Improving the grid frequency by optimal design of model predictive control with energy storage devices

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Summary
This paper proposes the optimal design of model predictive control (MPC) with energy storage devices by the bat-inspired algorithm (BIA) as a new artificial intelligence technique. Bat-inspired algorithm-based coordinated design of MPCs with superconducting magnetic energy storage (SMES) and capacitive energy storage (CES) is proposed for load frequency control. Three-area hydrothermal interconnected power system installed with MPC and SMES is considered to carry out this study. The proposed design procedure can account for generation rate constraints and governor dead bands. Transport time delays imposed by governors, thermodynamic processes, and communication telemetry can be captured as well. In recent papers, the parameters of MPC with SMES and CES units are typically set by trial and error or by the designer’s expertise. This problem is solved here by applying BIA to tune the parameters of MPC with SMES and CES units simultaneously to minimize the deviations of frequency and tie line powers against load perturbations. Simulation results are carried out to emphasize the superiority of the proposed coordinated design as compared with conventional proportional-integral controller and with BIA-based MPC without SMES and CES units.

KEYWORDS
bat-inspired algorithm (BIA), capacitive energy storage (CES), load frequency control (LFC), model predictive control (MPC), superconducting magnetic energy storage (SMES)

Nomenclature: $B_i$, frequency bias parameter; $ACE_i$, area $i$ control error; $U_i$, controller output; $R_i$, speed regulation (Hz/p.u); $T_{g}, T_{pi}$, governor and turbine time constants (s); $T_{sw}$, synchronizing torque coefficient between areas $i$ and $j$; $T_{io}$, time constant of reheater (s); $K_{o}$, gain of reheater; $T_{sw}$, hydro governor time constant (s); $T_{sw}$, water starting time (s); $\Delta P_{DL}$, load demand change; $\Delta P_{LC}$, change in tie line power (p.u. Mw); $T_{ps}$, power system time constant (s); $K_{ps}$, power system gain; $\Delta f$, system frequency deviation (Hz); $T_{d}$, transport time delay (s); $x_i, v_i$, bat position and velocity respectively; $\lambda$, wave length; $f_{min}, f_{max}$, minimum and maximum frequencies of bat pulse; $I_{p}$, mean loudness of all bats; $I_{max}$, maximum and minimum loudness levels; $r_{c}$, emission rate of ultrasonic pulses of bat $i$; $x_i^r, v_i^r$, position and velocity of bat $i$ at time instant $r$; $\rho$, initial pulse emission rate; $ACE_{ref}$, reference area control error (targeted at 0); $n_{max}$, maximum number of iterations; $E_{dc}, I_{oc}, K_{ps}$, the SMES voltage, current, and power resp; $\alpha$, converter firing angle; $E_{src}$, converter maximum open circuit voltage (kV); $P_{dc}, E_{src}, J_{Lc}$, the power, voltage, and current prior to load disturbance; $L_{c}$, self inductance of the SMES coil (H); $\Delta P_{dc}, \Delta E_{src}, \Delta I_{dc}$, the incremental change in power, voltage and current; $K_{ps}$, the gain of the SMES control loop (kV/kHz); $T_{dc}$, the converter time constant (s); $K_{ps}$, the gain of the current deviation negative feedback (kV/kA); $s$, the Laplace operator; $K_{vol}$, the gain of the voltage deviation negative feedback (kA/kV); $K_{vol}$, the gain of the CES control loop (kA/Hz); $C$, the capacitance of the CES capacitor (F); $x^r$, $x^s$, the lower and upper bounds of $x$ resp.; $A, B, C, D$, State-space realization of the system model; $x(k), y(k)$, system model state vector; $U(k)$, measured output; $U_{c}(k), d(k)$, $v(k)$, control input, measured disturbance, and measurement noise; $B_{mc}, B_{o}, B_{nc}$, input matrices for $U_{c}(k), d(k)$, and $v(k)$; $D_{mc}, D_{o}, D_{nc}$, input-output matrices for $U_{c}(k), d(k)$, $v(k)$; $S_{pc}, S_{o}, S_{nc}$, Diagonal matrices for scaling the input and output of the system model; $\Psi_{mc}, \Psi_{o}, \Psi_{nc}$, noise model state and output vectors resp; $A_{mc}, B_{mc}, C_{mc}, D_{mc}$, state-space realization of the disturbance model; $d(k)$, $v(k)$, unmeasured and measured disturbances resp; $x_{o}, y_{o}$, noise model state and output vectors resp; $A_{o}, B_{o}, C_{o}, D_{o}$, state-space realization of the noise measurement model; $\Psi_{o}$, $\Psi_{o}$, dimensionless white noise input to disturbance and noise models resp; $T_{sim}$, sampling period; $P, M$, integer prediction and control horizons resp; $Q, R$, Two scalars to weight both the input and error signal; $N$, number of the control inputs; $T_{lim}$, simulation time (s)
1 | INTRODUCTION

