A Novel Sooty Terns Algorithm for Deregulated MPC-LFC Installed in Multi-Interconnected System with Renewable Energy Plants

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Abstract: This paper introduces a novel metaheuristic approach of sooty terns optimization algorithm (STOA) to determine the optimum parameters of model predictive control (MPC)-based deregulated load frequency control (LFC). The system structure consists of three interconnected plants with nonlinear multisources comprising wind turbine, photovoltaic model with maximum power point tracker, and superconducting magnetic energy storage under deregulated environment. The proposed objective function is the integral time absolute error (ITAE) of the deviations in frequencies and powers in tie-lines. The analysis aims at determining the optimum parameters of MPC via STOA such that ITAE is minimized. Moreover, the proposed STOA-MPC is examined under variation of the system parameters and random load disturbance. The time responses and performance specifications of the proposed STOA-MPC are compared to those obtained with MPC optimized via differential evolution, intelligent water drops algorithm, stain bower braid algorithm, and firefly algorithm. Furthermore, a practical case study of interconnected system comprising the Kuraymat solar thermal power station is analyzed based on actual recorded solar radiation. The obtained results via the proposed STOA-MPC-based deregulated LFC confirmed the competence and robustness of the designed controller compared to the other algorithms.

Keywords: deregulated LFC; renewable energy; model predictive control; sooty terns optimization

1. Introduction

In the interconnected system, the frequency stabilization is very significant to keep the stability of the power system which is achieved by load frequency control (LFC). LFC aims at keeping the frequency at nominal value and vanishing the aberration in frequency and power flow in tie-lines to zero in case of sudden load disturbance. The objective of interconnecting multiplants is to share loads and maintain the system dependability in the event of curtailment of any generation plant. Recently, renewable energy sources (RESSs) have been combined with conventional plants and installed in electric grids [1–3]. The deregulated power system is a conventional power system with modified structure. It consists of many autonomous entities such as transmission companies (TRANSCOs), distribution companies (DISCOs), and generation companies (GENCOs). The GENCOs, as autonomous power units, may contribute in the LFC task. Moreover, DISCOs may contract unilaterally...
with GENCOs, nonconventional power source units, or independent power producers (IPPs) in different areas. In the deregulated system, control is highly decentralized and independent system operators (ISOs) are responsible for keeping the steady frequency and tie-line power flow within their acceptable limits [4,5]. The deregulated LFC is presented in many reported works with optimal control techniques. In [6], fuzzy proportional-integral-derivative (F-PID) was optimized via mine blast algorithm (MBA), and the presented controller was designed with five memberships. RESs and flexible alternating current transmission (FACT) are installed in the interconnected power system to minimize overshoot and settling time. Sine cosine algorithm is used to adapt cascade control fractional order (FO), integral FO (FOI), and proportional-derivative (FOPD) such that it minimizes the integral square error (ISE) [7]. Deregulated LFC with installed thyristor-controlled phase shifter (TCPS) and superconducting magnetic energy source (SMES) have been presented with the aid of adaptive neuro Fuzzy system (ANFIS) to improve the dynamic response of the system [8]. Improved particle swarm optimization (IPSO) has been presented to optimize tilted integral derivative (TID) and FOPID-based deregulated LFC installed with static synchronous series compensator (SSSC), the considered fitness function to be minimized was the integral time square error (ITSE) [9]. Deregulated LFC has been presented with incorporating dish-Stirling solar thermal system (DSTS), geothermal power plant (GTPP), and high-voltage direct current (HVDC)-based cascade FOPI-FOPID optimized via sin cosine algorithm (SCA) [10]. TID control has been adapted by hybrid teaching learning-based optimizer and pattern search (hTLBO-PS) with SMES and TCPS; the employed fitness function in that work was ISE [11]. Fuzzy-PID-LFC controller has been determined through bacterial foraging optimization algorithm (BFOA) for multisources interconnected systems [12]. Sliding mode control (SMC)-based output feedback has been employed to optimize LFC installed in multi-sources interconnected system, the target is to minimize the ISE via hybrid flower pollination and pattern search (hFPA-PS) [13]. In [14], cascade tilt-integral–TID (C-TI-TID) was presented to optimize deregulated LFC installed in four areas via water cycle algorithm (WCA), and the results were compared with C-PI-TD. Redox flow battery (RFB) was introduced to minimize the peak overshoot and settling time of the frequency and tie-line power responses for multi-interconnected system with multisources with LFC, using predictive functional modified PID (PFMPID) adjusted via grasshopper optimization algorithm (GOA); seven membership functions were employed to design the fuzzy controller [15]. In [16], the volleyball premier league algorithm (VPL) was presented to optimize cascade structure of a two-degree-of-freedom PI and FOPD controller with filter incorporated with HVDC and distributed generation (DG) in deregulated LFC. A quasi-oppositional harmony search algorithm (QOHSA) has been introduced to optimize deregulated LFC with Sugeno fuzzy-PID with three membership functions-integrated thyristor-controlled series compensator (TCSC); ISE was selected as the target [17–19]. In [20], PID with double-derivative (PIDD)-based deregulated LFC with integrated HVDC was introduced and optimized via fruit fly optimization algorithm (FOA). A cascade PID with filter (PIDF) and one plus FO derivative (1+FOD) were employed to simulate LFC with HVDC and SSSC, and the controller was optimized via salp swarm algorithm (SSA) [21]. In [22], FOA was introduced to tune a PID controller with filter incorporated in a deregulated LFC-unified power flow controller (UPFC) and HVDC. In [23], a PI controller was presented in a deregulated LFC installed with multisources and capacitive energy storage (CES) optimized via SCA. A modified virus colony search (MVCS) was studied to optimize PID controller-based deregulated LFC installed in four interconnected areas [24]. A PID controller was optimized via artificial cooperative search algorithm (ACSA)-based deregulated LFC with combined RFB and SMES [25]. A bat algorithm was presented to optimize FOPID-based deregulated LFC with incorporated SMES and UPFC to minimize ITAE [26].

Recently, there are some new approaches applied to simulate the deregulated LFC, such as SSA [27,28], crow search algorithm (CA) [29], the whale optimization [30], GOA [31], MBA [32], opposition-based interactive search algorithm (OISA) [33], and quasi-opposition
lion optimization algorithm (QOLOA) [34]). Table 1 presents comparison of previous studies reported in deregulated LFC on the basis of control type, optimization approach, and system construction. Moreover, comparison of the reported approaches that have been conducted in LFC in three areas with multisources deregulated is given in Table 2.

Regarding the reported works and the comparisons given in Tables 1 and 2, one can see that few researchers considered deregulated multi-interconnected systems including optimal MPC and RESs. Moreover, the application of metaheuristic approaches in this field is still limited. Furthermore, the traditional controllers reported in many previous works failed in vanishing the fluctuations in frequencies and tie-line powers for interconnected systems when nonlinearities of system are considered. Additionally, most of the metaheuristic approaches used in that field may trap in local optima.

The authors covered these defects by proposing a novel methodology incorporated the sooty terns optimization algorithm (STOA) to design the model-predictive control (MPC)-based LFC installed in multi-interconnected plants. The parameters of MPC are identified via STOA such that ITAE of aberrations in frequencies and powers in tie-lines is minimized. The contribution of this work is summarized as follows:

• A novel STOA approach is proposed to compute the MPC optimum parameters-based nonlinear deregulated LFC combined with conventional, RESs, and energy storage systems (ESSs).
• Wind turbine (WT), photovoltaic (PV) model with maximum power point tracker (MPPT), hydropower, diesel generator, and thermal plant are presented and modeled in deregulated LFC.
• Practical case study of interconnected system comprising the Kuraymat solar thermal power station is analyzed based on actual recorded solar radiation.
• The proposed MPC-LFC optimized via STOA achieved robust performance under changing some parameters of the system and random load disturbance.

