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Original Article

Covariance matrix adaptation evolution strategy for robust load frequency control of hydro power systems

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Abstract

Modern power systems are very complex and critical to electrical engineering services. The interconnections between various areas, nonlinear dynamics, and huge inertia of the components, make the problem very complex. Any load deviation in one area will affect the others, too. So, in this paper, a robust control strategy is utilized to offer minimal and non-oscillatory frequency swings in response to load deviation. The paper also explores and compares the use of covariance matrix adaptation evolution strategy (CMA-ES) based algorithm for the design of optimal robust controller. The controller has been expressed as the aggregate function of a multi-objective optimization problem. The results obtained show that the robust controller designed using CMA-ES offers a satisfactory response when compared to classical and other controllers obtained using time-based performance indices.

Keywords: load frequency control, robust control, evolutionary algorithms, covariance matrix adaptation evolution strategy

1. Introduction

The entire power system is complex due to its interconnections. The operation, security, and reliability of a power system depend upon the balance between generation and demand. The deviation between load demand and power generation shifts the operating point of a power system in terms of frequency deviation from the nominal value (Elgerd & Fosha 1970; Ibraheem, Kumar, & Kothari 2005; Kothari & Nagrath 2003). Therefore, the power system requires proper frequency control for operation within its nominal frequency range (Elgerd, 1983). Flywheel governor is generally used to minimize the frequency deviations. The control of these systems may be posed as single area or multiple area problem. The system consists of only single area when generator units have no tie line connection. Various methods like variable structure control (Chan, 1982), robust control (Amin Khodabakhshian & N. Golbon, 2005; Ray, Prasad, & Prasad, 1999), integrated control (Sonkar & Rahi, 2017) and adaptive control (Pan & Liaw, 1989) have been proposed by researchers to tackle load frequency control (LFC). The Artificial Intelligence techniques like ant colony optimization (Dhanasekaran, Siddhan, & Kaliannan, 2020), fuzzy logic (Mohammed, Momoh, & Shukla, 2017), genetic algorithm (Cam, Gorel, & Mamur, 2017) and particle swarm optimization (Kouba *et al.*, 2017) have been used to tackle the complexity and the non-linearity of load frequency control. The load frequency control method of a single area system with a time delay is reported by Jiang *et al.* (2012). The hybrid source (hydro/thermal/gas) in a single area problem was also addressed by Parmar *et al.*, 2012. The load frequency control in hydro plant for a single area system is

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presented in (Doolla & Bhatti 2006) and the study included reduced dump load for single area control. The AGC (automatic generation control) of hydro plant is also given by (Kusic *et al.*, 1988). Liu *et al.* (2019) presents a robust control methodology to tackle the power fluctuations in multi-area systems when subjected to cyber-attacks. Alhelou *et al.* (2018) presented a state of the art review on the various challenges and opportunities that can be explored in modern smart power systems and highlighted the need for robustness and reliability in such systems, as there are certain assumptions in the mathematical model and the model used for controller synthesis that are merely approximations of the real system.

In this paper, the focus is on design of an optimal robust controller for the single area load frequency control problem. Initially, a PID controller was tuned using the Ziegler-Nichols method, followed by optimal controller design in time domain performance using various evolutionary algorithms. But in both these cases overshoots have been observed, such that can lead to oscillations in the frequency during load changes. So, to assure robust responses, the design of a robust controller has been considered, where the controller synthesis problem has been posed as an optimization problem to minimizing both the time domain rise time and overshoot percentage, and for robustness minimizing the sup-norm of the complementary sensitivity function. The efficacy of the designed system has been tested in two cases, firstly for a parametric uncertain condition, and secondly when a dip in the system's frequency is observed.