In large-scale power systems, generating stations are typically connected by tie lines to exchange power among them. However, continuous load changes cause corresponding deviations in the system frequency and tie line powers. These deviations in the system frequency and tie line power lead to consequent changes in the generated power. In this regard, load frequency control (LFC) is utilized to retain both frequency and tie line power at their scheduled values during generation-load mismatches. The LFC is typically executed via 2 different control loops, namely, primary and supplementary speed control. The governors with the generators can perform primary control to compensate for sudden load changes, while supplementary control is dedicated to regulate the area control errors. To realize fast dynamic response, compensating load perturbations by the governor action has become inconvenient because both thermal and hydro power plants have dynamics with considerable large time constants. Consequently, the frequency and tie line power deviations may persist for long time durations even when a system, with optimized supplementary controllers, undergoes a small load disturbance. Hence, active power supplies with fast response are needed for fast compensation. Recently, superconducting magnetic energy storage (SMES) and capacitive energy storage (CES) units have been considered as effective countermeasures because they can inject active power as fast as expected. Accordingly, SMES and CES units can act as efficient stabilizers of power oscillation modes. Several research papers addressed the SMES and CES applications in the LFC. In these papers, SMES and CES systems proved better performance than the hybrid energy storage system in the multi-area interconnected power system. Various control strategies were considered for LFC design such as integral control, adaptive control, fuzzy control, and neural network where the specifications of the SMES units were considered unaltered. In Chainie and Tripathy, the parameters of integral-based LFC and SMES are optimized simultaneously by using cuckoo search algorithm. The improvement in automatic generation control (AGC), with the inclusion of small-capacity SMES units, subject to governor dead band (GDB) nonlinearity and boiler dynamics, was explained in Tripathy et al. In Sheikh et al, a fuzzy gain scheduled supplementary control scheme with SMES unit was applied to AGC in power systems to enhance the performance of LFC. Linear quadratic regulator-based LFC was addressed in Singla and Kumar, where the impact of linear quadratic regulator-controlled SMES on LFC was further assessed. Quasi-oppositional harmony search was considered in Mahto and Mukherjee to tune the proportional-integral-derivative controllers, SMES proportional controller, and the static synchronous series compensator damping controllers in hybrid distributed generation power system. Optimal parameters of proportional-integral-derivative-based LFC and SMES control loop were computed by using a pattern search algorithm in Farahani and Ganjefar where a multi-input SMES unit was considered to carry out the design. In Ngamroo et al, the SMES unit was coordinated with a solid-state phase shifter to enhance the LFC. The LFC in a 2-area system, comprising both SMES units and static synchronous series compensator damping controllers, was reported in Chatterjee et al. where realistic constraints including generation rate constraints (GRCs) and GDBs were considered. Bhatt et al proposed the coordinated operation between the thyristor-controlled phase shifter and the SMES subject to wind energy penetration. Several control approaches for control problems have been applied on power systems to design a controller with better performance over the past 6 decades. In Al-Dabbagh and Chen, several design considerations are addressed for a fully automated closed-loop wireless networked control system. It discussed the conditions required to design an optimal controller system for given plant and network. An $H_\infty$ control problem for a class of discrete-time Takagi-Sugeno fuzzy Markov jump systems with time varying delays and packet dropouts is introduced in Zhang et al. In Ferrari-Trecate et al, a state-smoothing algorithm for hybrid systems based on moving-horizon estimation is presented. A distributed state estimation method based on moving-horizon estimation for a class of 2-time-scale nonlinear systems is developed in Yin and Liu. Model predictive control (MPC) has been evolved as an effective control strategy to stabilize nonlinear dynamical systems having uncertainties and time delays, mainly in process control. Recently, the interest in MPC has improved significantly and is applied in more control applications such as network control systems. Progressive interest in MPC results from its fast response and stability against nonlinearities, constraints, and parameter uncertainties. These powerful features of MPC will enhance the performance of proposed controllers. In Angeli et al, the cost function of MPC involves the economic objective, but the performance is average and not the optimal steady state. Some primary results on MPC applications in LFC were presented in other studies. In Rerkpreedapong et al, MPC was applied in a multi-area power system to enhance the LFC and tolerate the economic dispatch constraints. In Kong and Xieo, a new constraint state-based MPC scheme was used for LFC of a multi-area interconnected power system. The concept of distributed MPC with the application to power system AGC was initially presented by Venkat et al. The LFC was carried out by a set of distributed feasible cooperation-based MPCs instead of 1 centralized MPC. In Shiroei et al, a multivariable constrained MPC was considered to compute the optimal control that can tolerate the GRCs where an exponentially weighted functional MPC was involved. The authors of Mohamed et al presented the design of decentralized MPC-based LFC that can cope with parametric uncertainties and system nonlinearities such as GRCs and
GDBs. In Zhang et al.,\(^4\) an economic model predictive control and a regular MPC are applied on the optimal control and operation of the thickener in a coal handling and preparation plant. The parameters of MPC controller (prediction horizon, control horizon, sampling interval, and weights) are obtained by experiences of designers that may lead to unacceptable performance. In Pahasa and Ngamroo,\(^4\) the weights of MPC for PHEV controller are found by a particle swarm optimization (PSO). Also, The MPC weights are tuned by PSO in Pahasa and Ngamroo\(^4\) but for pitch angle and PHEV controls. In Pahasa and Ngamroo,\(^4\) the input and output weights of a multiple-input and multiple-output MPC are optimized by using PSO. In Yang et al.,\(^4\) a multivariable generalized predictive control is applied on an isolated microgrid with electric vehicles and distributed generations for LFC. The parameters of MPC controller (prediction horizon, control horizon, and sampling interval) are obtained by trial and error method and experiences of designers. Furthermore, all of these strategies are applied on a linear power system and have proved to be insufficient with nonlinear power systems.

