Area control error enhancement of two-area power system using hybrid intelligence optimal controller

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Article Info

Article history:

Received Jul 5, 2022
Revised Jun 9, 2023
Accepted Jun 17, 2023

Keywords:

Area control error
Artificial immune system
Clean energy technology
Clonal selection algorithm
Linear quadratic regulator
Proportional integral controller

ABSTRACT

Area control error (ACE) is a critical factor in linked power systems. When a disturbance occurs, ACE is utilized to determine how much power should be deployed. As a result, it is critical that the ACE have as little inaccuracy as feasible. This research provided a strategy for improving the dynamic response of ACE in a power system. A hybrid optimal controller is the name given to this technology. Coordination between the proportional-integral (PI) controller and the state feedback controller based on the linear quadratic regulator (LQR) is the concept of a hybrid optimum controller. All controller parameters are created utilizing artificial immune system (AIS) clonal selection to improve coordination. The proposed control mechanism is demonstrated using a two-area power system as a test system. To investigate the efficacy of the suggested strategy, time domain simulation is used. The simulation results show that the suggested method outperforms the previous situations in this work (the overshot of frequency deviation in areas 1 and 2 is 0.00029 and 0.00015, respectively).

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1. INTRODUCTION

The major aspect in maintaining the reliability of delivering electricity to consumers is power system stability. The power system should be stable in order to assure the quality of the energy delivered to users. Power system stability is classified into three categories: rotor angle stability, voltage stability, and frequency stability [1]. The ability of a power system to sustain synchrounization after being perturbed is referred to as rotor angle stability [2]. Voltage stability refers to a power system's ability to maintain balance in a reactive power system [3]. The capacity of power systems to maintain a balance between generating and load is referred to as frequency stability [4]. One of the most critical aspects of sustaining power transfer dependability is maintaining the system's frequency stability.

To manage the frequency in a power system, four separate controller stages are used [5]. The primary controller is inertia correction, which is mostly provided by the generator's rotating machine [6]. This compensation cannot be regulated; it is based on the rotating machine's inherent response to adjust for inertia [7]. The governor is the second controller; in order to maintain the balance between power generation and load, the governor must modify the speed of the turbine when the load changes [8]. Because the turbine's speed is related to the generator's mechanical power. Load frequency control [9] is the third controller; this controller is an auxiliary controller that helps the system's frequency discover its steady state functioning (zero steady state error). If the system is a single region, the frequency deviation of the system is the third controller's input. Furthermore, if the system is multi-area, the input is area control error (ACE) from all areas. The last controller is an emergency controller, which is activated manually by the operator when the first three controllers fail [10]. When the fourth controller is engaged, one of the loads should be sheeded. If this occurs, the power system's reliability and quality are compromised. As a result, it is critical to keep the third controller running automatically and optimally. One method is to reduce the oscillation of the ACE.

Chidambaram and Paramasivam [11], describes the use of redox flow batteries and an interline power flow controller to improve load frequency controller performance. Chidambaram and Paramasivam [11] implement the interline power flow controller to make inter-area power more stable in order to make the ACE more stable. If the inter-area power is more steady, the ACE will be more stable as well. Furthermore, redox flow batteries were used in this study to deliver instatenous power to the load when there was a fast load change. Abraham *et al.* [12], developed a strategy for improving ACE by implementing capacito energy storage. Pappachen and Fathima [13] describes the use of FACTS devices and superconducting magnetic energy storage to improve the ACE transient responsiveness. When both controllers are used, the frequency is adjusted. It is notable that capacitor energy storage can regulate frequency by contributing active power to the grid. The application of fractional order fuzzy PID (FOFPID) with redox flow batteries to reduce overshoot and speed ACE settling time is demonstrated in [14]. In this study, FOPID is employed as the governor's controller to make the governor sensitive to any changes in the ACE. Furthermore, the application of redox flow batteries is similar to the study in [11]. Mahendran and Vijayan [15] describes the use of model-predictive control for ACE improvement. It is clear from this study that the model predictive controller can reduce overshoot and speed settling time. However, all of the preceding research has drawbacks in terms of cost and difficulty of implementing the proposed approach. As a result, it is critical to build a controller that is less complex and less expensive, such as a hybrid optimum controller.

