International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 2, Issue 12 (August 2013) PP: 23-28

Cuckoo Search Optimization Algorithm based Load Frequency Control of Interconnected Power Systems with GDB nonlinearity and SMES units

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Abstract: This study extensively presents the Load Frequency Control (LFC) application of Cuckoo Search Optimization Algorithm. This algorithm is one of the new optimization algorithms which have been proved effective in solving complex optimization problems. In this study, the Cuckoo search optimization algorithm is applied to a two area interconnected power system with Governor Dead Band nonlinearity and Superconducting Magnetic Energy Storage (SMES) units to tune the parameters of proportional plus integral controllers used for LFC. In a large scale power system, load frequency control in response to area load changes and abnormal system parameters requires fast minimization of frequency deviations and tie line power deviations of the area for stable operation of the system. The trial and error method of finding the gains by indirect optimization using ISE technique with an appropriate performance index appears not to be wise enough because of its complexity. AI techniques appear to be the right choice in finding the optimum gains of the controllers. Hence, in this work, the gains of the PI controllers are optimized using cuckoo search optimization algorithm. The cuckoo's behavior and the mechanism of Lévy flights have lead to the design of an efficient algorithm performing optimization search. Results show that the proposed algorithm achieves the LFC objectives effectively.

Keywords: *Cuckoo Search Optimization Algorithm, Governor Dead Band, Interconnected Power Systems, Load Frequency Control, Superconducting Magnetic Energy Storage.*

I. INTRODUCTION

The Load-Frequency Control (LFC) problem is attaining importance with the increase in size and complexity of interconnected power systems. During last decades, many techniques have been developed for LFC problem [1]. The objective of Load Frequency Control (LFC) is to keep the system frequency and the inter-area tie power within the scheduled values. The mechanical input power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. Most of these techniques are based on the classical proportional plus integral (PI) control due to the simplicity, ease of implementation, robustness and nature of control strategy.

However, even in the case of small load disturbances and with the optimized gains for the PI controller, the frequency oscillations and tie-line power deviations persist for a long duration. In these situations, the governor system may no longer be able to absorb the frequency fluctuations due to its slow response. Fast acting energy storage devices can effectively damp electromechanical oscillations in a power system, because they provide storage capacity in addition to the kinetic energy of the generator rotor, which can share the sudden changes in power requirement. To compensate for the sudden load changes, an active power source with fast response such as a Superconducting Magnetic Energy Storage (SMES) unit is expected to be the most effective counter measure [2]. The optimum parameter values of the conventional load-frequency controllers have been obtained by minimizing the integral of the squared error (ISE) criterion [3], which reduces the frequency and tie line power errors to zero in the steady state. In most cases, the power system has been oversimplified by ignoring the presence of system nonlinearities. In the presence of nonlinearities, the dynamic response of the system is associated with large overshoots and longer settling times [3]. Hence, it becomes meaningful to consider the system nonlinearities while designing the controllers of the system. In this paper, the Governor Dead Band (GDB) nonlinearity has been considered.

Modern metaheuristic algorithms have been developed with an aim to carry out global search. The efficiency of metaheuristic algorithms can be attributed to the fact that they imitate the best features in nature, especially the selection of the fittest in biological systems which have evolved by natural selection over millions of years. A new metaheuristic search algorithm, called Cuckoo Search (CS) Optimization, has been developed by Yang and Deb [4] which has gained success in solving complex optimization problems. Hence, the cuckoo search optimization algorithm has been implemented to solve the LFC optimization problem.

II. SMES UNIT CONTROL STRATEGY

The schematic diagram of SMES unit is shown in Fig.1. The SMES unit has a superconducting inductance and a 12 pulse bridge converter connected to the transformer. The exchange of energy between the superconducting coil and power system is controlled by bridge converter. During normal operation of the grid, the superconducting coil is charged to a set point less than the full charge capacity from the grid. The dc magnetic coil is connected to the ac grid through a power conversion system which consists of an inverter/rectifier. Once charged to its set point, the superconducting coil conducts current, which supports an electromagnetic field, with no loss. The coil is immersed in a bath of liquid helium to maintain the coil temperature below the critical temperature value. During a sudden increase in the load, the stored energy is immediately released to the grid as ac line quality. Immediately as the governor and other control mechanisms start working to set the power system to its new equilibrium condition, the coil charges back to its initial value of current. Similarly during the sudden release of loads, the coil gets charged towards its full value, thus absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released back and the coil current attains its set point [5].