This paper proposes the application of BIA for simultaneous tuning of MPC-based LFCs with SMES and CES units in a 3-area interconnected power system to damp out low-frequency oscillations. The design of MPC with SMES and CES units is formulated as an optimization problem where BIA is devoted to search for optimal controller parameters by minimizing a time-domain-based objective function. Realistic constraints imposed by GRCs, GDBs, and transport time delays are considered in the suggested design algorithm. The performance of the proposed BIA-based MPC with SMES and CES units is evaluated by comparison with conventional proportional-integral (PI) controllers and BIA-based MPC without with SMES and CES units. Simulation results on a 3-area nonlinear system are presented to confirm the superiority of the proposed control assembly. Furthermore, the robustness of the proposed design is tested against parametric uncertainties.

### 2 | SUPERCONDUCTING MAGNETIC ENERGY STORAGE

The SMES units can inject real power to compensate for load increments and absorb excess real power during load decrements via large superconducting inductor.\(^4\) A typical SMES unit comprises a superconducting inductor \(L\), \(Y - Y/\Delta\) transformer, and 12-pulse thyristor-controlled alternating current (AC)/direct current bridge converter as shown in Figure 1A. The superconducting inductor is connected to the AC grid through a power conversion system (PCS), which is a dual-mode converter because it can operate either as a rectifier or as an inverter to enable charging and discharging of the inductor, respectively. Obviously, the nature of load perturbation is responsible for determining which mode of operation is actioned. Rectifier mode of operation is enabled during the charging phase where an adequate positive voltage is applied to the inductor. Alternatively, inverter mode is enabled during the discharging phase where an adequate negative voltage is applied to the inductor. Switching either mode of operation is carried out by controlling the firing angle of the converter bridge as the converter output voltage in kV is given as follows\(^1\):

\[
\Delta v = \frac{1}{T_{dc}s + 1} \Delta E_d + \frac{1}{sL} \Delta I_d + I_{dc}
\]

**FIGURE 1** The superconducting magnetic energy storage (SMES) unit (A) circuit diagram and (B) corresponding block diagram
where $E_d$ is the direct current voltage applied to the inductor (kV), $E_o$ is the maximum open circuit voltage of the converter in kV, $\alpha$ is the firing angle in degrees, $I_d$ is the current through the inductor (kA), and $R_c$ is the equivalent commutating resistance (ohm). The voltage $E_d$ changes its polarity according to the mode of operation, while the inductor current $I_d$ is unidirectional. Hence, the direction and magnitude of the inductor power $P_d$ are controlled by continuously regulating the firing angle. The inductor is initially charged to its rated current by applying a small positive voltage depending on the desired charging period of the SMES unit. Once the rated current in the inductor is attained, it is kept constant by reducing the inductor voltage to 0 because the coil is superconducting. Once the rated current in the coil is attained, the SMES unit is ready to be coupled to the power system for LFC. The frequency change $\Delta f$ is used to control the SMES voltage $E_d$. When the system is subjected to sudden load increment, the energy is extracted first from the generator rotor inertia so that $f$ will be negative and the SMES has to discharge. The SMES voltage has to be negative because the inductor current cannot change its direction. The incremental voltage and current changes of the SMES coil are given as follows:

$$\Delta E_d = \frac{K_o}{1 + sT_{dc}} (\Delta f)$$

$$\Delta I_d = \frac{1}{sL} \Delta E_d$$

where $T_{dc}$ is the converter time constant in seconds, $K_o$ is the gain of the control loop in kV/Hz, and $s$ is the Laplace operator. As reported in Tripathy et al, the inductor current in an SMES unit will return to its nominal value very slowly. Essentially, the current of the SMES unit must be restored to its rated value as fast as possible to respond to next load perturbation immediately. Therefore, the inductor current deviation has to be sensed and used as a negative feedback signal in the SMES control loop to guarantee fast current recovery. Consequently, Equation 2 could be rewritten as follows:

$$\Delta E_d = \frac{1}{1 + sT_{dc}} (K_o \Delta f - K_{Id} \Delta I_d)$$

where $K_{Id}$ is the gain of the current deviation negative feedback in kV/kA. In the storage mode, there is no power transfer because the coil is short-circuited, ie, $E_{do} = 0$. So, the power in either phase (charging/discharging) is given by $P_d = E_{do}I_d$ and the initial power that follows into the inductor is $P_{do} = E_{do}I_{do}$, where $E_{do}$ and $I_{do}$ are the magnitudes of the voltage and current prior to load disturbance. Following a load disturbance, the power flow into the SMES coil is expressed as follows:

$$P_d = (E_{do} + \Delta E_d)(I_{do} + \Delta I_d)$$

$$= P_{do} + E_{do} \Delta I_d + I_{do} \Delta E_d + \Delta E_d \Delta I_d, \quad E_{do} = 0$$

Therefore, the real power incremental change $\Delta P_d$ of the SMES unit in MW is computed as follows:

$$\Delta P_d = P_d - P_{do} = I_{do} \Delta E_d + \Delta I_d \Delta E_d$$

The corresponding block diagram of an SMES incorporating the negative feedback of the current deviation is shown in Figure 1B.

Setting the parameters ($L, K_o, K_{Id},$ and $I_{dc}$) of the SMES unit to their optimistic values can enhance its role in achieving well-damped frequency responses. Herein, the application of BIA is suggested to search for the optimal parameters of the SMES and load frequency controller simultaneously.