2. Mathematical Model of Single Area Load Frequency Control

Single area in power system only supplies power from source end to a load directly. Usually, power systems offer very complex and nonlinear dynamics, which need to be linearized. Therefore, in this study a single generator has been consider to feed the power to a single area. This power unit consist of single area with governor $G_{GOV.}(s)$, turbine $G_{Turb.}(s)$, and load and $G_{Load}(s)$ 1/R droop characteristic as a feedback gain. Figure 1 shows the block diagram of turbine, governor, load and machine. The transfer function of a single area case is given as follows:

$$G_{Gov.}(s) = \frac{1}{\tau_g s + 1}$$

$$G_{Turb.}(s) = \frac{1}{\tau_t s + 1}$$

$$G_{Load}(s) = \frac{1}{I_M s + D}$$

Here, the governor time constant is (τ_g), the turbine time constant (τ_t), the governor inertial constant (I_M) and the damping coefficient is (D). The corresponding transfer function is:

$$G(s) = G_{Gov.}(s)G_{Turb.}(s)G_{Load}(s) = \frac{1}{(0.2s+1)(0.5s+1)(10s+0.8)} \quad (1)$$

3. Proposed Method to Tune PID Controller

3.1 Formulation of optimization problem

The main aim of the control designer while designing a feedback control system is to synthesise a controller that offers a satisfactory closed loop performance, such that various design requirements and constraints are satisfied. In classical control theory, several methods have been proposed to synthesise controllers, and the PID controller, given in equation (2), is one of the mostly widely used controller types in most industrial applications, because of its simplicity and ease of tuning (Nise, 2020). In classical control theory, several approaches exist to design a PID controller, like the Ziegler-Nichols method, Chien, Hrones, and Reswick (CHR) method, Cohen-Coon method etc. But, the performance of these methods is generally not optimal, and large overshoot percentages have been reported in the literature, and further, these controllers are not robust by their nature and can't mitigate the effects of plant uncertainties and disturbances. To address the plant uncertainties and disturbances, several robust control theories like, H_∞, μ-synthesis, etc., have been reported in the literature. But the controllers synthesised by these robust control strategies generally have a very high order, are generally non-optimal, and increase the complexity of the whole system.

So, the main motivation here is to design low order controllers that offer and satisfy the desired performance objectives and constraints, such that the designed closed loop system offers good time domain performance and also exhibits good robust behaviour resistant to parametric uncertainties. So, here in this paper, the design of an optimal PID controller has been considered such that offers good time and frequency domain responses. In this paper, algorithms have been used to optimally tune the PID controller, namely, genetic algorithm (GA), differential evolution (DE), and covariance matrix adaptation evolutionary strategy (CMA-ES). Figure 2 shows a schematic of the optimization process using a block diagram.

$$K(s) = K_P + \frac{K_I}{s} + K_D s \quad (2)$$

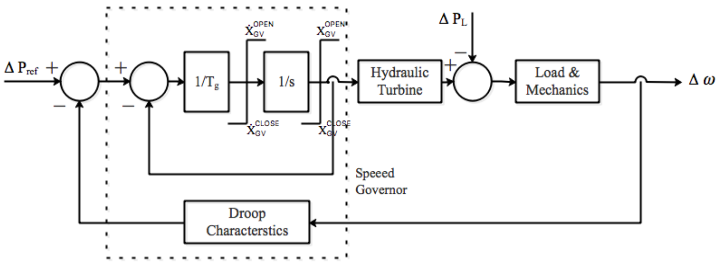

Figure 1. Block diagram of turbine, governor, load and machine

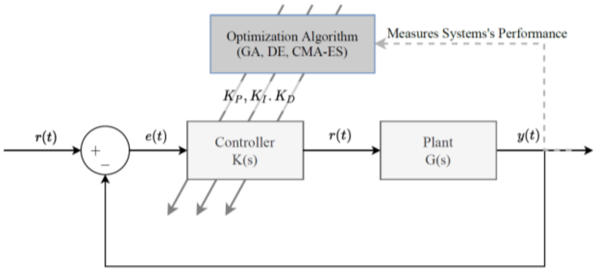

Figure 2. Optimization process to tune the PID controllers

3.1.1 Formulation of objective function related to time domain response

As, the controller obtained by using Ziegler-Nichols tuning offers an oscillatory response, the controller gains are not optimal and hence need to be further fine-tuned. So, here, the PID controller synthesis has been formulated as an optimization problem to minimize the time domain performance index of integral of squared error (ISE), and is given by equation (3).