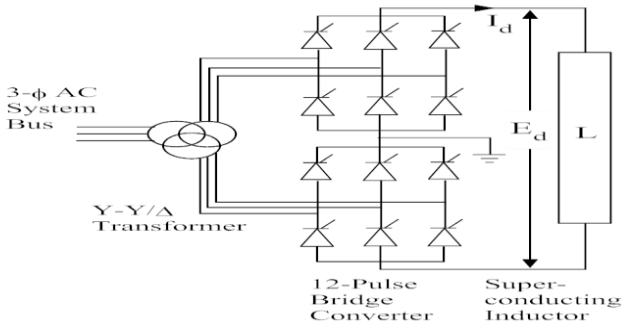


Fig.1. Schematic diagram of SMES unit

In LFC operation, the sensed area control error (ACE) is used to control the dc voltage E_d across the inductor coil. In this study, inductor voltage deviation of SMES unit of each area is based on ACE of the same area in power system. Moreover, the inductor current deviation is used as a negative feedback signal in the SMES control loop. So, the current variable of SMES unit is intended to be settling to its steady state value. [6]

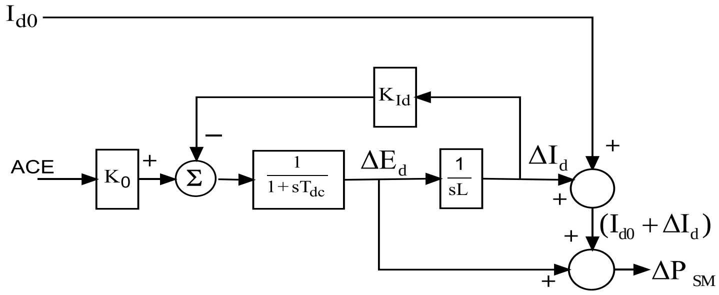


Fig.2. Transfer function model of SMES unit

The transfer function model used for the SMES unit is shown in Fig.2. SMES unit with suitable control can effectively reduce the frequency and tie-line power oscillations following sudden small load perturbations in power system.

III. STATEMENT OF THE PROBLEM

Interconnected power systems consist of many control areas connected by tie-lines. The block scheme of a two-area power system with SMES units is shown in Fig.3. Each area comprises of two thermal units and includes Governor Dead Band (GDB) nonlinearity. GDB is defined as the total magnitude of a sustained speed change within which there is no change in valve position. A describing function approach is used to incorporate the GDB nonlinearity [7],[8].

The dynamic behavior of the LFC system is described by the state space equation:

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BU} + \mathbf{\Gamma D} \qquad (1)$$

Where **X**, **U** and **D** are the state, control and disturbance vectors and **A** , **B** and **Γ** are respectively system state matrix, control input matrix and disturbance input matrix of appropriate dimension [3].

$$\mathbf{X} = \left[\Delta F_1\ \Delta P_{g11}\ \Delta X'_{e11}\ \Delta P_{g12}\ \Delta P'_{g12}\ \Delta X'_{e12}\ \Delta P_{tie1}\ \Delta F_2\ \Delta P_{g21}\ \Delta X'_{e21}\ \Delta P_{g22}\ \Delta P'_{g22}\ \Delta X'_{e22}\ \Delta E_{d1}\ \Delta I_{d1}\ \Delta E_{d2}\ \Delta I_{d2}\right]^T$$
$$\mathbf{U} = [\Delta P_{c1}\ \Delta P_{c2}]^T$$
$$\mathbf{D} = [\Delta P_{d1}\ \Delta P_{d2}]^T$$

The system matrices **A**, **B** and **Γ** can be obtained with the structure of the state, control and disturbance vectors and the transfer function block diagram representation of Fig.1.