The paper is organized as follows: Section 2 introduces the mathematical model of the deregulated LFC, Section 3 presents the proposed methodology, Section 4 presents simulation results, and Section 5 introduces conclusions.
Table 1. Comparison of reported works conducted in deregulated LFC.

| Author             | Year       | Deregulated/Conventional | Type of Controller | Optimization Approach | System Construction | Has RESs?/Type | Has ESs?/Type | Defects                                      |
|--------------------|------------|--------------------------|--------------------|-----------------------|---------------------|----------------|---------------|---------------------------------------------|
| Panwar, A. et al.  | 2018       | Conventional             | PID                | BFOA                  | 2 areas             | √ (Fuel cell) | ×             | − The deviation in frequency is large.      |
| Shiva, C.K. et al. | 2016–2017  | Deregulated              | PID                | QOHS                  | 2, 3 and 5 areas,   | ×             | ×             | − Weak performance in various operating    |
| Mohanty, B. et al.| 2015       | Deregulated              | PIDD               | FOA                   | 2-areas, multisources | ×             | ×             | conditions.                                 |
| Dhundhara, S. et al.| 2018      | Deregulated              | PI                 | SCA                   | 2 areas, multisources | ×             | √ (CES)       |                                             |
| Ghasemi-marzabali, A.| 2020     | Deregulated              | PID                | MVCS                  | 4 areas, multisources | ×             | ×             |                                             |
| Selvaraju, R.K. et al.| 2016   | Deregulated              | PI                 | ACSA                  | 2 areas, multisources | ×             | √ (SMES and RFB) |                                             |
| Kumar, R. et al.| 2020       | Deregulated              | PI                 | Wahle algorithm       | 2 areas, multisources | ×             | √ (CES)       |                                             |
| Shankar, R. et al.| 2019       | Deregulated              | PID                | FOA                   | 2 areas, multisources | ×             | ×             |                                             |
| Kumar, A. et al.| 2021       | Deregulated              | PIDN               | QOLOA                 | 2 areas, multisources | √ (WT and PV) | √ (SMES and RFB) |                                             |
| Morsali, J. et al.| 2018       | Deregulated              | FOPID              | MGSO                  | 2 areas, multisources | ×             | ×             | − More consumption time. To improve system |
| Prakash, A. et al.| 2020       | Deregulated              | PIDN(1+FOD)        | SSA                   | 2 areas, multisources | √ (WT)        | ×             | dynamics, several parameters of control    |
| Mishra, D.K. et al.| 2020       | Deregulated              | FOPID              | Bat Algorithm         | 2 areas, multisources | ×             | √ (SMES)      | must be optimally tuned.                   |
| Arya, Y. [2]      | 2019       | Deregulated              | FO-fuzzy PID       | BFOA                  | 2 and 3 areas,      | ×             | √ (RFB)       |                                             |
| Mishra, A.K. et al.| 2021      | Deregulated              | FO-fuzzy PID       | SSA                   | 3 areas, multisources | √ (WT, STPP and GTPP) | √ (RFB) |                                             |
| Author                  | Year | Deregulated/Conventional | Type of Controller | Optimization Approach | System Construction | Has RESs?/Type | Has ESs?/Type | Defects                                                                 |
|-------------------------|------|--------------------------|--------------------|----------------------|--------------------|----------------|--------------|-------------------------------------------------------------------------|
| Fathy, A. et al. [6]    | 2020 | Conventional/deregulated | Fuzzy PID          | MBA                  | 2 and 3 areas      | ×              | ×            | More consumption time due to fuzzy membership.                          |
| Arya, Y. et al. [12]    | 2017 | Conventional/deregulated | Fuzzy PI/PID       | BFOA                 | 2 area/2 areas, multisources | ×              | ×            |                                                                          |
| Sharma, M. et al. [27]  | 2020 | Deregulated              | Fuzzy PIDN         | SSA                  | 2 areas, multisources | ×              | √ (RFB)      |                                                                          |
| Veerasamy, V. et al. [1] | 2020 | Conventional             | Cascade PI-PD      | PSO-GSA              | 2 areas, multisources | √ (WT, Fuel cell) | √ (Battery) | Many controller parameters are required which increases the consumption time. Selection of primary and secondary loops of controller is critical to achieve best system responses. |
| Tasnin, W. et al. [7]   | 2019 | Deregulated              | FOI-FOPD          | SCA                  | 3 areas, multisources | √ (WT, STPP and GTPP) | ×            |                                                                          |
| Tasnin, W. et al. [10]  | 2018 | Deregulated              | FOI-FOPID         | SCA                  | 2 areas, multisources | √ (DSTS and GTPP) | ×            |                                                                          |
| Kumari, S. et al. [14]  | 2020 | Deregulated              | Calculus-based cascade TI-TID | WCA                | 4 areas, multisources | ×              | ×            |                                                                          |
| Prakash, A. et al. [16] | 2019 | Deregulated              | 2-DOF-PI-FOPDN    | VPL                  | 2 areas, multisources | ×              | ×            |                                                                          |
| Babu, N.R. et al. [23]  | 2021 | Deregulated              | FOPDN-FOPIDN      | CA                   | 3 areas, multisources | √ (Realistic DSTS) | ×            |                                                                          |
| Raj, U. et al. [33]     | 2020 | Deregulated              | 2DOF-PIDN-FOID    | OISA                 | 3 areas, multisources | √ (WT and PV)  | ×            |                                                                          |
| Pappachen, A. et al. [8] | 2016 | Deregulated              | ANFIS              | ×                    | 2 areas, multisources | ×              | √ (SMES)     | More complicated than other methods.                                    |
| Khamari, D. et al. [11] | 2020 | Deregulated              | TID                | hTLBO-PS            | 2 areas, multisources | √ (Solar thermal) | √ (SMES)    |                                                                           |
| Mohanty, B. [15]        | 2020 | Deregulated              | Output feedback SMC | hFPA-PS            | 2 areas, multisources | ×              | ×            | The parameters of controller have complete impact on the system dynamics. |
| Nosratabadi, S.M. et al. [15] | 2019 | Deregulated              | Modified PID      | GOA                  | 3 areas, multisources | √ (WT)         | √ (RFB)     |                                                                           |
| Das, M.K. et al. [31]   | 2021 | Deregulated              | PID-RLNN           | GOA                  | 3 areas, multisources | √ (WT)         | √ (SMES)     |                                                                           |
| Das, S. et al. [32]     | 2021 | Deregulated              | TID-(1+PI)        | MBA                  | 3 areas, multisources | √ (WT, GTPP and wave energy) | ×            |                                                                           |
| Present study           |      | Deregulated              | Optimal MPC       | STOA                 | 3 areas, multisources | √ (WT, PV and STPP) | √ (SMES)    |                                                                           |
Table 2. Comparison of reported works conducted in three-areas with multi-sources deregulated LFC.

| Author                   | Year | Type of Controller | Optimization Approach | Linear/Nonlinear | Type of Generator | Has RESs/?Type | Cases Study | Has ESs/?Type |
|--------------------------|------|--------------------|-----------------------|------------------|-------------------|----------------|-------------|--------------|
| Arya, Y. [2]             | 2019 | FO-fuzzy PID       | BFOA                  | Linear           | Thermal-hydro     | ×              | √           | (RFB)        |
| Tasnin, W. et al. [7]    | 2019 | Cascade FOI-FOPD   | SCA                   | Linear           | Thermal           | √ (WT, STPP and GTPP) | √           | √           | √           | ×           | ×           | ×           | ×           | (RFB)        |
| Nosratabadi, S.M. et al. [15] | 2019 | Modified PID       | GOA                   | Nonlinear (GRC-GDB) | Thermal-hydro-gas-diesel | √ (WT) | √           | √           | √           | √           | ×           | √ (WT) |
| Shiva, C.K. et al. [17]  | 2016 | PID                | QOHS                  | Linear           | Thermal           | ×              | √           | ×           | ×           | ×           | ×           | (WT) |
| Mishra, A.K. et al. [28] | 2021 | FO-fuzzy PID       | SSA                   | Nonlinear (GRC-GDB) | Thermal           | √ (WT, STPP and GTPP) | √           | √           | √           | ×           | (RFB)        |
| Babu, N.R. et al. [29]   | 2021 | Cascade FOPDN-FOPIDN | CA                   | Nonlinear (GRC)  | Thermal           | √ (Realistic DSTS) | √           | √           | √           | ×           | ×           | ×           |
| Das, M.K. et al. [31]    | 2021 | PID-RLNN           | GOA                   | Linear           | Thermal-hydro-gas-diesel | √ (WT) | √           | √           | ×           | (SMES)        |
| Das, S. et al. [32]      | 2021 | TIDN-(1 + PI)      | MBA                   | Linear           | Thermal-hydro     | ×              | √           | ×           | ×           | ×           | ×           | (WT) |
| Raj, U. et al. [33]      | 2020 | Cascade 2DOF-PIDN  | OISA                  | Linear           | Thermal-hydro-gas-diesel | √ (WT and PV) | √           | □           | □           | □           | □           | □           |
| Present study            |      | Optimal MPC        | STOA                  | Nonlinear (GRC-GDB) | Thermal-hydro-diesel | √ (WT, PV and STPP) | √           | √           | √           | √           | √           | √           | (SMES) |

1 = Unilateral-based transaction, 2 = bilateral transaction, 3 = contract violation transaction, 4 = random load disturbance, and 5 = actual solar radiation.
2. Mathematical Model of Deregulated LFC

The proposed system considered in this paper includes three interconnected plants; the first area comprises reheat thermal, wind power units, and DISCOs (DISCO1 and DISCO2). Area 2 includes hydro, diesel power units, and DISCOs (DISCO3 and DISCO4). Area 3 consists of reheat thermal, PV with MPPT, and DISCOs (DISCO5 and DISCO6). Each plant has SMES; Figure 1 shows the proposed multi-interconnected system topology in the deregulated LFC system. The system construction in the Simulink model is presented in Figure 2.