## 3 | CAPACITIVE ENERGY STORAGE

The CES plays an important role as the governor and other control mechanisms to adjust the power system equilibrium when there is a sudden rise or decrease in load demand. The static working of the CES makes it faster than of the governor. The CES circuit consists of a storage capacitor, which is formed by many discrete capacitance units connected in parallel. The CES
is connected to the AC grid through a PCS, which includes a rectifier/inverter in 12-pulse configuration as shown in Figure 2A. The dielectric and leakage losses of the capacitor bank are represented by the resistance $R$. The capacitor charges toward its full value when the load demand decreases suddenly, thus releasing an amount of the excess energy in the system. Contrary, when the load demand raises suddenly, the capacitor discharges to its initial value of the voltage to release the stored energy immediately through the PCS to the grid. The change of current direction in the capacitor during the charging and discharging is accommodated by a reversing switch arrangement using gate turn-off thyristors because the current direction through the bridge converter (rectifier/inverter) cannot change. The switches $S_1$ and $S_4$ are ON and $S_2$ and $S_3$ are OFF during the charging mode. Contrary in the discharging mode, $S_1$ and $S_4$ are OFF and $S_2$ and $S_3$ are ON. The charging and discharging of CES unit are occurred by controlling the firing angle of the thyristors to adjust the capacitor voltage as given in Equation 1.

The CES unit is ready to be coupled to the power system for LFC when the rated voltage across the capacitor is attained. The current $I_d$ of CES is controlled by sensing the frequency change $\Delta f$. When the system is subjected to a sudden increase in load, the energy is extracted first from the generator rotor inertia so that $f$ will be negative and the CES has to discharge. The incremental current changes of the CES are given as follows:

$$\Delta I_d = \frac{K_c}{1 + sT_{dc}}(\Delta f)$$  \hspace{1cm} (7)

where $K_c$ is the gain of the control loop in kA/Hz.

The CES voltage after a load disturbance must be restored quickly to its set value for the next load disturbance. Therefore, the capacitor voltage deviation has to be sensed and used as a negative feedback signal in the CES control loop to guarantee fast voltage recovery. Consequently, Equation 7 could be rewritten as follows:

$$\Delta I_d = \frac{1}{1 + sT_{dc}}(K_c\Delta f - K_{Ed}\Delta E_d)$$  \hspace{1cm} (8)

where $K_{Ed}$ is the gain of the voltage deviation negative feedback in kA/kV. In the storage mode, there is no power transfer because the capacitor is considered as an open circuit, ie, $I_{do} = 0$. So, the power is given by $P_{CS} = E_{do}I_{do}$ and the initial power that follows into the CES is $P_{CSo} = E_{do}I_{do}$, where $E_{do}$ and $I_{do}$ are the magnitudes of the voltage and current prior to load disturbance. Following a load disturbance, the power flow into the CES is given as follows:

$$P_{CS} = (E_{do} + \Delta E_d)(I_{do} + \Delta I_d)$$
$$= P_{CSo} + E_{do}\Delta I_d + I_{do}\Delta E_d + \Delta E_d\Delta I_d, \quad I_{do} = 0$$  \hspace{1cm} (9)

Thus, the real power incremental change $\Delta P_{CS}$ of the CES unit in MW is computed as follows:

$$\Delta P_{CS} = P_{CS} - P_{CSo} = E_{do}\Delta I_d + \Delta E_d\Delta I_d$$  \hspace{1cm} (10)
According to Equations 8 and 10, the block diagram of a CES unit incorporating the negative feedback of the voltage deviation is shown in Figure 2B.

The suitable choosing of CES unit parameters ($C$, $K_c$, $K_{Ed}$, and $E_{do}$) can enhance its work in achieving well-damped frequency responses. So, this paper proposes the application of BIA to find the optimal parameters of the CES and load frequency controller simultaneously.

4 | MODEL PREDICTIVE CONTROL: BRIEF REVIEW

A general unit of the MPC consists of 2 basic units, namely, prediction unit and controller unit, as shown in Figure 3A. Prediction unit forecasts the future behavior of the system based on its current output, disturbance, and control signal over a finite prediction horizon. Subsequently, the control unit uses the predicted output to minimize the objective function according to system constraints. In an MPC, the measured disturbance is compensated by using feed-forward control. Contrary to the feedback controller, feed-forward control can overcome most of the measured disturbance before affecting the system. The utilization of both feed-forward and feedback controls records the most powerful feature of the MPC. The feed-forward control can diminish most of the measured disturbance. However, the feedback control rejects the remainder. Unmeasured disturbances are rejected with similarly. Hereafter, the system model, disturbance model, and measurement noise model are explained in detail.

4.1 | System model

The system model is a linear time invariant (LTI). In an MPC, the estimation and optimization processes are preceded by 4 basic steps including conversion to state space, discretization, delay removal, and conversion to dimensionless input and output as follows:

![Diagram of Model Predictive Control (MPC) with Load Frequency Control (LFC)](image)

**FIGURE 3** Model predictive control (MPC) with load frequency control (LFC). A, General scheme of an MPC unit, B, moves of the measured output at the sampling instant $t$, C, moves of the control input at the sampling instant $t$, and D, an MPC-based LFC scheme.
\[ x_p(k + 1) = A_p x_p(k) + B S_i u_p(k) \]  
\[ y_p(k) = S_o^{-1} C x_p(k) + S_o^{-1} D S_i u_p(k) \]  

where

- \( S_i \): diagonal matrix of input scale factors.
- \( S_o \): diagonal matrix of output scale factors.
- \( x_p \): the system state vector.
- \( u_p \): a vector of plant input variables.
- \( y_p \): a vector of plant output variables.