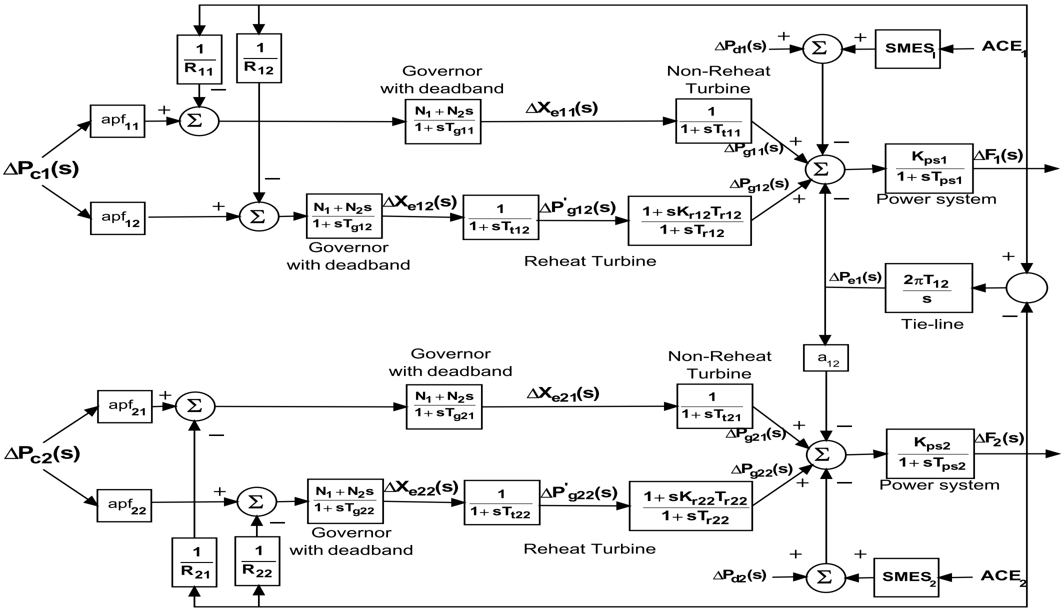


Fig.3. Block diagram of a two – area interconnected thermal power system with SMES units and GDB

The corresponding co-efficient matrices are obtained using the nominal system parameter values of the system. A step load disturbance of 1% has been considered as a disturbance in the system. For the frequency and tie-line power deviations to be zero at steady state, the Area Control Error (ACE) should be zero. To meet the above design requirement, the ACE is defined as:

$$\mathrm{ACE}_i = \Delta P_{tiei} + \beta_i \Delta F_i \qquad (2)$$

where 'i' represents the control area and 'β_i ' is the frequency bias constant. The objective is to obtain the optimum value of the controller parameters which minimize the performance index J [11]:

$$J = \int_0^t \left(\Delta F_1^2 + \Delta P_{tie1}^2\right) dt \qquad (3)$$

A new nature inspired metaheuristic search algorithm called as Cuckoo Search Optimization algorithm is used for the optimal designing of PI controller for LFC in two area interconnected power system to damp the power system oscillations. To simplify the analysis, the two interconnected areas are considered identical. The optimal parameter values are such that $K_{p1} = K_{p2} = K_p$ and $K_{i1} = K_{i2} = K_i$.

IV. CUCKOO SEARCH OPTIMIZATION

The basic Cuckoo Search (CS) Optimization algorithm [4] is primarily based on the natural obligate brood parasitic behavior of some cuckoo species in combination with the Lévy flight behavior of some birds and fruit flies. Cuckoos are naturally fascinating birds because of their lovely sound they produce and because of their intelligent reproduction strategy. Cuckoos lay their egg in the nest of other host birds, they also tend to destroy others egg to increase the hatching probability of their own egg so that when the eggs are hatched their chicks are fed by the other birds. Some species of cuckoo mimic the nature of host birds so that the host could not recognize them and give the cuckoo better chance of survival. If the host bird identifies the cuckoo egg despite all efforts of cuckoo, the host may either destroy the cuckoo egg or abandon the nest and build a new nest somewhere else.

