Coordinated SMES and TCSC Damping Controller for Load Frequency Control of Multi Area Power System with Diverse Sources

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Abstract: This paper investigates the load frequency analysis (LFC) of two area interconnected realistic power system with multi-fuel generating units. Each area consists of thermal, hydro and gas power generating plants. A new evolutionary algorithm is proposed, named Hybrid artificial electric field (HAEFA) optimization algorithm and integral square error (ISE) performance index is utilized to find classical PI/PID controller gains. Later, total analysis is carried out in presence of PID an account of its superiority functioning rather than PI. Moreover, the efficacy of the presented algorithm is deliberated by testing on two area conventional power system model of thermal unit with structure of non-reheat turbines and also on sphere benchmark function. As the load variation is dynamic in nature, mitigating the area frequency fluctuations and tie-line power variations could not been fulfilled by primary regulator and secondary controller. Effective governing needs additional devices. Therefore, superconducting magnetic energy storage (SMES) devices are incorporated in both areas in addition to Thyristor controlled series capacitor (TCSC) is connected in tie-line. Results, shows the system performance has been significantly improved with SMES and TCSC in the presence of HAEFA based PID controller. The potency of the HAEFA algorithm is compared with other optimizations covered in literature.

Key words: LFC; HAEFA; SMES; TCSC.

1. Introduction

General

The main objective of modern day power system is to generate quality power to meet the load demand. Quality power means maintaining system frequency and voltage magnitude within prescribed limits. The total power system involves more number of areas which are coursing in synchronism are connected via tie-lines. Each area constitutes various generation units of diverse sources. As the load is dynamic in nature, holding frequency is a major hurdle. However, the mismatch among generation and demand leads to frequency deviation from its nominal value. This creates the exchange of real power among control areas via tie-lines. The task of real power generation in reply to frequency variation with in the prescribed limits is known as LFC. LFC comprises of two controlling loops, one is loop of primary regulation and the other is secondary control loop employed to neutralise the frequency deviation in less time to drag system to steady state by keep on impressing area control error (ACE) towards zero. So, a sophisticated controller is essential due to system complexity.

Literature Review on LFC

A lot of research work is contributed by many authors in automatic generation control (AGC) problem. The system considered by authors for dynamic analysis comprises the combination of multi fuel systems like thermal units, hydro plants, gas units and diesel power plants and may more. Now days, power generation through renewable energy sources is on upper hand in view of global warming and other environmental issues. Stability analysis with step load perturbation (SLP) on renewable sources like solar, wind turbines and fuel cells are also contributed with several controllers in literature. Intelligent controllers like Fuzzy controller, adaptive fuzzy based controllers and neural network based controllers have been carried out in [1-3]. However, assigning of suitable membership functions in fuzzy logic controller involves a lot of assumptions obsolete its implementation. Moreover, usage of multiple layers in neural network

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with non-linear activation function based controllers makes the governing system more complex and less sensitive. The drawbacks involved in intelligent controllers recommend the usage of classical and modified classical controllers for LFC study. Classical controllers like PI [4]/PID [5-8] and modified classical controllers of fractional order (FO) type FOPI [9] and FOPID [10], FO cascade [11-15], fuzzy-FO cascade [16-19], neuro adaptive fuzzy [20] controllers are reported in literature. However, the performances of these controllers are highly dependent on the adaptation of optimization algorithms. Various optimization techniques like genetic algorithm (GA), particle swarm optimization (PSO) [4, 24], hybrid GA-PSO (HGA-PSO) [7], back tracking search algorithm (BSA) [5], grey wolf optimization (GWO) [8], Improved PSO (IPSO) [10], sine-cosine optimization (SCO) [11], whale optimization (WO) [12], volleyball premier league (VPL) [15], imperialist competitive (IC) [16-17, 19], Differential evolution (DE) [21], firefly algorithm (FA) [22, 30], AEFA [23], wind driven optimization (WDO) [25] etc. are covered in literature. As most of these optimizations are suffering from the disadvantages of premature convergence, getting trapped into local minima and fails to maintain the features of equilibrium among exploration and exploitation. This encourages the author to propose a novel HAEFA algorithm in this work which outplays the above drawbacks.