The resultant system model has the following equivalent form:

\[ x_p(k + 1) = A_p x_p(k) + B_p u_p(k) + B_p v(k) + B_p d(k) \]  
\[ y_p(k) = C_p x_p(k) + D_p u_p(k) + D_p v(k) + D_p d(k) \]  

where \( C_p = S_o^{-1} C \), while \( B_p, B_v, \) and \( B_d \) correspond to the columns of \( BS_i \). Similarly, \( D_p, D_v, \) and \( D_d \) are the corresponding columns of \( S_o^{-1} DS_i \). The measured and unmeasured disturbances are termed as \( v(k) \) and \( d(k) \), respectively.

### 4.2 Disturbance model

The disturbance model is an LTI object, and it shows how \( d(k) \) changes with time when the system is subjected to unmeasured disturbances. The discrete time state space model of the disturbance is given as follows:

\[ x_d(k + 1) = A_d x_d(k) + B_d \psi_d(k) \]  
\[ d(k) = C_d x_d(k) + D_d \psi_d(k) \]  

where

- \( d_d(k) \): unmeasured disturbances.
- \( d(k) \): white noise inputs.
- \( x_d(k) \): a vector of input disturbance model states.

Here, white noise is a discrete signal whose samples are regarded as a sequence of serially uncorrelated random variables with 0 mean and finite variance.

### 4.3 Measurement noise model

The controller needs a signal from measurement noise to identify disturbances. The measurement noise model overcomes this purpose and shows how the noise changes with time. The discrete time state space model of the measurement noise is given as follows:

\[ x_n(k + 1) = A_n x_n(k) + B_n \psi_n(k) \]  
\[ y_n(k) = C_n x_n(k) + D_n \psi_n(k) \]  

where
• \( x_n(k) \): a vector of noise model states.
• \( y_n(k) \): a vector of noise signals to be added to the measured plant outputs.
• \( \psi_n(k) \): a vector of white noise inputs.

More details about MPC modeling are in Camacho and Bordons\textsuperscript{33} and Bemporad et al.\textsuperscript{34} Remarkably, the MPC runs at discrete intervals with constant sampling period \( T_s \). If the MPC starts at 0 time, these intervals are integer multiples of the sampling period, ie, 0, \( T_s \), 2\( T_s \), 3\( T_s \), \( kT_s \), where the current sampling instant is indexed by \( k \). The states of a Simulation Single-Input Single Output-based MPC system that has been operating for some time are shown in Figures 3B and 3C. The currently measured output \( y_k \) and the previous measurements \( y_{k-1} \), \( y_{k-2} \), \ldots, are known as shown in Figure 3B, while the current and previous moves of \( u \), ie, \( u_k \), \( u_{k-1} \), \( u_{k-2} \), \ldots, are depicted in Figure 3C. The current move \( u_k \) is calculated by using 2 different phases as listed below:

![Flowchart of bat-inspired algorithm (BIA)](image-url)
FIGURE 5 Three-area interconnected power system installed with model predictive control (MPC) and energy storage devices. A, The configuration of 3-area hydrothermal interconnected power system with energy storage devices, B, Simulink model of 3-area interconnected power system, and C, Simulink model of boiler dynamics.
A. Estimation: To carry out an intelligent move, the MPC needs to know the current state of the system, which includes the true value of the controlled variable $y_k$ and any internal system variables that affect the future trend, i.e., $y_{k+1}, \ldots, y_{k+P}$.

B. Optimization: The set points, measured disturbances, and constraint values are defined over a finite horizon (prediction horizon, $P$) of future sampling instants $(k+1), (k+2), \ldots, (k+P)$, where the integer $P$ is greater than 1. Subsequently, the MPC computes the $M$ moves $u_k, u_{k+1}, \ldots, u_{k+M-1}$, where $1 \leq M \leq P$ and $M$ is termed as the control horizon. There are various formulations of the objective function that can be considered to carry out the design as those described in Maciejowski. The regular cost function that contains the deviation of the output from the set point is selected in this paper because the main aim of MPC is adjusting the predicted output and makes the set point equal. The MPC determines its moves by solving the following optimization problem formulated for $k$th sampling instant as follows:

$$
\min_{u_k, \ldots, u_{k+P-1}} \sum_{i=1}^{P} \left\{ Q(r_{k+i} - \bar{y}_{k+i})^2 + R(\Delta u_{k+i-1})^2 \right\}
$$

subject to

$$
u_{\text{min}} \leq u_{k+i} \leq u_{\text{max}}$$

$$y_{\text{min}} \leq \bar{y}_{k+i} \leq y_{\text{max}}$$

$$|\Delta u_{k+i}| \leq \Delta u_{\text{max}}$$

where $\Delta u_j = u_j - u_{j-1}$ is the move adjustment at the sampling instant $j$, while $Q$ and $R$ are nonnegative weights and $r_{k+i}$ is the target reference value.