Over the years, the use of metaheuristic algorithms to optimize controller parameters has yielded promising results. Razmjooy and Khalilpour [16] describes the use of the invansive weed optimization (IWO) algorithm for constructing PID controllers. It has been discovered that by designing a PID controller based on IWO, PID may give a better signal controller for the hydro governor to modify the turbine speed. This technology improved the frequency performance of the power system. Razmjooy *et al.* [17] describes the use of whale optimization in the design of a DC motor speed controller. It is notable that a speed controller based on whale optimization might reduce overshoot and speed up the settling period of a DC motor speed. New metaheuristic algorithm inspired by fifa world cup competition is reported in [17]. As reported by Razmjooy [18], the algorithm is used as the method for designing PID controller of automatic voltage regulator. From the results it is shown that the AVR could giving more stable voltage when PID controller is tuned by the algorithm. From above paper, it can be concluded that metaheuristic algorithms are giving a promising result for optimization problems.

This research offered a low-cost, less-complex controller concept for improving ACE transient response utilizing a hybrid optimum controller. Artificial immune system (AIS) clonal selection techniques are utilized to create the hybrid optimum controller to improve coordination. The remainder of the paper is structured as follows: Section 2 described the researched power system's dynamics model, the hybrid optimal controller concept, linear quadratic regulator applications, the AIS clonal selection technique, and how to develop the hybrid optimal controller using AIS. Section 3 focuses on the paper's experimental results and commentary. Section 3 also includes a comparison of the proposed approach to any other method. Section 4 emphasizes contribution, conclusions, and future directions.

2. METHOD

This section comprises of five subsections, focusing on how the proposed method is designed. The first sub-section is focusing on dynamic modelling of two-area power system. The second sub-section focused on how to model the hybrid optimal controller.

2.1. Dynamic representation of two-area power system

To capture the dynamic behavior of the system, the system is represented as a dynamic model in this paper. The dynamic representation of a two-area power system, as indicated in (1) and (2), can be recorded using state space representation [19].

$$\dot{x}(t) = Ax(t) + Bu(t) + Ld(t) \tag{1}$$

$$yx(t) = Cx(t) \tag{2}$$

In (1) and (2), system matrix, input matrix, output matrix, disturbance matrix, state variable, input variable, disturbance variable, and output variable are defined as *A*, *B*, *C*, *L*, *x(t)*, *u(t)*, *d(t)* and *y(t)*. To capture the dynamic model of power system state variable *x(t)* in (1) can be rewritten using (3). While the input and disturbance of the system can be further described using (4) and (5) [20].

$$x(t) = [\Delta f_1 \Delta P_{m1} \Delta P_{G1} \Delta P_{tie} \Delta f_2 \Delta P_{m2} \Delta P_{G2}]^T \quad (3)$$

$$u(t) = [u_1 u_2]^T = [\Delta P_{c1} \Delta P_{c2}]^T \quad (4)$$

$$u(t) = [d_1 d_2]^T = [\Delta P_{L1} \Delta P_{L2}]^T \quad (5)$$

In (5) $\Delta P_{L1} \Delta P_{L2}$ are the load variations in zones 1 and 2. The term "area control error" refers to the usage of an input signal for an additional controller. The ACE should be maintained to have less oscillation as possible. The controller should make the ACE have small overshoot and the fastest settling time as the ACE will be giving signal to governor for adjust the turbine speed when disturbance emerges [21]. Hence, the right additional controller is essential to maintain stable condition of the ACE transient response.

2.2. Hybrid optimal controller modelling

The concept of hybrid optimal controller is combination between proportional-integral (PI) controller and state feedback controller. By combining these two controllers the oscsillation of ACE when disturbance emerge can be reduced significantly. Figure 1 shows the dynamic representation of hybrid optimal controller installed to the single system while Figure 2 shows the dynamic representation of hybrid optimal controller installed in two-area power system. It is found that the input of PI controller is ACE signal, while the state feedback controller is added with the PI control signal. This added signal will be used as the control signal of governor to adjust the speed of the turbine. In this paper, the system is represented as dynamic model to capture the dynamic response of the system. The dynamic representation of two-area power system can be captured through state space representation as described in (1) and (2).