Literature review on LFC with SMES and FACTs devices

From extensive literature survey, came to know that- controller with optimization algorithm will ascertain the system variations up to certain extent only. For better system stability and full control, the complex interconnected power system must employ with SMES and FACTs devices. The inherent features of SMES device are having high performance, compatibility, less energy loss and cost effective motivates to implement in this resent work. FACTs devices has been connected in tie-lines to mitigate variations incurred in power flow of tie-line and helps to settle the system in less time. DE based fuzzy-PID control approach is implemented for thermal power plants with reheat turbines of similar area along with TCSC in [21]. TCSC-SMES mechanism is implemented for frequency mitigation of multi area system with multi-fuel units [26]. TCSC has been implemented to make system stable in [27]. In [28, 29], the results of TCSC are compared with other FACTS devices of TCPS and SSSC. TCPS and combination of TCPS with SMES and Ultra capacitor (UC) has been carried out in [30]. Unified power flow controller (UPFC) along with SMES and redox flow batteries are adopted in [31].

Contributions of paper

From literature it is absolved that, operational behaviour of interconnected system strongly reckons on usage of controller and optimization algorithm. Every optimization algorithms have their own merits and demerits. So, a new evolutionary algorithm called Hybrid artificial electric field algorithm (HAEFA) is proposed and a maiden application to LFC problem. The contributions of present work are.

- a. A Two area practical realistic combination of generating units (test system-2) has been considered [32].
- b. Design simplicity and efficient operational response of PID controller urged to implement as feedback controller, as more than 90% of industries still using.
- c. PID controller gains are optimized with presented HAEFA algorithm.
- d. HAEFA algorithm is tested on conventional power system model to demonstrate the performance and also on benchmark sphere function to validate the effectiveness.
- e. For better mitigating variations in frequency and tie-line power, TCSC controller is considered and SMES is connected in both areas.
- f. Sensitivity analysis is performed for $\pm 25\%$ variation of system parameters from nominal value.

2. Mathematical modelling

System under study

Power system models deliberated in this work are conventional power system model depicted in Figure 1 named as test system-1 and model shown in Figure 2 named as test system-2 consists of two areas. The parameters of the test system-1 are considered from [5, 7] and for test system-2 directly taken from [32]. In test system-2, each area comprises of thermal power plant, hydro power plant and gas generation unit. The hydro generating unit can be modelled as follows.



Figure 1. Two-area conventional power system model of thermal unit (test system-1)

$$G_{g}(s) = \frac{\Delta P_{hg}(s)}{\Delta P_{eh}(s)} = \frac{1}{1 + \tau_{h}(s)}$$
(1)

$$G_{hg}(s) = \frac{\Delta P_{hv}(s)}{\Delta P_{hg}(s)} = \frac{1 + s\tau_{rs}}{1 + s\tau_{rh}}$$
(2)

$$G_{ht}(s) = \frac{\Delta P_{ht}(s)}{\Delta P_{hv}(s)} = \frac{1 - s\tau_w}{1 + 0.5s\tau_w}$$
(3)

Where $G_g(s)$, $G_{hg}(s)$, $G_{ht}(s)$ are the transfer function models of speed governor, hydro governor and hydro turbines respectively.

$$G_{gr}(s) = \frac{\Delta P_v(s)}{\Delta P_{et}(s)} = \frac{1}{1 + \tau_{gr}s}$$
(4)

$$G_{tt}(s) = \frac{1}{1 + \tau_{Tr}s}$$
(5)

$$G_{tr}(s) = \frac{1 + s\tau_{re}K_{re}}{1 + s\tau_{re}}$$
(6)

Where $G_{gr}(s)$, $G_{tt}(s)$, $G_{tr}(s)$ are the transfer function models of governor, turbine and reheater of thermal power unit respectively.



Figure 2. Two-area system with diverse generation sources (test system-2)

The mathematical modelling of thermal generating unit is as follows. The mathematical models of subsystems in gas power generating unit is as follows:

$$G_{gg}(s) = \frac{\Delta G_d(s)}{\Delta P_{eg}(s)} = \frac{Xs+1}{Ys+1}$$
(7)

$$G_{fg}(s) = \frac{\Delta w_f(s)}{\Delta e_1(s)} = \frac{1 - s\tau_{CR}}{1 + s\tau_F}$$
(8)

$$G_{vg}(s) = \frac{\Delta e_1(s)}{\Delta G_d(s)} = \frac{a}{bs+c}$$
(9)

$$G_{cg}(s) = \frac{\Delta P_g(s)}{\Delta w_f(s)} = \frac{1}{1 + s\tau_{CD}}$$
(10)

Where $G_{gg}(s)$, $G_{fg}(s)$, $G_{vg}(s)$, $G_{cg}(s)$ are models of governing system, fuel system, valve positioner and compressor discharge chamber respectively.