5 | MODEL PREDICTIVE LOAD FREQUENCY CONTROL

The suggested MPC controllers will receive the area control error $ACE_i$, load perturbation $\Delta P_{Di}$, and the reference values of $ACE_i$ as inputs, to generate the control signal output. The target reference values of $ACE_i$ are all assumed to be zeros. Each local controller will involve only local signals, so data exchange between different interconnected areas is not necessary. Figure 3D shows an MPC-based LFC scheme. The MPC toolbox in Matlab Simulink is used to carry out the proposed design in this paper. The proposed design is started by deriving the LTI model of the suggested system to be controlled. The required LTI models of the system can be obtained by removing all nonlinearities. The LTI model of Area 1 is obtained by disconnecting such area from other areas then open MPC1 and click design. This LTI model of Area 1 is exported to Matlab workspace and saved. The corresponding LTI models of other areas are computed in a similar manner. If a sampling period ($T_s$) and a number of injected control signals ($N$) are considered, then the MPC controller is operated at a rate of $1/NT_s$. The injected control signals ($N$) are often set to $N=1$. The length of each prediction step depends on the sampling interval. So, the choosing of an appropriate sampling interval is vital. Such value is basically selected to achieve good tracking performance. Moreover, the prediction horizon ($P$) and control horizon ($M$) affect the performance of an MPC controller. Finally, 2 weighting factors $Q$ and $R$ have to be carefully imposed on the system output and input, respectively. Finally, BIA is applied to get the optimistic values $T_s, P, M, Q,$ and $R$ of the optimal MPC.

6 | BAT-INSPIRED ALGORITHM

The bat-inspired algorithm (BIA) is a new artificial intelligence technique that is built based on the echolocation behavior of bats in searching their victims. These bats locate its prey by emitting a series of ultrasound pulses, thus listening for the echoes. The reflected ultrasound waves have different sound levels and time delays that enable each bat to get a specific prey. The BIA is summarized in the following steps:
Step 1. All bats use echolocation to evaluate the distance and identify between prey and barrier.
Step 2. Each bat flies with a velocity \( v_i \) at position \( x_i \), having fixed frequency \( f_{\text{min}} \) varying wavelength \( \lambda \) and loudness \( L_o \) to seek a prey. The bat tunes the frequency of its emitted pulse in the range \( \left( f_{\text{min}}, f_{\text{max}} \right) \) and adjusts the rate of pulse emission \( r \) in the range of \([0,1]\) according to target closeness.
Step 3. Frequency, loudness, and pulse emission rate of each bat are varied.
Step 4. Their loudness changes from a large value \( L_o \) to a minimum constant value \( L_{\text{min}} \).

The position \( x_i \) and velocity \( v_i \) of each bat are updated during the optimization process where the positions \( x^t_i \) and velocities \( v^t_i \) at a time step \( t \) are computed as follows:

\[
f_i = f_{\text{min}} + (f_{\text{max}} - f_{\text{min}}) \alpha, \quad \alpha \in [0,1] \quad (21)
\]

\[
v^t_i = v^{t-1}_i + (x^{t-1}_i - x^t_i) f_i \quad (22)
\]

\[
x^t_i = x^{t-1}_i + v^t_i \quad (23)
\]

where \( \alpha \) is a random vector derived from a uniform distribution function. The current global best location \( x^* \) is obtained after comparing all locations among all bats. Because the velocity is given \( v_i = \lambda_i f_i \), a variance in either \( f_i \) or \( \lambda_i \) results in a velocity change. The algorithm is started by defining a random frequency \( f_i \in [f_{\text{min}}, f_{\text{max}}] \) for every bat. The best solution is selected between current solutions in the local search. Thus, by using random walk, a new solution for each bat is developed locally.

\[
x_{\text{new}} = x_{\text{old}} + \varepsilon L^t_i, \quad \varepsilon \in [-1,1] \quad (24)
\]

where \( \varepsilon \) is a random number and \( L^t_i \) is the mean loudness of all bats at this time step. Loudness decreases, and the rate pulse emission increases after a bat get its prey, then any convenience value can be selected to loudness. When the bat has just found a prey, this means that loudness is 0 and the bat temporarily stops emitting any sound. This is governed by the following equations:

\[
L^{t+1}_i = \beta L^t_i, \quad 0 < \beta < 1, \quad r^{t+1}_i = r^t_i (1 - e^{-\gamma t}), \quad \gamma > 0 \quad (25)
\]

As the time approaches infinity, 0 loudness is achieved and \( \gamma^t_i = \gamma_i^t \). The flowchart of the BIA is shown in Figure 4.

### 7 THREE-AREA HYDROTHERMAL INTERCONNECTED POWER SYSTEM

The configuration of 3-area hydrothermal interconnected power system with energy storage devices and its suggested Simulink-model installed with MPC are shown in Figures 5A and 5B, respectively. Remarkably, the proposed model can account for nonlinearities imposed by GDBs, GRCs, and transport time delays \( \exp(-sT_d) \). In the thermal units, the boiler dynamics as shown in Figure 5C are considered as well. Dead bands are imposed in the model by using backlash nonlinearities, and GRCs are imposed by using saturation limits as depicted. The system nonlinearities are given in Table 1. Further, modeling details can be found in Bevrani.²