In cuckoo search algorithm cuckoo egg represents a potential solution to the design problem which has a fitness value. The algorithm uses three idealized rules as given in [4]. These are:

a) Each cuckoo lays one egg at a time and dumps it in a randomly selected nest.
b) The best nest with high quality eggs will be carried over to the next generation.
c) The number of available host nests is fixed and a host bird can discover an alien egg with a probability of P_a [0, 1].In this case, the host bird can either throw the egg away or abandon the nest to build a completely new nest in a new location. Initially, a population of *n* eggs, each a potential solution to the problem under consideration is selected. Then, *n* solution vector of $x = x_1 ... x_{ng}^t$ is generated with *ng* variables. For each solution vector, the value of objective function f(x) is calculated. For cuckoo *i*, the algorithm generates a new solution $x_i^{v+1} = x_i^v + \beta\lambda$,where x_i^{v+1} and x_i^v are the previous and new solutions. The step size is selected as $\beta > 1$ according to the problem. λ is the step size which is determined according to random walk with Levy flights [9]. Fruit flies explore their landscape using a series of straight flight paths punctuated by a sudden 90 degree turn, leading to Lévy flight search pattern. This behavior has been applied to optimization and optimal search. When generating new solutions for a cuckoo, a Lévy flight is performed.

The pseudo code for CS algorithm [10] is:
Start Objective function f(x), $x = (x_1, x_2 \ldots x_n)^T$

Generate initial population of *n* host nests x_i (i=1, 2…n)
While (t<MaxGenerations) or (stop criterion)
Move a cuckoo randomly via Lévy flights
Evaluate its fitness F_i
Randomly choose nest among *n* available nests (for example j)
If ($F_i > F_j$) Replace j by the new solution;
Fraction P_a of worse nests is abandoned and new nests are being built;
Keep the best solutions or nests with quality solutions;
Rank the solutions and find the current best
End while
Post process and visualize results
End

V. OPTIMIZATION OF PI CONTROLLER PARAMETERS USING CUCKOO OPTIMIZATION ALGORITHM

Cuckoo algorithm is applied for optimizing the gains of a proportional plus integral controller for a two area interconnected thermal power system. The objective is to obtain the optimum values of the controller parameters which will minimize the performance index i.e. objective function, J given in (3).

Initialization of control parameters is done for the proposed optimization problem by selecting the number of host nests, n = 20, levy flight random walk step size, $\alpha = 1.5$, probability of discovery rate, $P_a = 0.25$ and number of iterations=50 as control variables. During each iteration, quality of eggs (J) is calculated for corresponding nest values (K_p and K_i). In each iteration, better nests are generated after elimination of worst nests and new nests (updated K_p and K_i values) are generated based on levy flight random walk. The search for best nest (optimum K_p and K_i) is proceeded until the stopping criteria (maximum number of iterations) is met.

VI. SIMULATION AND RESULTS

Performance of cuckoo algorithm tuned optimal controllers has been done and the results are shown in Fig.4, Fig.5 and Fig.6 for 0.01 pu step load perturbation in area 1. Comparison of magnitude of frequency deviation and the time taken to damp out oscillations for the controller clearly reveal that CA tuned optimal controller provides better response. The peak overshoot and settling time parameters of the system have been shown. The summary of observation of results in Figs.4 to 6 is as follows:

It has been shown in the present work that SMES units with suitable control can effectively reduce the frequency and tie-line power oscillations following sudden small load perturbations. Figs.4 and 5 show the change in frequency in area-1and area-2 respectively. It is observed that the peak overshoot in case of system with SMES unit is 0.015 Hz as compared to 0.023 Hz for system without SMES unit in area-1 and the peak overshoot in case of system with SMES unit is 0.009 Hz as compared to 0.0245 Hz for system without SMES unit in area-2. This shows that peak deviation reduces for the former case. It is also observed that the settling time in case of system with SMES unit is 12.14 seconds where it is 22.24 seconds in case of system without SMES unit in area-1and the settling time in case of system with SMES unit is 13.08 seconds where it is 21.42 seconds in case of system without SMES unit in area-2. Hence, system settles faster in case when SMES is used. Fig.6 shows the change in tie-line power. It is observed that the peak deviation of tie-line power in case of system with SMES unit is 0.0032 Hz as compared to 0.0066 Hz for system without SMES unit, resulting in reduced peak deviation. It is also observed that the settling time in case of system with SMES unit is 14.12 seconds where it is 24.52 seconds in case of system without SMES unit. The simulation results demonstrate the effectiveness in the damping and settling of transient responses. Table 1 shows the optimum PI controller values and the corresponding cost function value (J). It is apparent from table 1 that the objective function is very much reduced when SMES units are included in the power system model. For the proposed model, standard notations and standard data given in [11] are used.