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The generator over all transfer function model is approximated as

$$G_{p}(s) = \frac{K_{ps}}{1 + sT_{ps}}$$
(11)

Where $K_{ps} = 1/D$ and $T_{ps} = 2H/fD$

The tie-line power variation can be expressed as

$$\Delta \mathbf{P}_{\text{tie1,2}} = \mathbf{T}_{12} (\Delta \delta_1 - \Delta \delta_2) \tag{12}$$

In power system frequency variation is in proportional to variation in phase angle, can be expressed as

$$\Delta \delta_1 = 2\Pi \int \Delta f_1 dt \tag{13}$$

$$\Delta \delta_2 = 2\Pi \int \Delta f_2 dt \tag{14}$$

Then, power flow in tie- line is approximated as

$$\Delta P_{\text{tiel},2} = 2\Pi T_{12} \int (\Delta f_1 - \Delta f_2) dt \tag{15}$$

On applying Laplace transform above equation (15) becomes $|x_{\ell}||x_{\ell}|$

$$P_{\text{tiel},2} = \frac{|V_1| |V_2|}{X_{12}} \sin(\delta_1 - \delta_2)$$
(16)

Using equations (13) and (14), equation (15) can be redefined as

$$\Delta P_{\text{tiel},2} = T_{12} (\Delta \delta_1 - \Delta \delta_2) \tag{17}$$

$$T_{12} = \frac{|V_1| |V_2|}{X_{12}} \cos(\delta_1 - \delta_2)$$
(18)

Where T_{12} is synchronizing power coefficient, then

$$\Delta P_{\text{tie1},2}(s) = \frac{211 \text{ T}_{12}}{s} (\Delta f_1(s) - \Delta f_2(s))$$
(19)

TCSC modelling in LFC

The capacity of the transmission line may be regulated by varying line reactance with TCSC. It whirls both capacitive and inductive reactance by adjusting the firing angle. TCSC is constructed by connecting capacitor in parallel with Thyristor controlled reactor (TCR). [33]TCSC will insert capacitive reactance with the tie-line in series; by this overall line reactance reduces. So, the line reactive and real power flow will regulate, as a result the system frequency variation be mitigated and enhancement in both angle and voltage magnitude expeditiously than other FACTs devices.

The current flows in the tie-line from area-1 to area-2 is modelled as

$$I_{12} = \frac{|V_1| \angle (\delta_1) - |V_2| \angle (\delta_2)}{j(X_{12} - X_{TCSC})}$$
(20)

Where X_{12} is tie-line reactance and X_{TCSC} is TCSC reactance.

The complex power in tie-line is approximated as

$$P_{\text{tiel2}} - jQ_{\text{tiel2}} = V_1^* I_{12} = |V_1| \angle (-\delta_1) [I_{12}]$$
(21)

On solving the above equation the real part can be expressed as

$$P_{\text{tie12}} = \frac{|V_1| |V_2|}{X_{12} (1 - k_{\text{pc}})} \sin(\delta_1 - \delta_2)$$
(22)

Where $k_{pc} = \frac{X_{TCSC}}{X_{12}}$, k_{pc} is % compensation tendered by TCSC.

The linear model of tie-line can be achieved by restructuring the above equation as

$$\Delta P_{\text{tie1,2}} = \frac{|V_1| |V_2|}{X_{12} (1 - k_{\text{pc}})^2} \sin(\delta_1 - \delta_2) * \Delta k_{\text{pc}} + \frac{|V_1| |V_2|}{X_{12} (1 - k_{\text{pc}})} * \cos(\delta_1 - \delta_2) (\Delta \delta_1 - \Delta \delta_2)$$
(23)

If
$$J_{12} = \frac{|V_1| |V_2|}{X_{12}} \sin(\delta_1 - \delta_2)$$
 and $T_{12} = \frac{|V_1| |V_2|}{X_{12}} \cos(\delta_1 - \delta_2)$ the above expression can be

expressed as
$$\Delta P_{\text{tie}12} = \frac{J_{12}}{(1 - k_{\text{pc}})^2} \Delta k_{\text{pc}} + \frac{T_{12}}{(1 - k_{\text{pc}})} (\Delta \delta_1 - \Delta \delta_2)$$
 (24)

Since $\Delta \delta_1 = 2\Pi \int \Delta f_1 dt$ and $\Delta \delta_2 = 2\Pi \int \Delta f_2 dt$

On applying Laplace transform to the above equation (24) will be expressed as

$$\Delta P_{\text{tie12}}(s) = \frac{J_{12}}{(1 - k_{\text{pc}})^2} \Delta k_{\text{pc}}(s) + \frac{2\Pi T_{12}}{s(1 - k_{\text{pc}})} (\Delta f_1(s) - \Delta f_2(s))$$
(25)

The input and output signals of TCSC are error $\Delta E(s)$ and $\Delta k_{pc}(s)$ respectively.