<table>
<thead>
<tr>
<th>Backlash</th>
<th>Area 1 (Thermal)</th>
<th>Area 2 (Thermal)</th>
<th>Area 3 (Hydro)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05%</td>
<td>0.05%</td>
<td>0.02%</td>
</tr>
<tr>
<td>GRC</td>
<td>0.0017 MW/s</td>
<td>0.0017 MW/s</td>
<td>0.045 MW/s (increasing)</td>
</tr>
<tr>
<td>Time delay ( T_d )</td>
<td>2-3 s</td>
<td>2-3 s</td>
<td>2-3 s</td>
</tr>
<tr>
<td>Area #1</td>
<td>Conventional PI</td>
<td>MPC Without SMES</td>
<td>MPC With SMES</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>------------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_s = 0.9731$</td>
<td>$T_s = 0.021$, $P_1 = 4$</td>
</tr>
<tr>
<td></td>
<td>$K_p = 0.099$</td>
<td>$P_1 = 36, M_1 = 26$</td>
<td>$M_1 = 1, Q_1 = 20$</td>
</tr>
<tr>
<td></td>
<td>$K_{I1} = 0.0594$</td>
<td>$Q_1 = 2.9787, R_1 = 23.53568$</td>
<td>$R_1 = 3.879$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area #2</th>
<th>Conventional PI</th>
<th>MPC Without SMES</th>
<th>MPC With SMES</th>
<th>SMES</th>
<th>MPC With CES</th>
<th>CES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_s = 0.6508$</td>
<td>$T_s = 0.015$</td>
<td>$K_{o2} = 199.999$, $K_{Ed2} = 2$</td>
<td></td>
<td>$T_s = 0.857$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K_p = 0.099$</td>
<td>$P_2 = 3, M_2 = 3$</td>
<td>$P_2 = 3, M_2 = 3$</td>
<td>$L_2 = 9.999$, $I_{do2} = 4.402$</td>
<td>$P_2 = 3, M_2 = 3$</td>
<td>$K_{C2} = 113.171$, $K_{Ed2} = 0.767$</td>
</tr>
<tr>
<td></td>
<td>$K_{I2} = 0.0594$</td>
<td>$Q_2 = 4.8321, R_2 = 26.0814$</td>
<td>$Q_2 = 19.997, R_2 = 3.453$</td>
<td>$Q_2 = 10.663, R_2 = 7.484$</td>
<td>$C_2 = 3.62$, $E_{do2} = 4.839$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area #3</th>
<th>Conventional PI</th>
<th>MPC Without SMES</th>
<th>MPC With SMES</th>
<th>SMES</th>
<th>MPC With CES</th>
<th>CES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_s = 0.8261$</td>
<td>$T_s = 10$</td>
<td>$K_{o3} = 53.501$, $K_{Ed3} = 1.745$</td>
<td></td>
<td>$T_s = 1.435$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K_p = 0.099$</td>
<td>$P_3 = 49, M_3 = 36$</td>
<td>$P_3 = 1, M_3 = 1$</td>
<td>$L_3 = 9.999$, $I_{do3} = 8.823$</td>
<td>$P_3 = 4, M_3 = 2$</td>
<td>$K_{C3} = 93.044$, $K_{Ed3} = 1.701$</td>
</tr>
<tr>
<td></td>
<td>$K_{I3} = 0.0594$</td>
<td>$Q_3 = 32.9843, R_3 = 7.4846$</td>
<td>$Q_3 = 6.575, R_3 = 3.428$</td>
<td>$Q_3 = 7.274, R_3 = 7.343$</td>
<td>$C_3 = 6.452$, $E_{do3} = 8.256$</td>
<td></td>
</tr>
</tbody>
</table>

$J$ 14.5826 6.5134 0.3999 0.9196

Table 2: Controller parameters and the corresponding objective functions ($J$).
The typical values of the system parameters under study are given below:

\[ P_{r1} = 1000 \text{ MW}, \quad T_{t1} = 0.3 \text{ seconds}, \quad T_{g1} = 0.2 \text{ seconds}, \quad T_{r1} = 10 \text{ s}, \quad K_{r1} = 0.333, \quad P_{r2} = 1000 \text{ MW}, \quad T_{t2} = T_{t1}, \quad T_{g2} = T_{g1}, \]
\[ P_{r3} = 1000 \text{ MW}, \quad T_{t3} = 48.7 \text{ seconds}, \quad T_{g2} = 0.513 \text{ seconds}, \quad T_{r3} = 10 \text{ s}, T_{w} = 1 \text{ seconds}, \quad T_{p1} = T_{p2} = 20 \text{ s}, \quad T_{p3} = 13 \text{ seconds}, \]
\[ K_{p1} = K_{p2} = 120 \text{ Hz/p.u.MW}, \quad K_{p3} = 80 \text{ Hz/p.u.MW}, \quad T_{ij} = 0.0707 \text{ MW/rad}, \quad a_{ij} = -1, \quad R_{1} = R_{2} = R_{3} = 2.4 \text{ Hz/p.u.MW}, \]
\[ B_{1} = B_{2} = B_{3} = 0.425 \text{p.u.MW/Hz}. \]

Boiler data (oil fired): \( K_{1} = 0.85, \quad K_{2} = 0.095, \quad K_{3} = 0.92, \quad C_{b} = 200, \quad T_{f} = 10, \quad K_{ib} = 0.03, \quad T_{ib} = 26, \quad T_{rb} = 69. \]