In deregulated LFC, contracts conducted via GENCOs with DISCOs are made based on the DISCOs Participation Matrix (DPM). The DISCOs number represents the column numbers of DPM, and the GENCOs number is the row numbers of DPM in interconnected systems, the sum of each column in the matrix should be equal to unity. The elements of the matrix depend on contract participation factor (cpf), and the DPM is described by Equation (1).

$$DPM = \begin{bmatrix}
    cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} & cpf_{15} & cpf_{16} \\
    cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} & cpf_{25} & cpf_{26} \\
    cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} & cpf_{35} & cpf_{36} \\
    cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} & cpf_{45} & cpf_{46} \\
    cpf_{51} & cpf_{52} & cpf_{53} & cpf_{54} & cpf_{55} & cpf_{56} \\
    cpf_{61} & cpf_{62} & cpf_{63} & cpf_{64} & cpf_{65} & cpf_{66}
\end{bmatrix}, \sum cpf_{ij} = 1 \ (1)$$

The scheduled steady-state power flow on the tie-line from area i to j is defined as follows:

$$dP_{tie,ij, scheduled} = ((\text{demand of DISCOs in area}_j \text{ from GENCO in area}_i) - (\text{demand of DISCOs in area}_i \text{ from GENCO in area}_j))$$

$$dP_{tie,ij, scheduled} = \sum_{i=1}^{Dn} \sum_{j=1}^{Gn} dP_{i,j}cpf_{ij} - \sum_{j=1}^{Gn} \sum_{i=1}^{Dn} dP_{i,j}cpf_{ji} \ (2)$$

where $Dn$ is the DISCOs number, $Gn$ is the GENCOs number, and $dP_{Li}$ is the load disturbance in area $i$. The actual power flow on tie-line ($dP_{tie,ij, actual}$) can be described as follows:

$$dP_{tie,ij, actual} = (dF_i - dF_j) \times \frac{2\pi T_{ij}}{s} \ (3)$$

where $dF_i$ and $dF_j$ are the frequency deviations in area $i$ and area $j$, $T_{ij}$ is the coefficient of synchronizing between areas $i$ and $j$. The error in tie-line power between area $i$ and area $j$ can be expressed as

$$dP_{tie,ij, error} = dP_{tie,ij, actual} - dP_{tie,ij, scheduled} \ (4)$$
Figure 2. Three interconnected areas with deregulated LFC: (a) Simulink model; (b) subsystem of the proposed MPC-LFC.
The input signal to MPC is the area control error (ACE) which can be written as follows:

$$ACE_i = dF_i \times B_i + dP_{tie, error_i}$$  \hspace{1cm} (5)$$

where $B_i$ is the bias factor of frequency in area $i$.

3. Sooty Terns Optimizer Characteristics

Gaurav Dhiman [35] presented the sooty terns optimization algorithm (STOA) in 2019. Sooty terns are wide range of types with variable sizes and weights, they are sea birds that eat amphibians, earthworms, insects, fish, reptiles, etc. Sooty terns (STs) establish the sound of rain, such as catching worms concealed underground by feet and using crumbs of baking to entice the fish. Generally, STs live in colonies and use their cleverness to locate their prey and attack it. Immigration and attacking the prey are prominent aspects of STs behaviors, and migration is identified as the movement of seasonal STs to search for food-rich areas that provide adequate energy. During migration, the STs move in groups following the strongest one and, therefore, they adjust their initial positions to avoid collision with each other. The behavior of STs during migration can be described as follows:

$$\vec{C}_{st} = S_A \times \vec{P}_{st}(z)$$  \hspace{1cm} (6)$$

$$S_A = C_f - z \times \frac{C_f}{Iter_{max}}$$  \hspace{1cm} (7)$$

where $\vec{C}_{st}$ is the position of a sooty tern that does not conflict with another one, $\vec{P}_{st}$ represents the ST’s current position, $z$ represents current iteration, $S_A$ is ST motion in a certain search area, while $C_f$ is a variable controlling to set $S_A$. STs search for the best neighbor and converge with it after avoiding a clash based on the following equation:

$$\vec{M}_{st} = C_B \times (\vec{P}_{bst}(z) - \vec{P}_{st}(z))$$  \hspace{1cm} (8)$$

$$C_B = 0.5 \times R_{rand}$$  \hspace{1cm} (9)$$

where $\vec{M}_{st}$ refers to STs’ different positions, $\vec{P}_{bst}$ is the best ST, $C_B$ is a random variable, while $R_{rand}$ refers to random number in scale of $[0, 1]$. The ST or search agent can refresh its location with regards to the best ST.

$$\vec{D}_{st} = \vec{C}_{st} + \vec{M}_{st}$$  \hspace{1cm} (10)$$

where $\vec{D}_{st}$ indicates the disparity between the ST and the fittest ST. When attacking the prey, STs change their speeds and create a spiral behavior which is defined as follows:

$$x' = R_{adi} \times \sin(i)$$  \hspace{1cm} (11)$$

$$y' = R_{adi} \times \cos(i)$$  \hspace{1cm} (12)$$

$$z' = R_{adi} \times i$$  \hspace{1cm} (13)$$

$$r = u \times e^{kv}$$  \hspace{1cm} (14)$$

where $R_{adi}$ refers to the radius of every spiral turn, $i$ is variable in scale $[0 \leq k \leq 2\pi]$, $v$ and $u$ identify the constant of spiral form, and $e$ refers to normal logarithm. STs update their positions based on the following equation:

$$\vec{P}_{st}(z) = \vec{D}_{st} \times (x' + y' + z') \times \vec{P}_{bst}(z)$$  \hspace{1cm} (15)$$

where $\vec{P}_{st}(z)$ updates the position of another ST and saves the optimal solution.
4. The Proposed Approach

This section presents the major structure of MPC. Additionally, it clarifies the proposed approach combining MPC and STOA.

4.1. Model-Predictive Control (MPC)

MPC is a modern control concept that relies on future predictions to resolve the trouble under study. MPC is commonly utilized in the manufacturing systems. The MPC has many advantages, such as combinations of direct variables, system delay compensation, the ability to handle limitations, and online optimization. Figure 3 presents the MPC structure, which has prediction and controller units [36,37]. The unit of prediction predicts the future results of the system according to its current output, while the control unit utilizes the forecast output to reduce the restrictive equation of the objective function. If restrictions exist, the objective function can be reduced by utilizing the performance prediction function via the control unit. The basic concept of MPC relies on the calculation of the difference between the reference signal and the plant’s actual output. The future output is then estimated over time intervals, known as sampling, until the output matches the reference signal.

![MPC block diagram](image)

Figure 3. MPC block diagram.

In the MPC algorithm, the system can be described as linear or nonlinear. The plant input and output are presented in the following formula:

\[
x(k + 1) = Ax(k) + BS_j u_p(k)
\]

(16)

\[
y(k) = S_o^{-1}Cx(k) + S_o^{-1}DS_i u_p(k)
\]

(17)

where \(A\), \(B\), \(C\), and \(D\) represent the system state-space matrices, \(S_o\) and \(S_i\) indicate the output and input diagonal array, respectively, while \(u_p\) refers to a nondimensional vector of input variables. The input of MPC can be calculated as \(u(k) = u(k - 1) + \Delta u(k))\); by solving the problem with respect to sequence of input, one can get the following expression:

\[
\min_{\Delta u(k), \ldots, \Delta u(k+M-1)} \left\{ \sum_{j=0}^{M-1} \Delta u^T(k+j)R\Delta u(k+j) + \sum_{i=0}^{P-1} \Delta y^T(k+i)Q\Delta y(k+i) \right\}
\]

(18)

where \(M\) refers to the control horizon, \(P\) refers to the prediction horizon \((1 \leq M \leq P)\), \(T\) is the sample time, \(Q\) and \(R\) represent weighting factors, while \(y(k+i|k)\) refers to the forecasted output.