Then the linearized model of TCSC is modelled as

$$\Delta k_{pc}(s) = \frac{K_{TCSC}}{1 + sT_{TCSC}} \Delta E(s)$$
(26)

K_{TCSC}= TCSC controller Gain constant; T_{TCSC}=TCSC controller time constant.

Generally TCSC controller is equipped in the tie-line near to area-1, Δf_1 is normally taken as error.



Figure 3. Single line representation of test system with SMES and TCSC

SMES modelling in LFC

When sudden load disturbances occur, the synchronous generators are not able to respond instantly to match the generation with demand every time, because of turbine governor high time constants. So, energy storage devices are essential to meet the sudden load on time taken by the generating unit turbines to adjust their valve openings to maintain system stable. Of all energy storage devices, SMES devices are fast responsive, most efficient and cost effective because of its static operation. SMES consists of superconducting inductive coil stores energy in the magnetic form, which is enclosed in helium or liquid nitrogen vessel. SMES stores energy by drawing current from the grid and aids at sudden load durations. In this paper, SMES units are installed in both the areas to damp out frequency oscillations. The input and output of SMES controller are frequency deviation (Δf) and change in control vector (ΔP_{SMES}) respectively. The time and gain constant of SMES controller is optimized by HAEFA algorithm as K_{SMES} =0.180, T_{SMES} =0.075 Sec.

3. Objective Function

A maiden attempt is made to design the HAEFA based PID controller for the considered test system. Any controller is designed based on adaptation of proper objective function as performance index. In this paper ISE is chosen to evaluate the fitness of presented HAEFA algorithm. Area control error (ACE) is taken as input to the PID controller, that error is minimized using the proposed HAEFA algorithm over the ISE subjected to constraints. The proportional, integral, and derivative gains of best fitness value are taken as optimum parameters.

$$ISE = \int_{0}^{1_{sim}} (\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie12}^2) dt$$
(28)

The ACE of each area is expressed as

$$ACE_1 = \Delta P_{\text{tiel},2} + B_1 \Delta f_1 \tag{29}$$

$$ACE_2 = \Delta P_{tie2,1} + B_2 \Delta f_2 \tag{30}$$

Where B_1 and B_2 are area-1 and area-2 area bias parameters.

The Constraints that are considered in the optimization process is shown in below equations.

$K_{PMin} \le K_P \le K_{PMax}$	(31)
$K_{IMin} \le K_I \le K_{IMax}$	(32)
$K_{DMin} \le K_D \le K_{DMax}$	(33)
$K_{SMES,Min} \leq K_{SMES} \leq K_{SMES,Max}$	(34)
$T_{SMES,Min} \leq T_{SMES} \leq T_{SMES,Max}$	(35)
$K_{TCSC, Min} \le K_{TCSC} \le K_{TCSC, Max}$	(36)
$T_{TCSC,Min} \le T_{TCSC} \le T_{TCSC,Max}$	(37)

4. Hybrid Artificial Electric Field Algorithm

HAEFA is new optimization algorithm application for solution of load frequency stabilization. Anita et. al. [34] proposed the artificial electrified algorithm derived from the concept of electro static filed theory of coulomb's law.

Mathematical modelling

First randomly initialise the particles for K_{Pn} , K_{In} , $K_{Dn} \forall n = 1, 2, ..., N$ (Total number of population)

$$X = \begin{bmatrix} K_{P1} & K_{I1} & K_{D1} \\ K_{P2} & K_{I2} & K_{D2} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ K_{PN} & K_{IN} & K_{DN} \end{bmatrix}$$
(38)

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The particles in each population are fed in to the controller in SIMULINK file one by one, and for each particle simulation will be done for specified time period. Then the objective function calculation will be done and will be treated as local best solutions. Then the respective fitness value is calculated using

Fitness function =
$$\frac{1}{1 + \text{Objective Function}}$$
 (39)

From those local best solutions, the population whose objective function is low and fitness function is high be declared as global best solution. In view of problem in solutions diversity, the local best solutions are guided towards the global best solution a novel velocity equation is developed as follows

$$v_{i}(K+1) = rand() * v_{i}(K) + a_{i}(K) + C_{1}rand_{1}() * (P_{best,n} - currentposition_{n}) + C_{2}rand_{2}() * (G_{best,n} - currentposition_{n})$$

$$(40)$$

The position of particles is calculated using equation (41)

$$X_{i}(K+1) = X_{i}(K) + v_{i}(K+1)$$
(41)

Here, ' i ' represents the particle, 'K' iteration , 'v' particle velocity, 'X' particle position, 'a' particle acceleration

 C_1 and C_2 are chaotic parameters whose values calculated as

$$C_{i} = 1 + \frac{1}{1 + \exp(\frac{-iter}{itermax})}, i = 1, 2$$

$$(42)$$

Acceleration of each particle will be calculated as

$$a_{i}(K) = \frac{Q_{i}(K) * E_{i}(K)}{M_{i}(K)}$$
(43)

