, $R_j = 2.4$ p.u. MW/Hz, $B_j = 0.425$ p.u. MW/Hz, $T_{jy} = 0.08$ s, $T_{jy} = 0.3$ s, $T_{jy} = 10$ s, $K_{ji} = 0.5$, $T_{jy} = 20$ s, $K_j = 1.8$, $T_j = 1.8$ s, $T_{jy} = 1.0s$, $T_{jy} = 3.0$ s, SLP = 1%

b. RDSTS

$$K_{DSTS} = 1, T_{DSTS} = 5 \text{ s}$$

c. RHVDC tie-line

$$S_{VSC} = 600 \text{ MW}, V_{DC} = 300 \text{ KV}, C_{DC} = 0.148 \text{ mF}, N_{DC} = \text{three capacitors}, H_{VSC} = 5 \text{ s}, T_{eqv,DC} = 0.1732, P_{max} = 200 \text{ MW}, I_{DC} = 50\%$$

Tuned parameters of various algorithms

a. Cuckoo search algorithm

Number of nests = 50, discovery rate = 0.5, levy exponent = 1.5, maximum generation = 500, number of dimensions = 10.

b. Firefly algorithm

Firefly size = 50, maximum generation = 500, alpha = 0.25, beta = 0.8, gamma = 1

c. Flower pollination algorithm

Population size = 50, maximum generation = 500, switching probability = 0.8, levy distribution index = 1.5, levy step size scaling factor = 0.01.

d. Crow-search algorithm

Flock size ($n$) = 50, flight length = 0.2, awareness probability = 0.1, maximum generation = 500.