4.2. Optimal Deregulated LFC Solving Problem

This section introduces the deregulated LFC using MPC optimized via the proposed STOA. The MPC parameters \((M, P, T, Q, \) and \(R)\) are identified via the proposed methodol-
ogy of STOA to minimize the ITAE of aberrations in frequencies and powers in tie-lines as follows:

$$\text{ITAE} = \int_0^t \left( \sum_{i=1}^{n} (|dF_i| + |dP_{tie,i}|) \right) dt$$  \hspace{1cm} (19)$$

where $t$ and $n$ are the time of simulation and area number, $dF_i$ is the frequency deviation in area $i$, and $dP_{tie,i}$ refers to the deviation in tie-line power of area $i$. In this work, the MPC design is based on linear time invariant (LTI) which can be determined through MPC toolbox for each area with the aid of Matlab/Simulink. Figure 4 shows the MPC adaptation mechanism implemented through the suggested STOA; the MPC parameters' constraints are selected as $1 \leq M, 1 \leq P, 1 \leq R, Q \leq 10$, and $0.1 \leq T \leq 10$. The MPC is fed by three inputs which are reference signal, deviation in frequency of the LFC system, and load disturbance measurement. The ITAE is computed depending on current aberrations in frequencies and powers in tie-lines and then fed to the proposed STOA. The MPC optimum parameters can be identified by STOA through minimizing the ITAE. Figure 5 explains the steps for implementing the proposed STOA.

![Figure 4. The suggested MPC adjusted by STOA.](image)

![Figure 5. Flowchart of proposed STOA to optimize MPC-LFC.](image)
5. Simulation Results

In this work, the MPC optimal parameters are determined via the proposed STOA-based deregulated LFC installed in multi-interconnected plants with RESs and SMES. The controlling parameters of STOA are assigned as 50 for population size, and maximum iteration of 100. The proposed approach is applied on the system shown in Figure 2 which consists of nonlinear three areas with multi-sources and deregulated LFC environment through three cases. The proposed system parameters are tabulated in Table A1 in Appendix A, while governor dead band (GDB) and generation rate constraint (GRC) are specified to be 3%. The obtained results via the proposed approach are compared to those obtained by MPC optimized via differential evolution (DE), stain bower braid algorithm (SBO), firefly algorithm (FA), and intelligent water drops algorithm (IWD).

5.1. Unilateral-Based Transaction

In this case, there is unilateral contract between DISCOs and GENCOs in area 1; this can be represented as given in Equations (20) and (21). The demand power is 0.005 pu for DISCO₁ and DISCO₂ (DISCO₁ = DISCO₂ = 0.005), while the total load disturbance in area 1 (dP₁D₁) is 0.01 pu, which presents the sum demand load in DISCO₁ and DISCO₂. However, there is no demand for power by DISCO₃, DISCO₄, DISCO₅, DISCO₆, and load disturbance in areas 2 and 3.

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

(20)

\[
dP₁₁ = DISCO₁ + DISCO₂ = 0.01 pu

dP₁₂ = DISCO₃ + DISCO₄ = 0 pu

dP₁₃ = DISCO₅ + DISCO₆ = 0 pu
\]  

(21)

The change in the response of the generation units for each GENCO can be written as follows:

\[
dP_{GENCO₁} = \sum_{j=1}^{6} cpf_{1j} \times dDISCO_j = (0.5 + 0.5) \times 0.005 = 0.005 pu.MW
\]  

(22)

\[
dP_{GENCO₂} = \sum_{j=1}^{6} cpf_{2j} \times dDISCO_j = (0.5 + 0.5) \times 0.005 = 0.005 pu.MW
\]  

(23)

Table 3 illustrates the errors (integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time square error (ITSE)) that are obtained by the different algorithms compared to the proposed technique with/without SMES. The optimum parameters of MPC-based deregulated LFC obtained by the presented methodologies are illustrated in Table 4. The aberrations in frequencies and powers flow in tie-lines are shown in Figure 6, while Table 5 presents the system performance specifications including peak undershoot (PUs), peak overshoot (POs), and settling time (Ts) of the fluctuations in frequencies and powers in tie-lines. The settling time and overshoot are minimized by the proposed STOA with/without SMES.
Table 3. Different errors obtained by the suggested STOA compared to different algorithms.

| Algorithm  | ITAE   | IAE    | ITSE   | ISE    |
|------------|--------|--------|--------|--------|
| GOA [31]   | 1.5881 | 0.1035 | 0.00064| 0.0012 |
| IWD        | 1.6434 | 0.1796 | 0.0022 | 0.0006 |
| FA         | 1.5204 | 0.2097 | 0.0036 | 0.00099|
| DE         | 0.7078 | 0.1176 | 0.00096| 0.00041|
| SBO        | 0.9502 | 0.1573 | 0.0020 | 0.00073|
| STOA       | 0.3736 | 0.0862 | 0.00057| 0.00036|
| STOA with SMES | 0.1302 | 0.0357 | 0.00011| 0.00011|

Table 4. MPC optimal parameters with unilateral-based transaction obtained via the presented methodologies.

| Algorithm  | Cont. | Parameter |
|------------|-------|-----------|
| IWD        | MPC1  | T 1.0188, P 4.0000, M 3.6313, R 8.0187, Q 9.4088 |
|            | MPC2  | T 4.5778, P 7.0000, M 2.9508, R 7.1024, Q 4.9171 |
|            | MPC3  | T 7.9330, P 7.0000, M 2.8788, R 6.8717, Q 2.1063 |
| FA         | MPC1  | T 4.9778, P 7.0000, M 2.5678, R 7.0123, Q 4.9171 |
|            | MPC2  | T 7.9330, P 7.0000, M 2.8788, R 6.8717, Q 2.1063 |
|            | MPC3  | T 4.9778, P 7.0000, M 2.5678, R 7.0123, Q 4.9171 |
| DE         | MPC1  | T 1.0188, P 4.0000, M 3.6313, R 8.0187, Q 9.4088 |
|            | MPC2  | T 4.5778, P 7.0000, M 2.9508, R 7.1024, Q 4.9171 |
|            | MPC3  | T 7.9330, P 7.0000, M 2.8788, R 6.8717, Q 2.1063 |
| SBO        | MPC1  | T 1.0188, P 4.0000, M 3.6313, R 8.0187, Q 9.4088 |
|            | MPC2  | T 4.5778, P 7.0000, M 2.9508, R 7.1024, Q 4.9171 |
|            | MPC3  | T 7.9330, P 7.0000, M 2.8788, R 6.8717, Q 2.1063 |
| STOA       | MPC1  | T 1.0188, P 4.0000, M 3.6313, R 8.0187, Q 9.4088 |
|            | MPC2  | T 4.5778, P 7.0000, M 2.9508, R 7.1024, Q 4.9171 |
|            | MPC3  | T 7.9330, P 7.0000, M 2.8788, R 6.8717, Q 2.1063 |
| STOA with SMES | MPC1  | T 1.0188, P 4.0000, M 3.6313, R 8.0187, Q 9.4088 |
|            | MPC2  | T 4.5778, P 7.0000, M 2.9508, R 7.1024, Q 4.9171 |
|            | MPC3  | T 7.9330, P 7.0000, M 2.8788, R 6.8717, Q 2.1063 |

Table 5. Performance analysis of unilateral-based transaction.

| Sig.  | MPC via IWD | MPC via FA | MPC via DE |
|-------|-------------|------------|------------|
|       | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) |
| dF1   | 27.0376 | -0.0086 | 0.0168 | 19.0569 | -0.0067 | 0.0179 | 14.6580 | -0.0066 | 0.0164 |
| dF2   | 31.1874 | -0.0056 | 0.0052 | 31.7522 | -0.0004 | 0.0007 | 20.7756 | -0.0019 | 0.0066 |
| dF3   | 33.0361 | -0.0048 | 0.0090 | 26.9591 | -0.0092 | 0.0018 | 22.6277 | -0.0047 | 0.0023 |
| dPtie1| 25.5028 | -0.0049 | 0.0033 | 19.0569 | -0.0067 | 0.0179 | 14.6580 | -0.0066 | 0.0164 |
| dPtie2| 28.6876 | -0.0049 | 0.0083 | 26.9591 | -0.0092 | 0.0018 | 22.6277 | -0.0047 | 0.0023 |
| dPtie3| 49.6124 | -0.0032 | 0.0024 | 35.4933 | -0.0034 | 0.0021 | 31.7522 | -0.0019 | 0.0066 |