The electric field of i^{th} particle in K^{th} iteration $E_i(K)$ is

$$E_{i}(K) = \frac{F_{i}(K)}{Q_{j}(K)}$$
(44)

The total force exerting on the ith charge particle in K^{th} iteration $F_i(K)$ is

$$F_{i}(K) = \sum_{j=1, j \neq i}^{n} rand() * F_{ij}(K)$$
(45)

The amount of force acting on i^{th} charge particle from j^{th} charge particle in K^{th} iteration $F_{ij}(K)$ is

$$F_{ij}(K) = k(K) \frac{Q_i(K)^* Q_j(K)^* (P_j(K) - X_j(K))}{R_{ij}(K) + \varepsilon}$$
(46)

The coulomb's constant in Kth iteration k(K) calculated as

$$k(K) = k_0 * \exp(-\alpha \frac{iter}{itermax})$$
(47)

where \mathbf{k}_0 and α are constants.

The force exerted by the electric field on each particle depends on the Euclidian distance, lower the Euclidian distance more will be the force exerted on the particles, then the Euclidean distance is approximated as

$$R_{ij}(K) = 0.5* \left\| X_i(K) - X_j(K) \right\|_2$$
(48)

$$Q_{i}(K) = \frac{q_{i}(K)}{\sum_{i=1}^{n} q_{i}(K)}$$
(49)

Where $Q_i(K)$, $Q_i(K)$ are charges of ith and jth particle respectively at Kth iteration

$$q_{i}(K) = \exp(\frac{\text{fit}_{i}(K) - \text{worst}(K)}{\text{best}(K) - \text{worst}(K)})$$
(50)

 $fit_i(K)$ is fitness value of ith particle at Kth iteration, here the problem is minimization one then the best(K), worst(K) are evaluated as shown in Equation (51, 52)

 $best(K) = min(fit_{i}(K)), j \in (1, 2, ----N)$ (51)

$$worst(K) = max(fit_{j}(K)), j \in (1, 2, ----N)$$
 (52)

This entire procedure is carried out for three iterations to conditioning the particles searching capability. After this a pair wise comparison is performed to make the total populations into half (best populations from first three iterations). Due to this time taken to complete the total iterative process decreases and the computational burden on CPU will gone. *Process of Pair wise comparison*

 $fit_1, fit_2, fit_3, \dots, fit_n$ are the fitness functions of n particles in the solution.

If $fit_1 > fit_2$ then forward fit_1 to second stage

If $fit_3 < fit_4$ then forward fit_4 to second stage

If $fit_5 > fit_6$ then forward fit_5 to second stage

If $fit_{n-1} < fit_n$ then forward fit_n to second stage

After pairwise comparison, the cross over operation is incorporated from fourth iteration to minimize the solution divergence.

(53)

Then, the cross over operation have been done using

$$Y^{new} = (1 - \lambda) \times Y^{ref} + \lambda \times Y^{old}$$

Where, λ is the random number between [0,1].

Algorithm Pseudo code of HAEFA

Step 1 Randomly initialize the population of size N

Step 2 Calculate objective function of every particle in each population

Step 3 select particles of best solution

Step 4 Calculate k(K), best(K) and worst (K)

Step 5 for iter ; (K=0; $K \le 3$; K++) do

If $K \le 3$ Update velocity: $v_i(K+1) = rand() * v_i(K) + a_i(K) + C_1 rand_1() * (P_{best,n} - currentposition_n) + C_2 rand_2() * (G_{best,n} - currentposition_n)$ Update Position: $X_i(K+1) = X_i(K) + v_i(K+1)$

End if

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Else for $(K \le K_{max})$ do If (K=4)Perform pair wise comparison Update particle velocity Perform cross over operation $Y^{new} = (1-\lambda) \times Y^{ref} + \lambda \times Y^{old}$ Update position End if Else Display Global best values End



Furthermore, the executional performance of the presented HAEFA algorithm is tested on sphere standard benchmark test function which is given in Equation (54). Figure 5 indicates the

(54)

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function values variation at initial and final assessment for AEFA and HAEFA algorithms of sphere function for 100 trails at a population size of 100 for both the algorithms. Noticing the Figure.5, it is elucidated that the function values with presented HAEFA searching mechanism are stared with less initial value and ends with decent function value compared to AEFA technique almost at every trail. Also, it is evident that the final function values of the HAEFA algorithm are more close to the mean value in most of the trails, this shows the efficacy of the presented searching mechanism in finding the optimal solutions and it is only possible due to the inheritance feature of the HAEFA technique possessing the tendency of maintaining the average equilibrium between exploration and exploitation.