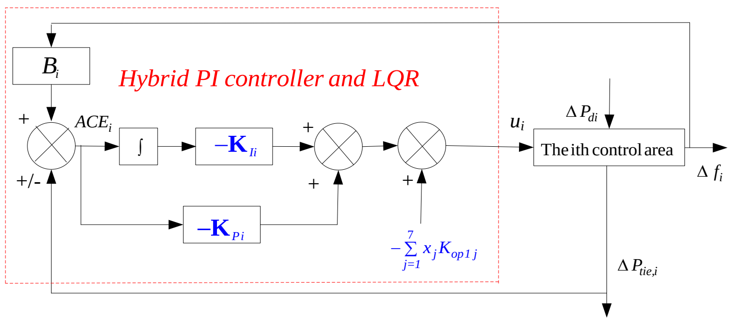

Figure 1. Dynamic model of hybid optimal controller on single area system

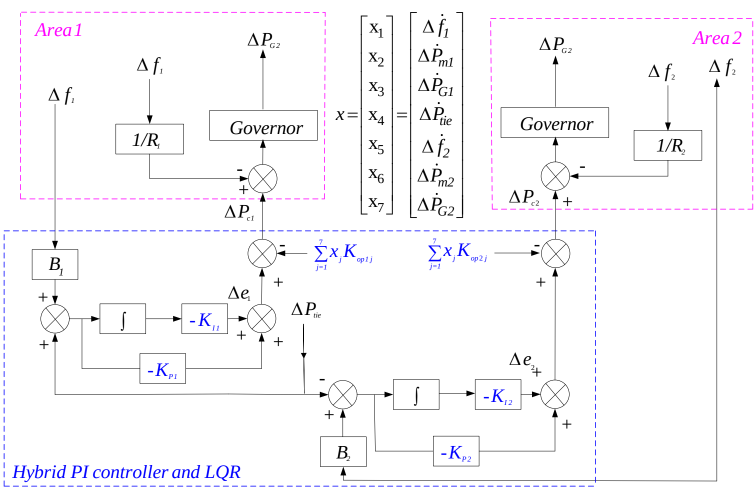

Figure 2. Dynamic model of hybid optimal controller on two-area system

2.3. Linear quadratic regulator optimal control

Linear quadratic regulator (LQR) is a practical control plant system based on optimal control whose function is to reduce the error signal in the plant system [22]. The schematic diagram of LQR optimum control placed in the plant system is shown in Figure 3. To obtain an adequate control signal u, Kop is a feedback gain that should be obtained using the LQR optimum control approach [23]. As indicated in Figure 3, the gain feedback input is the computed value between the plant's input and output. By taking into account both inputs, LQR generates a specific gain feedback that can be used to reduce the error between the input and the output.

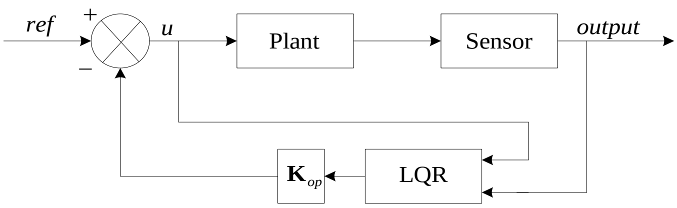

Figure 3. Block diagram of LQR optimal control

It is assumed that the plant system is a linear time-invariant (LTI) system model. An appropriate control signal is computed using LQR optimal control theory as follows [24]. To address the problem, a quadratic criterion with its performance index, as defined in (6), is applied. where t0 is the system's initial condition, S(T) 0 (positive semi-definite), Q 0 (positive semi-definite), and R > 0 (positive definite), with dimensions Qnxn and Rmxm, respectively. Q and R are the LQR optimum control weighting matrices [25].

$$J(t_0) = \frac{1}{2}x^T(T)S(T)x(T) + \frac{1}{2}\int_{t_0}^{T}[x^T(t)Qx(t) + u^T(t)Ru(t)]dt \quad (6)$$

To reduce the mathematical burden in (6), the restructure of the mathematical representation is essential. The performance index of LQR can be further rewritten as described in (7).

$$J(t) = \frac{1}{2}x^T(t)S(t)x(t) + \frac{1}{2}\int_{t}^{T}\|R^{-1}B^TSx + u\|_R^2 dt \quad (7)$$

The (7) can be further reduced as described in (8). Furthermore, the sokution of (8) can be formed as described in (9).

$$J(t) = \frac{1}{2}x^T(t)S(t)x(t) \quad (8)$$

$$-\dot{S} = A^TS + SA - SBR^{-1}B^TS + Q \quad (9)$$

From (8) and (9) the optimal value of gain Kop can be described using (10) and (11). In addition, the closes loop state space of the system with gain feedback is described using (12):

$$K_{OP}(t) = R^{-1}B^TS(t) \quad (10)$$

$$u(t) = -K_{OP}(t)x(t) \quad (11)$$

$$\dot{x}(t) = (A - BK_{OP})x \quad (12)$$

as mentioned in (13), the Riccatio equation of a closed loop system matrix is evolving into a Joseph stabilized formulation. In general, the weighting matrix can be determined through trial and error until the objective value of J is reached.

$$-\dot{S} = (A - BK_{OP})^TS + S(A - BK_{OP}) + K_{OP}{}^TRK_{OP} + Q \quad (13)$$