MPM via SBO | MPC via STOA | MPC via STOA with SMES |
|------------|-------------|------------------------|
| dF1        | 19.7260     | -0.0075 | 0.0187 | 10.0692 | -0.0064 | 0.0178 | 10.9544 | -0.0055 | 0.0133 |
| dF2        | 29.1531     | -0.0004 | 0.0007 | 15.7320 | -0.0020 | 0.0053 | 7.8413  | -0.0003 | 0.0022 |
| dF3        | 33.0361     | -0.0062 | 0.0093 | 11.3257 | -0.0078 | 0.0119 | 10.3924 | -0.0006 | 0.0024 |
| dPtie1     | 21.2646     | -0.0016 | 0.0083 | 10.9328 | -0.0028 | 0.0069 | 10.2124 | -0.0012 | 0.0045 |
| dPtie2     | 20.5120     | -0.0097 | 0.0010 | 10.9060 | -0.0046 | 0.0026 | 9.3023  | -0.0024 | 0.0006 |
| dPtie3     | 33.0939     | -0.0035 | 0.0022 | 10.7960 | -0.0032 | 0.0022 | 10.2997 | -0.0021 | 0.0006 |
5.2. Bilateral Transaction

In this case, the DISCOs contract with any GENCOs are bound by the terms of the contract concluded between them. Assume that the power demand for each DISCO is 0.005 (\(DSCO_1 = DSCO_2 = DSCO_3 = DSCO_4 = DSCO_5 = DSCO_6 = 0.005\)), while the total load disturbance in all areas is 0.01 pu \((dP_{D1} = dP_{D2} = dP_{D3} = 0.01\) pu\), and the DPM is assigned as in Equation (24).

\[
DPM = \begin{bmatrix}
0.3 & 0.25 & 0.3 & 0.2 & 0.2 & 0 \\
0.2 & 0.15 & 0 & 0.2 & 0.1 & 0 \\
0 & 0.15 & 0.4 & 0 & 0.2 & 0.4 \\
0.2 & 0.15 & 0 & 0.2 & 0.2 & 0.1 \\
0.2 & 0.15 & 0.3 & 0.3 & 0.2 & 0.5 \\
0.1 & 0.15 & 0 & 0.1 & 0.1 & 0
\end{bmatrix}
\] (24)

\[
dP_{D1} = DSCO_1 + DSCO_2 = 0.01 \text{ pu}
\]
\[
dP_{D2} = DSCO_3 + DSCO_4 = 0.01 \text{ pu}
\]
\[
dP_{D3} = DSCO_5 + DSCO_6 = 0.01 \text{ pu}
\] (25)

The power change of the generation units for each GENCO is illustrated as follows:

\[
dP_{GENCO_1} = \sum_{j=1}^{6} cpf_{fj} \times dDSCO_j = (0.3 + 0.25 + 0.3 + 0.2 + 0.2 + 0) \times 0.005 = 0.00625 \text{ pu.MW}
\] (26)

\[
dP_{GENCO_2} = \sum_{j=1}^{6} cpf_{2j} \times dDSCO_j = (0.2 + 0.15 + 0 + 0.2 + 0.1 + 0) \times 0.005 = 0.00325 \text{ pu.MW}
\] (27)

\[
dP_{GENCO_3} = \sum_{j=1}^{6} cpf_{3j} \times dDSCO_j = (0 + 0.15 + 0.4 + 0 + 0.2 + 0.4) \times 0.005 = 0.00575 \text{ pu.MW}
\] (28)
\[ dP_{\text{GENCO}_4} = \sum_{j=1}^{6} cp_{f4j} \times d\text{DISCO}_j = (0.2 + 0.15 + 0 + 0.2 + 0.2 + 0.1) \times 0.005 = 0.00425 \text{ pu.MW} \] (29)

\[ dP_{\text{GENCO}_5} = \sum_{j=1}^{6} cp_{f5j} \times d\text{DISCO}_j = (0.2 + 0.15 + 0.3 + 0.3 + 0.2 + 0.5) \times 0.005 = 0.00825 \text{ pu.MW} \] (30)

\[ dP_{\text{GENCO}_6} = \sum_{j=1}^{6} cp_{f6j} \times d\text{DISCO}_j = (0.1 + 0.15 + 0 + 0.1 + 0 + 0) \times 0.005 = 0.00225 \text{ pu.MW} \] (31)

The best obtained fitness function is via the proposed approach compared to IWD, FA, DE, and SBO, as tabulated in Table 6. MPC optimum parameters obtained by different approaches with deregulated LFC under bilateral transaction case are tabulated in Table 7. Aberrations in frequencies and powers in tie-lines are shown in Figure 7. Table 7 introduces the system performance specifications for curves presented in Figure 7. The effect of installed SMES in the system to minimize ITAE is clarified and given in Table 6, Table 8 and Figure 7.

Table 6. The errors given by the suggested STOA compared to different algorithms.

| Algorithm | ITAE  | IAE   | ITSE  | ISE   |
|-----------|-------|-------|-------|-------|
| IWD       | 35.6750 | 2.1620 | 0.2921 | 0.0385 |
| FA        | 33.2202 | 2.4408 | 0.4506 | 0.0499 |
| DE        | 30.1369 | 2.3571 | 0.4204 | 0.0493 |
| SBO       | 32.1007 | 2.3821 | 0.4301 | 0.0487 |
| STOA      | 3.2369  | 0.3996 | 0.0102 | 0.0028 |
| STOA with SMES | 0.6619 | 0.1343 | 0.0011 | 0.00055 |

Table 7. MPC optimal parameters with deregulated LFC obtained by different approaches.

| Algorithm | Cont. | Parameter |
|-----------|-------|-----------|
| IWD       | MPC1  | 6.1667    | 3.7863    | 8.2602    | 6.2492    |
|           | MPC2  | 2.0503    | 3.8281    | 1.4377    | 5.5301    |
|           | MPC3  | 1.8900    | 3.5589    | 5.8544    | 5.7842    |
| FA        | MPC1  | 6.8705    | 2.5811    | 6.4681    | 3.3892    |
|           | MPC2  | 2.3363    | 2.5216    | 5.2274    | 5.8524    |
|           | MPC3  | 9.3026    | 1.6665    | 7.1737    | 4.7571    |
| DE        | MPC1  | 2.5035    | 2.2353    | 7.0311    | 1.8310    |
|           | MPC2  | 2.6587    | 3.6384    | 2.6987    | 9.4498    |
|           | MPC3  | 9.4381    | 1.6674    | 10.000    | 6.0715    |
| SBO       | MPC1  | 2.9720    | 1.2831    | 9.6783    | 2.6398    |
|           | MPC2  | 1.1842    | 1.6785    | 4.3008    | 4.5068    |
|           | MPC3  | 9.3530    | 4.0784    | 5.1313    | 2.1758    |
| STOA      | MPC1  | 0.3460    | 3.1737    | 1.0000    | 1.1277    |
|           | MPC2  | 5.4724    | 3.3661    | 1.0000    | 7.1087    |
|           | MPC3  | 0.1000    | 3.2439    | 1.0000    | 10.000    |
| STOA with SMES | MPC1  | 0.1068    | 3.1802    | 1.2149    | 7.1680    |
|           | MPC2  | 0.1051    | 1.8494    | 1.1014    | 7.6772    |
|           | MPC3  | 0.1000    | 3.0439    | 1.0000    | 10.000    |
Figure 7. Aberrations in $dF$ and $dP_{tie}$ under bilateral transaction case.

Table 8. Performance analysis bilateral transaction.

| Sig. | MPC via IWD Ts (s) PUs (Hz) Pos (Hz) | MPC via FA Ts (s) PUs (Hz) Pos (Hz) | MPC via DE Ts (s) PUs (Hz) Pos (Hz) |
|------|-------------------------------------|-------------------------------------|-------------------------------------|
|      | $dF1$ 63.9004 $-0.0072$ 0.0306 53.6476 | $dF1$ 63.7074 $-0.0072$ 0.0306 53.6476 | $dF1$ 63.7074 $-0.0072$ 0.0306 53.6476 |
|      | $dF2$ 60.1116 $-0.0442$ 0.0680 56.1535 | $dF2$ 60.1116 $-0.0442$ 0.0680 56.1535 | $dF2$ 60.1116 $-0.0442$ 0.0680 56.1535 |
|      | $dP_{tie1}$ 68.2425 $-0.0306$ 0.0075 45.1001 | $dP_{tie1}$ 68.2425 $-0.0306$ 0.0075 45.1001 | $dP_{tie1}$ 68.2425 $-0.0306$ 0.0075 45.1001 |
|      | $dP_{tie2}$ 61.5340 $-0.0246$ 0.0236 54.0869 | $dP_{tie2}$ 61.5340 $-0.0246$ 0.0236 54.0869 | $dP_{tie2}$ 61.5340 $-0.0246$ 0.0236 54.0869 |
|      | $dP_{tie3}$ 54.8649 $-0.0039$ 0.0463 49.0363 | $dP_{tie3}$ 54.8649 $-0.0039$ 0.0463 49.0363 | $dP_{tie3}$ 54.8649 $-0.0039$ 0.0463 49.0363 |