Figure 5. Initial and final function value variations of sphere function for 100 trails using AEFA and HAEFA algorithms

Table1. Controller optimum gains for test system-1								
	Optimization algorithms							
Parameters	PID: HAEFA	PID: HGA- PSO[7]	PID: AEFA	PID: GWO[8]	PID: BSA[5]	PID: PSO	PI: PSO[4]	
K _{P1}	1.9757	1.6476	1.5447	1.2278	0.9160	0.9296	0.7579	
K _{P2}	1.8296	1.7762	1.6413	1.2467	0.9398	1.0021	0.8779	
K _{I1}	0.0098	0.0445	0.0358	0.0050	0.0550	0.0209	0.3016	
K ₁₂	0.0137	0.0412	0.0091	0.0196	0.0012	0.0190	0.3016	
K _{D1}	1.0621	0.7210	0.9074	0.9149	0.7291	0.5860		
K _{D2}	1.1428	0.7635	1.0911	0.8536	0.6922	0.5747		
ISE	0.1051	0.3298	0.5908	0.7634	1.0987	1.1052	1.6302	
Settling time: Δf_1	2.724	4.141	4.890	7.485	7.981	8.962	9.752	
Settling time: ΔP_{tie}	5.126	6.207	8.470	8.573	8.738	9.323	9.693	
Settling time: Δf_2	3.214	4.276	4.991	5.184	8.275	8.708	9.752	

5. Simulation results and Discussion

Scenario-I: Analysis of test system-1 for 1%SLP in area-1.

To showcase the superiority execution of HAEFA algorithm, it is implemented on two area conventional model of thermal unit which is widely accepted by the researchers that is reported in recent literature. Area-1 of test system-1 is subjugated with a perturbation of 1% step load (1% SLP) to analyse the dynamic behaviour. The classical PI/PID controllers are optimized with various optimization algorithms that are available in recent literature along with the presented HAEFA algorithm. Up on reviewing the system responses portrayed in Figure.6, it is crystal clear that the system dynamic behaviour is highly regulated with the HAEFA controlling approach under load disturbances compared to other controlling schemes of PSO [4], BSA [5], GWO [8], AEFA, and HGA-PSO [7]. This shows the exaggerated functioning of HAEFA algorithm based controlling approach. The responses settling time along with the gain parameters of the controller are noted in Table 1.

Scenario-II: Analysis of test system-2 with classical PI controller for 1%SLP in area-1.

Initially, the analysis is done with the PI controller optimized with HAEFA algorithm for test system-2 depicted in Figure 2 for area-1 subjugated with 1%SLP, without considering SMES and TCSC devices. The test system is designed in MATLAB/ SIMULINK platform. The response results are shown in below Figure 7. The results are compared with the available PSO and AEFA algorithms. The numerical results are tabulated in Table 2. The setting time (T_s) of area-1 frequency controlled by PSO optimized PI controller is 32.46 sec, which is dragged down to 22.47 sec by PI controller optimized with proposed HAEFA algorithm noted in Table-2. Similarly the area-II frequency deviations and tie-line power flows are also mitigated from optimization with existing algorithms to the proposed algorithm.

	Setting time (T_S) Sec			Peak			
Controller				Λf ₁ (Hz)	$\Delta f_{2}(Hz)$	$\Delta P_{tie,21}$	ISE
Controller	$\Delta f_1 \qquad \Delta f_1$	Δf_2	$\Delta P_{tie,21}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$
						(Pu.MW)	
PSO:PI	32.46	28.39	28.44	15.910	6.285	7.684	1.8531
AEFA:PI	26.36	25.46	26.94	11.983	4.594	5.226	1.5874
HAEFA:PI	22.47	24.53	24.91	10.764	4.117	4.806	1.4146
PSO:PID	21.66	23.31	24.28	12.560	4.926	6.135	1.6813
AEFA:PID	19.58	21.80	23.05	6.525	2.681	2.566	1.3754
HAEFA:PID	14.07	19.03	18.33	5.234	2.061	1.804	1.0188

Table 2. Numerical results of test system-2 responses under PI and PID controller

Scenario-III: Analysis of test system-2 with classical PID controller for 1%SLP in area-1.

Later, the total analysis of the considered interconnected system is carried out with the PID controller to further mitigate the frequency oscillations. The system responses for this case are portrayed in Figure.8 and the responses are numerically interpolated in view of settling time and undershoot which are noted in Table-2. The numerical and graphical result shows that the PID controller works effective with the proposed algorithm when compared with the existing algorithms. Moreover, the ISE function value with HAEFA based PID regulator is enhanced by 39.88% and 26.27% with PSO and AEFA respectively. The controller optimal parameters are placed in table-3.