2.4. Artificial immune system clonal selection

The immune system of living creatures inspired the AIS [26]. In AIS, there is a process known as clonal selection. The goal of clonal selection is to identify and protect the body from potentially harmful organisms (known as antigens). This clonal selection algorithm can help with optimization problems [27]. The procedure of the algorithm is consistent with the following step [28]:

a) Produce a collection P of potential solutions. Memory cells M and the residual population Pr make up this antibody population (P=Pr +M).
b) Select the n best individuals Pn from the population P using the affinity measure.
c) Clone n best individuals from the population, resulting in a transient population of clone C. The clone size increases when the antigen's affinity is measured.
d) Subject the clone population to a hypermutation strategy in which the hypermutation is proportional to the antibody's affinity. C* represents a matured antibody population.
e) Select the enhanced persons from C* once more to complete the memory set. Some members of the P set can be replaced with improved C* members. This stage also includes the replacement of low affinity antibodies.
f) Interation process will be stoped until reach maximum generation.

In this algorithm, steps b and c are critical. If we choose n = N in Step 2, i.e. the number of persons with the highest affinity equals the number of candidates, each member of the population will be a potential candidate solution. This is known as a greedy search, and it may or may not be effective.

2.5. Procedure of the proposed method

In this research AIS clonal selection is used to optimize the parameters of PI controller and the weighting matrix of LQR optimal control. The weighting matrix of LQR optimal control is described as Q and R matrix. The procedure of designing the proposed method include the following step.

- Generate the first antibody in the population at random.
- The performance index used as the objective function is as shown in (14):

$$J = (\int_0^{t_f}(ACE_1(t)^2 + ACE_2(t)^2)dt) + \frac{1}{2}x^T(t)S(t)x(t) \tag{14}$$

subject to:

$$\begin{aligned} &Kp_{min} \leq Kp \leq Kp_{max} \\ &Ki_{min} \leq Ki \leq Ki_{max} \\ &Q_{min} \leq Q \leq Q_{max} \\ &R_{min} \leq R \leq R_{max} \end{aligned} \tag{15}$$

- In step two, the performance index is used to compute affinity. The best antibody in this algorithm is one with a high affinity.
- Antibodies with high affinity in the population are more likely to be cloned.
- Based on step two, each antibody is re-selected.
- Antibody with lower affinity will be replaced.

3. RESULTS AND DISCUSSION

The efficacy of the proposed method is thoroughly investigated in this section. The software MATLAB is used to investigate the performance of the proposed technique. In this study, two case studies are used to demonstrate the superiority of the proposed strategy. The suggested controller is tested using a two-area power system to evaluate how it might improve area controller error performance. The first case study looked at how ACE responded to small perturbations. Furthermore, the second case study concentrated on how the ACE reaction affected the frequency response of the power system.

3.1. ACE response

The ACE response is thoroughly examined in this section. A modest disturbance is applied to the system in order to awaken the weak mode. The perturbation is represented as a step input with a modest load change. Figures 4 and 5 depict the ACE response of a two-area power system in areas 1 and 2. To demonstrate the efficacy of the proposed controller, a comparison with other methods is performed. Four different scenarios are studied in Figures 1 and 2 to demonstrate the efficacy of the suggested strategy. The first scenario (shown by the purple line) is a hybrid optimum control method (TEM). The hybrid optimum control utilizing the morisky medication adherence scale (MMAS) method (shown by the black line) represents the second case. The third scenario is the hybrid optimum control based on genetic algorithms (GA) (shown by the blue line). The fourth scenario (hybrid optimal control based on the artificial immune system) is the method proposed in this paper. The proposed method is also highlighted by the red line.