Table 1. Optimal PI controller values and corresponding cost functions

	K_p	K_i	J
Without SMES	0.3269	1.2462	1.3741
With SMES	0.3453	2.3952	0.3648

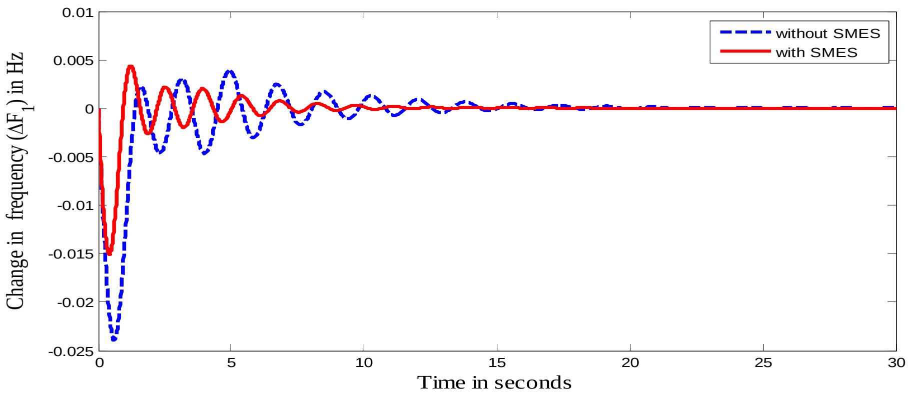
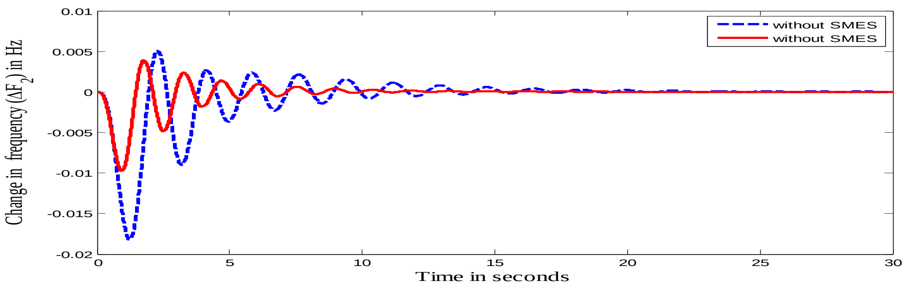


Fig. 4. Change of frequency in area -1



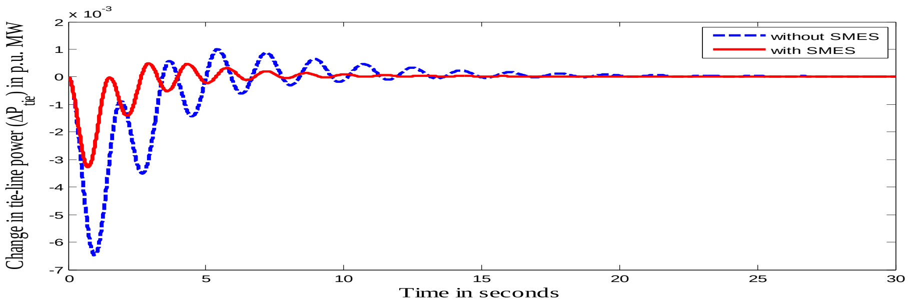


Fig. 5. Change of frequency in area -2

Fig. 6. Change in tie-line power

VII. CONCLUSION

In this work, the application of a recent nature inspired algorithm called cuckoo search optimization algorithm for power system optimization problem is presented. A two area interconnected power system with SMES units is used to demonstrate the method. By considering the governor dead band, the dynamic behavior of realistic interconnected power systems has been presented. The GDB non-linearity cause system to be severely non-linear and therefore tuning of controller parameters is not so straight forward. The Cuckoo search optimization algorithm is used to calculate the proportional integral controller gain which conducts the system to a normal condition following disturbances. The proposed algorithm reduces efficiently the population size and the number of iterations to have the optimal solution. The computer simulation on the two area system show the effectiveness of cuckoo optimization in obtaining the optimal PI-controller for better control performance in terms of peak overshoot and settling time.

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