| Sig. | MPC via SBO Ts (s) PUs (Hz) Pos (Hz) | MPC via STOA Ts (s) PUs (Hz) Pos (Hz) | MPC via STOA with SMES Ts (s) PUs (Hz) Pos (Hz) |
|------|-------------------------------------|-------------------------------------|-------------------------------------|
|      | $dF1$ 50.5606 $-0.0077$ 0.0328 21.8899 | $dF1$ 50.5606 $-0.0077$ 0.0328 21.8899 | $dF1$ 50.5606 $-0.0077$ 0.0328 21.8899 |
|      | $dF2$ 49.7371 $-0.0046$ 0.0315 41.6452 | $dF2$ 49.7371 $-0.0046$ 0.0315 41.6452 | $dF2$ 49.7371 $-0.0046$ 0.0315 41.6452 |
|      | $dF3$ 55.3097 $-0.0188$ 0.0553 18.4991 | $dF3$ 55.3097 $-0.0188$ 0.0553 18.4991 | $dF3$ 55.3097 $-0.0188$ 0.0553 18.4991 |
|      | $dP_{tie1}$ 42.3331 $-0.0306$ 0.0061 24.2308 | $dP_{tie1}$ 42.3331 $-0.0306$ 0.0061 24.2308 | $dP_{tie1}$ 42.3331 $-0.0306$ 0.0061 24.2308 |
|      | $dP_{tie2}$ 51.1851 $-0.0211$ 0.0044 46.4254 | $dP_{tie2}$ 51.1851 $-0.0211$ 0.0044 46.4254 | $dP_{tie2}$ 51.1851 $-0.0211$ 0.0044 46.4254 |
|      | $dP_{tie3}$ 45.8561 $-0.0089$ 0.0487 41.7109 | $dP_{tie3}$ 45.8561 $-0.0089$ 0.0487 41.7109 | $dP_{tie3}$ 45.8561 $-0.0089$ 0.0487 41.7109 |

5.3. Contract Violation Transaction

Usually, the demand for power increases and DISCOs strive to achieve the profits, therefore there is a violation of contracts with the GENCOs. The GENCOs must meet the increase of power demand from DISCOs. Given the contracting procedures mentioned in Section 5.2 and Equations (22) and (23), the power demand requested by the DISCO1 and DISCO2 are modified to 0.01, while the other DISCOs requests remain the same, at 0.005.
Moreover, the power change of the GENCO₁, GENCO₂, and load disturbance in all areas are given as follows:

\[
dP_D^1 = DISCO_1 + DISCO_2 = 0.02 \text{ pu}
\]

\[
dP_D^2 = DISCO_3 + DISCO_4 = 0.01 \text{ pu}
\]

\[
dP_D^3 = DISCO_5 + DISCO_6 = 0.01 \text{ pu}
\]

\[
dP_{GENCO_1} = \sum_{j=1}^{6} cpf_1j \times dDISCO_j = (0.3 + 0.25 + 0.3 + 0.2 + 0.2 + 0) \times 0.01 = 0.0125 \text{ pu.MW}
\]

\[
dP_{GENCO_2} = \sum_{j=1}^{6} cpf_2j \times dDISCO_j = (0.2 + 0.15 + 0 + 0.2 + 0.1 + 0) \times 0.01 = 0.0065 \text{ pu.MW}
\]

When the system given in Figure 2 is simulated under this case, the ITAE obtained via the proposed STOA is 1.0102. Table 9 presents a comparison between the values of errors obtained by the proposed approach and the other simulated algorithms. The MPC optimum parameters obtained by different approaches with deregulated LFC are presented in Table 10. The frequencies and tie-line powers’ aberrations are displayed in Figure 8. The corresponding performance specifications for such cases are tabulated in Table 11. The settling time and overshoot are minimized by the proposed STOA.

Table 9. The errors obtained via the presented algorithms.

| Algorithm | ITAE | IAE | ITSE | ISE |
|-----------|------|-----|------|-----|
| IWD       | 53.9881 | 3.1885 | 0.6218 | 0.0785 |
| FA        | 49.0131 | 3.7460 | 1.1571 | 0.1293 |
| DE        | 46.3893 | 3.6482 | 1.0186 | 0.1222 |
| SBO       | 47.0683 | 3.5857 | 1.0208 | 0.1184 |
| STOA      | 5.1892  | 0.6027 | 0.0210 | 0.0056 |
| STOA with SMES | 1.0106 | 0.2071 | 0.0025 | 0.0012 |

Table 10. Optimum parameters of MPC-deregulated LFC under contract violation.

| Algorithm | Cont. | Parameter | T | P | M | R | Q |
|-----------|-------|-----------|---|---|---|---|---|
| IWD       |       | MPC1      | 6.1667 | 8.0000 | 3.7863 | 8.2602 | 6.2492 |
|           |       | MPC2      | 2.0503 | 5.0000 | 3.8281 | 1.4377 | 5.5301 |
|           |       | MPC3      | 1.8900 | 10.000 | 5.5589 | 5.8544 | 5.7842 |
| FA        |       | MPC1      | 5.2872 | 6.0000 | 2.9868 | 6.3122 | 4.0850 |
|           |       | MPC2      | 1.2944 | 8.0000 | 1.7920 | 5.3635 | 6.3384 |
|           |       | MPC3      | 9.3368 | 9.0000 | 1.5967 | 4.5315 | 3.9342 |
| DE        |       | MPC1      | 10.000 | 6.0000 | 1.0000 | 10.000 | 4.1331 |
|           |       | MPC2      | 2.3147 | 9.0000 | 2.3905 | 1.0000 | 3.4827 |
|           |       | MPC3      | 9.2692 | 10.000 | 1.3766 | 7.5380 | 8.5526 |
| SBO       |       | MPC1      | 2.8428 | 7.0000 | 1.0952 | 9.8400 | 2.6615 |
|           |       | MPC2      | 1.3013 | 6.0000 | 1.6362 | 3.7066 | 5.3726 |
|           |       | MPC3      | 9.3763 | 10.000 | 1.3055 | 7.5704 | 3.4958 |
| STOA      |       | MPC1      | 0.3863 | 6.0000 | 1.3697 | 1.0000 | 10.000 |
|           |       | MPC2      | 1.3889 | 10.000 | 1.7762 | 1.0000 | 10.000 |
|           |       | MPC3      | 0.1000 | 4.0000 | 4.0000 | 1.0000 | 10.000 |
| STOA with SMES |       | MPC1      | 0.1061 | 8.0000 | 1.1080 | 1.1258 | 8.9523 |
|           |       | MPC2      | 0.1092 | 4.0000 | 1.2645 | 2.1158 | 8.0565 |
|           |       | MPC3      | 0.1000 | 7.0000 | 2.4561 | 1.0000 | 10.000 |
The proposed approach has the robust performance and competence under changing the system parameters.

| Sig.     | MPC via IWD                | MPC via FA                  | MPC via DE                  |
|----------|----------------------------|-----------------------------|-----------------------------|
|          | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) |
| dF1      | 63.9340 | −0.0165  | 0.0454   | 47.9268 | −0.0166  | 0.0557   | 51.4054 | −0.0167  | 0.0507 |
| dF2      | 63.5803 | −0.0238  | 0.0497   | 49.1896 | −0.0074  | 0.0511   | 53.2465 | −0.0033  | 0.0450 |
| dF3      | 60.3591 | −0.0558  | 0.0901   | 55.4846 | −0.0242  | 0.0882   | 53.9884 | −0.0259  | 0.0826 |
| dPtie1   | 68.2835 | −0.0448  | 0.0054   | 47.3875 | −0.0447  | 0.0081   | 47.4371 | −0.0558  | 0.0080 |
| dPtie2   | 61.5780 | −0.0344  | 0.0305   | 53.6804 | −0.0333  | 0.0107   | 54.8810 | −0.0256  | 0.0115 |
| dPtie3   | 55.0195 | −0.0047  | 0.0649   | 48.6736 | −0.0102  | 0.0747   | 49.5926 | −0.0066  | 0.0706 |
|          | MPC via SBO             | MPC via STOA               | MPC via STOA with SMES      |
|          | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) |
| dF1      | 53.5217 | −0.0168  | 0.0516   | 20.5473 | −0.0142  | 0.0331   | 11.4963 | −0.0125  | 0.0176 |
| dF2      | 56.2937 | −0.0047  | 0.0450   | 37.5205 | −0.0004  | 0.0203   | 11.8392 | −0.0002  | 0.0170 |
| dF3      | 53.2066 | −0.0240  | 0.0817   | 19.9847 | −0.0073  | 0.0388   | 10.6878 | −0.0040  | 0.0214 |
| dPtie1   | 42.3381 | −0.0482  | 0.0058   | 22.3325 | −0.0124  | 0.0003   | 12.8129 | −0.0059  | 0.0005 |
| dPtie2   | 53.7500 | −0.0287  | 0.0120   | 35.5661 | −0.0088  | 0.0063   | 21.0663 | −0.0042  | 0.0041 |
| dPtie3   | 46.4073 | −0.0083  | 0.0751   | 41.1126 | −0.0003  | 0.0122   | 11.7787 | −0.0002  | 0.0099 |