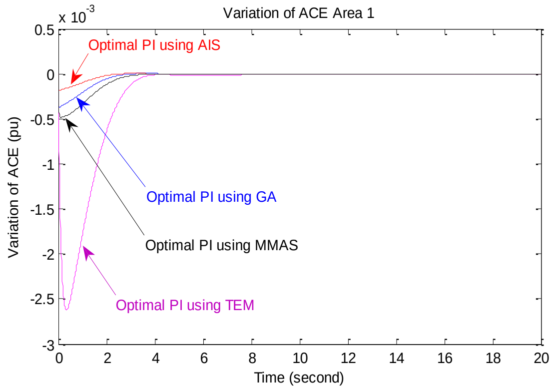

Figure 4. ACE response in area 1

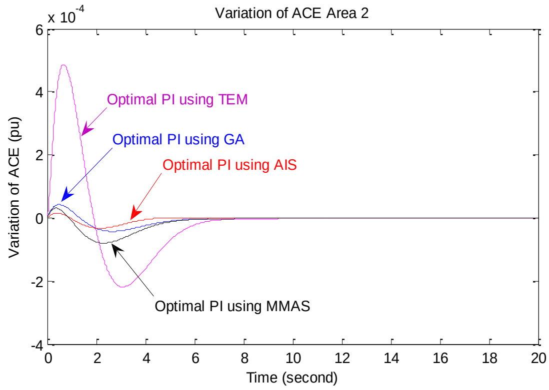

Figure 5. ACE response in area 2

From Figures 4 and 5 it is observed that the proposed method is superior compared to other scenarios. This is indicated by the smallest overshoot of the ACE transient response. In addition, the settling time of the system with proposed controller is the fastest in all the scenarios. If the ACE of the system have small overshoot and fastest settling time this means that proposed controller can give a best control signal to the governor. Hence, the governor can give adjust the speed of turbine to produce the mechanical power that the system needed. The balance between mechanical power from turbine and electrical power from the load will reduce the overshoot and accelerated the frequency response of the power system. As a result, it is critical to analyze the frequency response of the system when the suggested controller is used in a two-area power system. As a result, it is critical to analyze the frequency response of the system when the suggested controller is used in a two-area power system.

3.2. Frequency response

This section examined the frequency response of a two-area power system in both areas 6 and 7. As previously stated, frequency oscillation can be decreased when a turbine can deliver mechanical power that is inversely proportional to electrical power from changing loads. Figures 3 and 4 depict the dynamic response of the frequency in areas 1 and 2. This section, like the previous one, considers four different scenarios to demonstrate the efficacy of the suggested controller technique.

The suggested technique clearly outperforms the other scenarios, as shown in Figures 6 and 7. It is evidenced by the frequency response in both areas 1 and 2. When the system is fitted with the proposed controller approach, the frequency response in areas 1 and 2 has the smallest nadir. Furthermore, the proposed approach may shorten the settling period of the frequency dynamic response. As a result, a low frequency nadir and a quick settling period indicate that the system's rate-of-change-of-frequency (RoCoF) is low. If the RoCoF is minimal, the system is more resistant to disruption. In addition, this result is also validating the previous section results. When the overshoot and settling time of ACE is small and faster than the governor can adjust the speed of the turbine to produce mechanical power that inversely proportional to the load change.

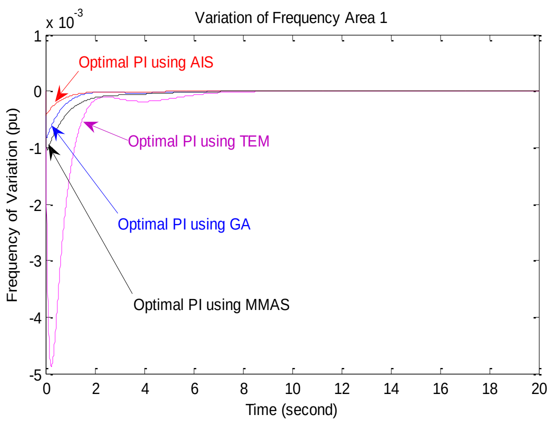

Figure 6. Frequency response in area 1

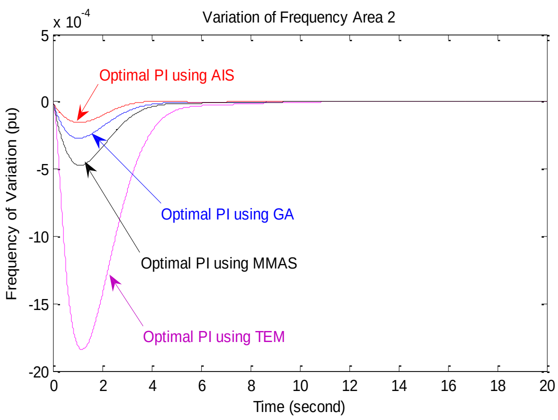

Figure 7. Frequency response in area 2

4. CONCLUSION

This research developed an intelligent hybrid optimum control strategy for lowering oscillation on area control error in an interconnected power system. The test system for this research is a two-area power system. Furthermore, time domain simulation is used to demonstrate the effectiveness of the proposed controller. According to the simulation findings, the ACE of the system with the suggested technique has the minimum overshoot and the fastest settling time (settling time of frequency areas 1 and 2 are 17.18 and 17 seconds, respectively). In addition, the transient response of ACE is proportional with the transient response of system frequencies. Hence, the better the ACE response the better the frequency of the system. Further research can be conducted by testing the proposed system under larger system (three area or four area). In addition, the integration of inverter-based power plant can be also considered to investisgate how the proposed method handle system with low inertia.

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