Superconducting magnetic energy storage and CES data: \( T_{dc} = 0.026 \text{ seconds}, \quad R = 100 \Omega, \) and the limits of \( \Delta P_{SM} \) and \( \Delta P_{CS} = \pm 10 \text{ MW}. \)

This study focuses on the optimal tuning of MPC-based LFC with SMES and CES control loop simultaneously by using BIA. The aim of the optimization is to search for the optimistic MPC, SMES, and CES parameters that can improve the damping characteristics of the system under consideration. The proposed design includes the system nonlinearities resulting from the GRC, GDB, and time delays. The optimization is carried out by minimizing the integral time square error performance index, which is defined over the simulation time (\( T_{\text{sim}} \)) as follows:

\[ \text{FIGURE 6} \quad \text{Frequency deviations and tie line power deviations subject to disturbance scenario I} \quad \Delta f_{1}, \quad \Delta f_{2}, \quad \Delta f_{3}, \quad \Delta P_{\text{tie1}}, \quad \Delta P_{\text{tie2}}, \quad \text{and} \quad \Delta P_{\text{tie3}} \quad \text{[Colour figure can be viewed at wileyonlinelibrary.com]} \]
\[ J = \int_0^{T_{\text{sim}}} \left( \Delta f_1^2 + \Delta f_2^2 + \Delta f_3^2 + \Delta P_{\text{tie1}}^2 + \Delta P_{\text{tie2}}^2 + \Delta P_{\text{tie3}}^2 \right) dt \] (26)

8 | SIMULATION RESULTS

Herein, BIA is devoted to get the optimistic parameters of the proposed MPC-based LFC, SMES, and CES control loop when the system is subjected to 1% simultaneous step load perturbation, while 2 second transport time delays are assumed. To enable decentralized design, the LTI models required for MPC designs are computed based on single-area decoupled system, i.e., \( T_{ij} = 0 \). The optimal parameters of conventional PI, BIA-based MPC with and without SMES and CES units are listed in Table 2 where the corresponding objective functions are computed. The applied disturbance scenarios test different controllers based on these parameters. These scenarios are represented in the magnitude of load changes and the transport time delays. Noticeably, the MPC with SMES has the minimum objective value.

8.1 | Scenario I: The system undergoes a 1% simultaneous step load perturbation and it is subjected to 2 second transport delay

The frequency deviations in the 3 areas and the change in tie-line powers, subject to disturbance scenario I, are shown in Figure 6. Noticeably, conventional PI and MPC-based controllers undershoot likewise due to the inclusion of GRCs as depicted in Figure 6 while incorporating SMES and CES unit result in significant reduction of such frequency undershooting due to its energy storage capability. Further, the system response with MPC and SMES units can settle down in less than 20 seconds as depicted in Figure 6, while the response with MPC only needs around 40 seconds to do so.

FIGURE 7  Frequency deviations in Hz subject to disturbance scenario II (A) \( \Delta f_1 \), (B) \( \Delta f_2 \), and (C) \( \Delta f_3 \) [Colour figure can be viewed at wileyonlinelibrary.com]
8.2 | Scenario II: Load perturbations by 1.5%, 1%, and 1% in the 3 areas, respectively

The performance of the proposed design when the system undergoes increased load demand is investigated where the load of Area 1 is increased by 1.5%. The frequency deviations, in this case, are shown in Figure 7. This response reflects the fact that the inclusion of SMES and CES units can enhance the system stability and performance under increased load demands. Remarkably, the proposed design can limit the frequency deviations significantly, whereas $\Delta f_i, i = 1, 2, 3$ is reduced to less than 0.1 Hz.

8.3 | Scenario III: The system undergoes a simultaneous step load perturbation of 1% and time delay of 3 seconds

Also, the proposed design is tested under increased time delays where the time delays incorporated in the system due to thermal, mechanical dynamics, and communication channels are assumed to be increased to 3 seconds. The system response is shown in Figure 8. It is clear that the MPC with SMES and CES units can tolerate excessive time delays while preserving good damping characteristics.

8.4 | Scenario IV: The system undergoes a simultaneous step load perturbation of 1% with parametric uncertainties

To study the robustness of the MPC controller with SMES, the system parametric uncertainties are considered. The frequency deviation of each area, with 50% parametric uncertainties in the synchronizing torque coefficient between the 3 areas, is shown in Figure 9. It is clear that developed controllers can damp the system oscillatory modes under system parametric uncertainties with a nonsignificant change in the system response.

**FIGURE 8** Frequency deviations subject to disturbance scenario III and transport delay of 3 seconds (A) $\Delta f_1$, (B) $\Delta f_2$, and (C) $\Delta f_3$ [Colour figure can be viewed at wileyonlinelibrary.com]
Model predictive control with the SMES and CES units has been devoted to improve the performance of LFC. Bat search algorithm has been applied for optimal and simultaneous tuning of the parameters of MPCs with the SMES and CES units in a 3-area interconnected hydrothermal system. The proposed design has been tested under different disturbance scenarios considering excessive time delays and parametric uncertainties. Further, it has been compared with MPC without with the SMES and CES and to conventional PI controllers. Simulation results emphasized that the system performance has less overshoots and settling times in case of MPC with SMES compared with others. Moreover, the effectiveness and robustness of the MPC with SMES units are emphasized. Also, it is found that the inclusion of SMES units can enhance the performance of the MPC significantly when the system undergoes different disturbances over a wide range of operating conditions.

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