5.4. Sensitivity Analysis

To confirm the robustness and reliability of the proposed approach-based deregulated LFC, the constructed MPC is investigated under changing of the system parameters and random load disturbance. Sensitivity analysis is conducted on deregulated three interconnected plants with LFC and SMES in bilateral and contract violation transactions cases through changing the system parameters, such as $T_r$, $K_r$, $T_t$, $K_p$, and $T_p$, to ±25% and ±50%. The obtained ITAEs in this case are given in Table 12. The proposed approach has the robust performance and competence under changing the system parameters.
Table 12. Errors of deregulated LFC with changing parameters.

| Parameter | Bilateral Transaction | Contract Violation |
|-----------|-----------------------|--------------------|
|           | ITAE (0.6619)         | ITAE (1.0106)      |
|           | −50%                  | −25%               | +25%               | +50%               |
| Tg        | 0.6619                | 0.6619             | 0.6619             | 0.6618             | 1.0106             | 1.0106             | 1.0106             | 1.0106             |
| Kr        | 0.6619                | 0.6619             | 0.6619             | 0.6618             | 1.0106             | 1.0106             | 1.0106             | 1.0106             |
| Tr        | 0.6619                | 0.6619             | 0.6619             | 0.6618             | 1.0106             | 1.0106             | 1.0106             | 1.0106             |
| Tt        | 0.6619                | 0.6619             | 0.6619             | 0.6618             | 1.0106             | 1.0106             | 1.0106             | 1.0106             |
| Kp        | 0.7049                | 0.6651             | 0.6607             | 0.6606             | 1.1089             | 1.0157             | 1.0094             | 1.0090             |
| Tp        | 0.6826                | 0.6606             | 0.6640             | 0.6678             | 1.0105             | 1.0094             | 1.0137             | 1.0195             |

The application of random load disturbance is vital as the load demand is not usually constant on the system all the time. To confirm the reliability of the proposed technique, the random load change shown in Figure 9 is applied through the DISCO1 and DISCO2 for the same control values and conditions in contract violation case described in Section 5.3, while the total load on area 1 is the sum of DISCO1 and DISCO2. Figure 10 illustrates the aberrations in frequencies and powers in tie-lines under random load change. As the reader can see, the time responses of frequencies and tie-line powers’ violations pass through four time intervals according to the load disturbance shown in Figure 10. The proposed MPC-LFC designed via STOA succeeded in vanishing the perturbations in frequencies and tie-line powers in all intervals, with less oscillations compared to the others. The overshoot and undershoot are minimized by the proposed STOA with/without SMES compared to DE and SBO.

![Figure 9. Random load disturbance.](image)

5.5. Practical Case Study

It is important to investigate the proposed MPC-LFC optimized via STOA on a practical plant, this is done by replacing the PV model with the Kuraymat solar thermal power station. Figure 11 shows the location of Kuraymat, which is 90 miles south of Cairo, Egypt. It is a combined cycle plant that has gas turbines with capacity of 80 MW and steam turbine of 40 MW, in addition to one parabolic trough solar system with rating of 20 MW. The solar field covers an area of about 130,800 m² and consists of 40 rows of collectors, with each row having four SKAL-ET 150 parabolic trough collectors, and each collector consists of 12 modules [38,39]. In this work, the solar thermal plant is represented in Matlab/Simulink, as shown in Figure 12, to clarify the effect of changing solar radiation on the system. This plant comprises a solar field which represents collectors of parabolic troughs, governor, and steam turbine; the combined heat by collectors is utilized to heat the fluid and water to produce steam and drive the turbine. The recorded solar radiation by the plant shown in Figure 13 is used, and these data are fed to the solar thermal energy unit. The solar radiation was transformed over the day to match the simulation time of the system, and
all conditions and restrictions mentioned in Section 5.2 were applied to obtain the results in this case. The obtained results of the actual case are reported in Table 13, which shows the errors obtained by different approaches at the Kuraymat solar thermal power station. The optimum parameters of MPC obtained by different methodology-based deregulated LFC with solar thermal plant are tabulated in Table 14. The aberrations in frequencies and powers in tie-lines are shown in Figure 14, while Table 15 presents the system performance specifications for curves presented in Figure 14. The settling time and peak overshoot are minimized by the proposed STOA with/without SMES. The obtained results confirm the robustness and competence of the proposed MPC-LFC optimized via STO in this such case.

Figure 10. Deviations in $dF_i$ and $dP_{tie,i}$ under random load change.

Figure 11. Location of Kuraymat.
Figure 12. Simulink model of deregulated LFC with solar thermal plant.

Figure 13. Actual solar radiation of the Kuraymat plant.

Table 13. The errors obtained via the presented algorithms.

| Algorithm      | ITAE    | IAE     | ITSE    | ISE     |
|----------------|---------|---------|---------|---------|
| IWD            | 8.1699  | 0.7598  | 0.0419  | 0.0074  |
| FA             | 5.7623  | 0.5724  | 0.0253  | 0.0052  |
| DE             | 2.7636  | 0.2837  | 0.0054  | 0.0012  |
| SBO            | 6.0784  | 0.5965  | 0.0230  | 0.0055  |
| STOA           | 1.9642  | 0.2347  | 0.0036  | 9.74 × 10^{-4} |
| STOA with SMES | 0.7647  | 0.1092  | 6.65 × 10^{-4} | 3.03 × 10^{-4} |
The system was simulated under deregulated cases as unilateral, bilateral, and contract violation-based transactions. The presented fitness function to be minimized is the integral time absolute error (I\text{TAE}), comprising the frequencies and inertial couples' deviations. The system's performance specifications with solar thermal plant and SMES are depicted in Table 14.

### Table 14. Optimum parameters of MPC-deregulated LFC with solar thermal plant.

| Algorithm | Cont. | Parameter |
|-----------|-------|-----------|
|           |       | T        | P  | M  | R  | Q   |
| IWD       | MPC1  | 2.2386   | 6.0000 | 2.7958 | 3.1128 | 8.6028 |
|           | MPC2  | 2.0960   | 5.0000 | 1.7696 | 3.0907 | 5.4609 |
|           | MPC3  | 3.2193   | 10.000 | 2.8946 | 2.7096 | 9.1469 |
| FA        | MPC1  | 2.3419   | 5.0000 | 2.5255 | 3.8603 | 7.9511 |
|           | MPC2  | 1.1804   | 5.0000 | 1.6602 | 2.6835 | 5.7731 |
|           | MPC3  | 2.6442   | 9.0000 | 2.1220 | 2.1650 | 9.2610 |
| DE        | MPC1  | 0.1000   | 7.0000 | 2.6028 | 1.1892 | 9.7307 |
|           | MPC2  | 0.1003   | 8.0000 | 1.0000 | 1.0010 | 9.8950 |
|           | MPC3  | 0.1000   | 10.000 | 4.0000 | 1.0007 | 9.9993 |
| SBO       | MPC1  | 2.2841   | 6.0000 | 2.5856 | 3.1844 | 8.4974 |
|           | MPC2  | 1.8531   | 6.0000 | 1.6108 | 3.1598 | 5.2159 |
|           | MPC3  | 3.0371   | 9.0000 | 2.3412 | 1.0113 | 9.2644 |
| STOA      | MPC1  | 0.1306   | 6.0000 | 1.1957 | 1.6546 | 4.2269 |
|           | MPC2  | 0.1072   | 10.000 | 1.4580 | 1.2117 | 4.0086 |
|           | MPC3  | 0.1000   | 6.0000 | 1.1957 | 1.6546 | 4.2269 |
| STOA      | MPC1  | 0.0001   | 5.0000 | 3.2188 | 1.0000 | 10.000 |
| with SMES | MPC2  | 0.0001   | 10.000 | 1.9825 | 1.0000 | 8.5687 |
|           | MPC3  | 0.0001   | 5.0000 | 1.1332 | 1.0000 | 10.000 |