Controller	K _P		K	I	K _D	
controller	Area-1	Area-2	Area-1	Area-2	Area-1	Area-2
PSO:PI	0.4518	0.4518	0.2514	0.2514	-	-
AEFA:PI	1.3920	1.3920	0.9741	0.9741	-	-
HAEFA:PI	1.9702	1.9702	1.2654	1.2654	-	-
PSO:PID	0.9516	0.9516	0.7500	0.7500	0.2500	0.2500
AEFA:PID	2.9176	2.9176	1.7541	1.7541	0.6891	0.6891
HAEFA:PID	3.7141	3.7141	2.7167	2.7167	1.3491	1.3491

Table 3. Optimum gains of PI and PID controller by reported algorithms for test system-2

Scenario-IV: TCSC and SMES coordinated control strategy on test system-2.

Though the effective ness of HAEFA based PID controller is supremacy when likened with PI controller, to improve the system stability further, the test system-2 is equipped with TCSC and SMES devices. SMES devices are connected in both the areas and TCSC device is connected in the tie line to enhance the power flow through the tie-line by injecting the capacitive series reactance with the line, results in diminish in overall line reactance. The system responses with SMES and TCSC coordinated control mechanism are deliberated in Figure 9 and the numerical results are noted in Table-4. The optimal controller gains are given in Table 5. The result shows the sovereign coordinated control of proposed HAEFA based PID controller with SMES and TCSC devices.

Table 4. Numerical results with incorporation of SMES and TCSC

	Setting time (T_S) Sec			Peak undershoot (U _s)			
Controller	Δf_1	Δf_2	$\Delta P_{\text{tie},21}$	$\begin{array}{l} \Delta f_1({\rm Hz}) \\ \times 10^{-3} \end{array}$	$\begin{array}{l} \Delta f_2(\mathrm{Hz}) \\ \times 10^{-3} \end{array}$	$\Delta P_{tie,21}$ $\times 10^{-3}$ (Pu.MW)	$1SE \times 10^{-3}$
HAEFA:PID	14.07	19.03	18.33	5.234	2.061	1.8040	1.0188
HAEFA:PID With SMES	13.83	13.47	17.28	4.524	1.806	1.3080	1.1097
HAEFA:PID With SMES & TCSC	12.45	13.10	15.64	3.932	1.629	0.9438	1.0062

Table 5. Optimum gains of HAEFA based PID controller under some cases

HAEFA:	K _P		K	-I	K _D	
some cases	Area-1	Area-2	Area-1	Area-2	Area-1	Area-2
Without SMES & TCSC	3.7141	3.7141	2.7167	2.7167	1.3491	1.3491
With SMES only	4.0152	4.0152	2.9241	2.9241	1.7935	1.7935
With SMES & TCSC	4.3504	4.2503	3.0148	3.0049	1.9256	1.9746



Figure 6. Test system-1 responses (Scenario-1)



Figure 7. Test system-2 responses (Scenario-2)



Figure 8. Test system-2 responses (Scenario-3)



Figure 9. Test system-2 responses (Scenario-4)



Figure 10. Shows the Bar diagram representation of Settling time (Sec) of test system-2 responses under various cases.

The comparative analysis of the settling time for studied optimization algorithms for both PI and PID controllers along with and without considering SMES and TCSC devices are shown in Figure 10.



Figure 11. Algorithms Convergence characteristics

Effectiveness of the presented HAEFA algorithm is showcased by comparing the convergence characteristics with the PSO and AEFA algorithms for ISE performance index. The objective function minimization through PSO and AEFA algorithms are settled after 25 iterations and the variations are very clear in Figure 11. The objective function is settled at 21st iteration when optimized the problem with proposed HAEFA algorithm.

Here the sensitivity analysis is carried out by aiming parameters of the system such as area bias parameter (B_i), loading in area-1 (ΔP_{d1}), compressor discharge time constant (τ_{CD}) of gas unit , turbine time constant (τ_{Tr}) of thermal unit, hydro governor time constant (τ_h) in ±25% of variation from nominal value in both the areas to show proposed control methodology robustness. The sensitivity analysis of only one case is depicted in Figure.12 and the numerical results of all the remaining cases are noted in Table-6. Up on noticing the Table-6 it is elucidated that, even the system parameters are subjected to much higher variations the deviations in system responses are hardly varying. This shows the rigid ness of the proposed coordinated control mechanism and it is concluded that the system control parameters are not necessary to be altered even under the situation of parametric variations and load variations.