![Figure 14](image-url). Aberrations in $dF_i$ and $dP_{tie}$ under bilateral transaction with solar thermal plant.
### Table 15. Performance specifications of the interconnected system with solar thermal plant.

| Sig. | MPC via IWD | MPC via FA | MPC via DE |
|------|-------------|------------|------------|
|      | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) |
| dF1  | 38.2310 | 0.0157  | 0.0163  | 35.5070 | 0.0091  | 0.0124  | 29.0191 | 0.0079  | 0.0117  |
| dF2  | 33.5896 | 0.0207  | 0.0106  | 33.0856 | 0.0178  | 0.0106  | 28.0973 | 0.0078  | 0.0117  |
| dF3  | 34.2854 | 0.0273  | 0.0300  | 33.3888 | 0.0297  | 0.0240  | 38.2454 | 0.0132  | 0.0117  |
| dPtie1| 32.4268 | 0.0055  | 0.0172  | 31.6296 | 0.0011  | 0.0126  | 30.9189 | 0.0007  | 0.0118  |
| dPtie2| 30.0549 | 0.0077  | 0.0141  | 29.4559 | 0.0075  | 0.0089  | 30.1285 | 0.0014  | 0.0051  |
| dPtie3| 34.7497 | 0.0174  | 0.0020  | 31.8582 | 0.0187  | 0.0026  | 30.9790 | 0.0017  | 0.0011  |

| Sig. | MPC via SBO | MPC via STOA | MPC via STOA with SMES |
|------|-------------|---------------|-------------------------|
|      | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) | Ts (s) | PUs (Hz) | Pos (Hz) |
| dF1  | 35.4207 | 0.016  | 0.0165  | 25.3660 | 0.0087  | 0.0117  | 15.3465 | 0.0073  | 0.0115  |
| dF2  | 35.2094 | 0.0132 | 0.0106  | 25.7349 | 0.0068  | 0.0115  | 14.3275 | 0.0027  | 0.0115  |
| dF3  | 32.8255 | 0.0308 | 0.0287  | 26.5229 | 0.0118  | 0.0103  | 14.9977 | 0.0082  | 0.0054  |
| dPtie1| 30.6435 | 0.0053 | 0.0170  | 27.0556 | 0.0012  | 0.0051  | 20.9348 | 0.0006  | 0.0034  |
| dPtie2| 32.5795 | 0.0121 | 0.0073  | 22.5349 | 0.0004  | 0.0045  | 13.8070 | 1.6 × 10⁻⁶ | 9.4805  |
| dPtie3| 32.9513 | 0.0173 | 0.0029  | 27.0283 | 0.0005  | 0.0006  | 11.7035 | 4.5 × 10⁻⁵ | 5.6 × 10⁻⁵ |

6. Conclusions

This paper proposed a novel structure of load frequency control (LFC) installed in a multi-interconnected system with renewable energy sources and storage systems. The proposed controller is represented by model predictive control (MPC) optimized via recent metaheuristic optimizer of sooty terns optimization algorithm (STOA). The proposed methodology that incorporated STOA was employed to determine the optimal parameters of MPC-LFC. The presented fitness function to be minimized is the integral time absolute error (ITAE), comprising the frequencies and in tie-lines powers’ deviations. The constructed MPC-deregulated LFC was combined in an interconnected nonlinear system involving photovoltaic (PV) with maximum power point tracker (MPPT), wind turbine (WT), and superconducting magnetic energy source (SMES). The system was simulated under deregulated cases as unilateral, bilateral, and contract violation-based transactions with/without SMES. The performance specifications (undershoots, peak overshoot, and settling time) of the time responses for frequencies and tie-line powers’ aberrations obtained by the proposed STOA were compared to those of different optimizers in all cases. Moreover, the constructed MPC was examined under changing of the system parameters and random load change. Furthermore, a practical case study interconnecting Kuraymat solar thermal power station with others was analyzed based on actual recorded solar radiation. The best fitness function in unilateral transactions case was 0.3736, obtained via STOA, and 0.1302, when SMES was used. In the bilateral transactions case, the best fitness function was 3.2369, obtained using STOA, and 0.6619, with STOA-SMES. On the other hand, the values of ITAE at the contract violation-based transactions case were 5.1892 and 1.0106 by STOA with/without SMES, respectively. The proposed control achieved minimum target of 1.9642 and 0.7647 by STOA with/without SMES for LFC with solar thermal plant. The obtained results confirm the robustness and reliability of the proposed approach incorporating STOA in minimizing the aberration in frequencies and powers in tie-lines and achieving the system stability during load disturbances in the least time. In future work, enhancement of the STOA algorithm to reduce the consumption time is mandatory.

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Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| STOA         | Sooty terns optimization algorithm |
| ST           | Sooty terns |
| LFC          | Load frequency control |
| SBO          | Stain bower braid algorithm |
| MPC          | Model predictive control |
| FA           | Firefly algorithm |
| TRANSCOs     | Transmission companies |
| DE           | Differential evolution |
| DISCOs       | Distribution companies |
| PUs          | Peak undershoot |
| GENCos       | Generation companies |
| POs          | Peak overshoot |
| SMES         | Superconducting magnetic energy storage |
| Ts           | Settling time |
| DPM          | DISCOs Participation Matrix |
| cpf          | contract participation factor |

Symbols

| Symbol | Description |
|--------|-------------|
| A, B, C and D | The system state space matrices |
| e      | Normal logarithm |
| dP_{Li} | The load disturbance in area i |
| R_{adi} | The radius of every spiral turn |
| T_{ij} | The coefficient of synchronizing between areas i and j |
| R_{rand} | The random number in scale of [0, 1] |
| C_{B}  | The random variable |
| dP_{Di} | total load disturbance in area i |
| C_{st} | The position of ST that does not conflict with ST another |
| x(k)   | The system state |
| C_{f}  | Controlling variable |
| y(k)   | The system outputs |
| P_{st} | The current position of sooty tern |
| z      | The current iteration |
| P_{st} (z) | The ST positions of other |
| u and v | The constant of spiral form |
| D_{st} | The disparity between the ST and excellent fittest ST |
| K_{dies} | The constant gain of diesel unit |
| S_{o} and S_{i} | the output and input diagonal array |
| K_{g} | The gain of steam plant governor |
| T      | Sample time of MPC |
| K_{gh} | The gain of hydro plant governor |
| M and P | The control and prediction horizons |
| K_{p}  | The gain of generator and power system |
| Q and R | Weighting factors |
| K_{PV1} and K_{PV2} | The gains of PV system |
| t      | Simulation time |
| K_{pw1}, K_{pw2} and K_{pw3} | Wind plant gains |
| dF_{i} | The frequency deviation of i area |
| K_{r}  | The gain of reheater |
The power deviation of tie-line in area i

The gain of steam turbine

Time constant of governor (sec.)

Time constant of re heater (sec.)

Time constant of hydro governor (sec.)

Reset time constants of hydro governor (sec.)

Time constant of generator and power system (sec.)

Hydro governor transient droop

Time constants of PV system (sec.)

Time constant of steam turbine (sec.)

Time constants of wind plant (sec.)

Nominal start time of the water in penstock (sec.)

### Appendix A

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $T_g$     | 0.08 s | $K_{pv1}$ | -18   | $K_{diesel}$ | 16.5 |
| $T_r$     | 10 s   | $T_{pv1}$ | 100 s | $R$       | 0.425 pu MW/Hz |
| $T_t$     | 0.3 s  | $T_{pv2}$ | 50 s  | $apf_1$   | 0.65 |
| $K_p$     | 120 Hz/pu MW | $K_{apf1}$ | 1.25 | $apf_2$ | 0.35 |
| $T_p$     | 20 s   | $K_{apf2}$ | 1.4   | $T_{opt1}$ | 6 s |
| $T_{WL}$  | 1 s    | $T_{apf2}$ | 0.041 s | $T_{rs}$ | 0.513 s |
| $T_{rh}$  | 10 s   | $T_{gh}$  | 48.7 s | $K_s$   | 1.8 |
| $T_s$     | 1.8    | $T_{gs}$  | 1.0   | $T_{ts}$ | 3.0 |
| $K_{smes}$|       | $T_1$     | 1.0    | $T_2$    | 0.1279 |
|           |       | $T_2$     | 1.0    | $T_3$    | 0.1057 |
|           |       | $T_3$     | 1.0    | $T_4$    | 0.1000 |
|           |       | $T_4$     | 1.0    | $T_{smes}$ | 0.6131 |
| SMES1     | 0.8550 |        |       |          | 0.0144 |
| SMES2     | 0.8181 |        |       |          | 0.0849 |
| SMES3     | 0.5336 |        |       |          | 0.4638 |

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