Figure 12. Test system-2 responses under SMES and TCSC coordinated control scheme with HAEFA based PID for $\pm 25\%$ variation of B_i from nominal value

		Settir	ng time ('	$(\Gamma_{\rm S})$ Sec	Peak undershoot (U _s)			
Parameter	% Change	Δf_1	Δf_2	$\Delta P_{\text{tie},21}$	$\begin{array}{c} \Delta f_1 \\ (Hz) \\ \times 10^{-3} \end{array}$	$\begin{array}{c} \Delta f_2 \\ (Hz) \\ \times 10^{-3} \end{array}$	$ \Delta P_{\text{tie},21} \\ \times 10^{-3} \\ (\text{Pu.MW}) $	
	Nominal Conditions	12.45	13.10	15.64	3.932	1.629	0.9438	
ΔP _{d1}	+25% of nominal loading	12.54	13.32	16.18	4.226	1.63	1.06	
	-25% of nominal loading	12.36	12.56	15.21	3.437	1.62	0.739	
D	+25% of nominal value	12.39	13.07	15.73	3.908	1.620	0.9398	
Di	-25% of nominal value	12.60	13.46	15.69	3.891	1.893	0.9418	
	+25% of nominal value	13.06	13.99	16.09	4.42	1.67	1.127	
۲r	-25% of nominal value	11.75	12.08	14.87	3.21	1.506	0.679	
τ_{h}	+25% of nominal value	12.67	13.32	15.76	4.29	1.665	1.052	
	-25% of nominal value	12.24	12.99	15.03	3.36	1.574	0.723	
τ	+25% of nominal value	13.67	13.47	16.91	4.119	1.67	1.088	
τ _{CD}	-25% of nominal value	12.59	13.61	15.11	3.45	1.59	0.757	

Table 6. Numerical results for sensitive analysis

6. Conclusion

In this paper, a Hybrid artificial electric field algorithm (HAEFA) is proposed for the load frequency stabilization problem. First, the considered test system responses are analysed with the Optimized PI and PID controllers with the proposed algorithm and the results are compared with the existing algorithms. Here, an illation is drawn that the presented algorithm is superior. Moreover, performance of the presented techniques is validated by testing it on conventional power system and also on standard benchmark sphere function. Further, the problem is extended to the coordinated control of SMES and TCSC devices along with HAEFA based PID controller, with this dynamic responses of the multi-area interconnected system is improved, controlled the tie-line power flow is done and attained stability in less time. Finally, sensitive analysis is conducted by varying the system parameters in the range of $\pm 25\%$ of variations from nominal values to demonstrate the presented control methodology robustness. After examining the total analysis, concluded that the controller parameters based on HAEFA searching mechanism are need not to be adjusted even when the system is quashed to huge load variations. The proposed HAEFA may be applied to solve other engineering problems.

7. References

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Appendix-A: Test system-1 parameters: $P_r = 2000$ MW, f = 60Hz, $B_i = 0.425$ P.u.MW/Hz, $R_i = 2.4$ Hz/p.u. MW, $K_{pi} = 120$, $T_{pi} = 20$ s, $T_{ti} = 0.3$ s, $T_{gi} = 0.08$ s, $T_{12} = 0.545$ s. Test system-2 parameters: $P_r =$ Rated power=2000MW; f = 60Hz; H =inertia constant=5MWsec/P.u.; D=frequency sensitive load coefficient=0.8MW(p.u)/Hz; $R_t = R_h = R_g = 2.4$ Hz/P.u.MW; $B_1 = B_2 = 0.425$ P.u.MW / Hz; $a_{12} = -1$; $T_{12} = 0.545$ P.u.; Thermal plant $\tau_{gr} = 0.08$ sec; $\tau_{re} = 10$ sec; $\tau_{Tr} = 0.3$ sec; $K_{re} = 0.3$; Hydro power plant $\tau_h = 0.3$ sec; $\tau_{rs} = 5$ sec; $\tau_{rh} = 28.75$ sec; $\tau_W = 0.025$ sec; Gas power plant X=0.6sec; Y=1.0sec; a = c = 1sec; b = 0.05sec; $\tau_{CR} = 0.01$ sec; $\tau_F = 0.23$ sec; $\tau_{CD} = 0.2$ sec;

Appendix-B: Controller parameters limits $0 \le K_P \le 5$; $0 \le K_I \le 5$; $0 \le K_D \le 5$; $0 \le K_{SMES} \le 2$; $0 \le T_{SMES} \le 1$ $0 \le K_{TCSC} \le 2$; $0 \le T_{TCSC} \le 1$; SMES Data: K_{SMES} =0.180, T_{SMES} =0.075 Sec. TCSC Data: K_{TCSC} =2, T_{TCSC} = 0.016 Sec.



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