$$J_{ISE} = \int \left(e(t)\right)^2 dt \tag{3}$$

Three evolutionary algorithms, namely GA, DE and CMA-ES, have been used to obtain the optimal gains. The number of parents/populations in all the three algorithms has been taken as 60.

3.1.2 Formulation of objective function related to robust control

The control system synthesis is a multi-objective design problem, since to design a good feedback control system, one needs to address several time and frequency domain design objectives and constraints. So, in order to improve the overall response of the closed loop system both in time and frequency domains, so that the control system offers a robust response, here the controller synthesis problem has been formulated as a multi-objective optimization problem. The two conflicting time domain objectives are the minimization of overshoot percentage equation (4) and the rise time in equation (5), these have been considered along with the frequency domain performance targets of minimizing the sup-norm of the complementary sensitivity function, equation (6), to assure robustness. The algorithms GA, DE and CMA-ES with population size of 60 have been used to obtain the optimal gains. The optimization problem has been expressed in the aggregate of function of equation (7), where weights α_i have been assigned to these three performance indicators. In the current study, equal preference has been given to each of the three objectives, hence the values of α_i were chosen as [10, 10, 5].

$$J_{OS} = e^{\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\right)} \tag{4}$$

$$J_{RT} = \frac{\pi - \theta}{\omega_d} \tag{5}$$

$$J_{\|T(j\omega)\|_\infty} = \left\| \frac{G(j\omega)K(j\omega)}{1 + G(j\omega)K(j\omega)} \right\|_\infty \tag{6}$$

$$J = \alpha_1 \cdot J_{OS} + \alpha_2 \cdot J_{RT} + \alpha_3 \cdot J_{\|T(j\omega)\|_\infty} \tag{7}$$

3.2 Covariance matrix adaptation evolutionary strategy (CMA-ES)

Hansen (2007) proposed a continuous evolutionary algorithm that samples the probability distribution of the members in the population to generate the new one. One of the biggest advantages of CMA-ES is the non-elitism property, that aids in converging towards a global solution even with a lesser population size. The algorithm efficiently handles the tradeoff between the exploration and exploitation of the search space, while converging towards the solution, which boosts the likelihood of convergence to a global solution. The algorithm firstly generates a population/ generation using normal distribution, evaluates the mean of the fitness function of all the members in search space, updates the covariance matrix to converge towards the global solution and finally updates the global step size.

4. Results and Discussion

Classical control theory offers many methods to directly synthesize the PID controller for a given plant. Here, the use of Ziegler-Nichols (ZN) method has been considered for the initial controller synthesis. The PID controller gains obtained using Ziegler-Nichols frequency method are given in equation (4). The time and frequency domain responses of the closed loop system can be seen in Figure 3, from which it can be observed that the ZN tuned PID controller offers an oscillatory response.

$$K_{ZN}(s) = 43.383 + \frac{43.911}{s} + 10.726s$$

4.1 Optimal controller synthesis using time domain approaches

The controllers obtained after optimizations using GA, DE and CMA-ES are given by equations (6), (7) and (8), respectively. The plots for assessing convergence are shown in Figure 7. The time and frequency domain responses of the closed loop systems can be seen in Figure 4. From the figure, it can be observed that these tuned PID controllers offer satisfactory responses in time domain, but in frequency responses peaks can be observed in the magnitude curve of the Bode plot.

$$K_{GA-ISE}(s) = 4.36 + \frac{2.199}{s} + 6.75s$$

$$K_{DE-ISE}(s) = 7.71 + \frac{3.08}{s} + 8.93s$$

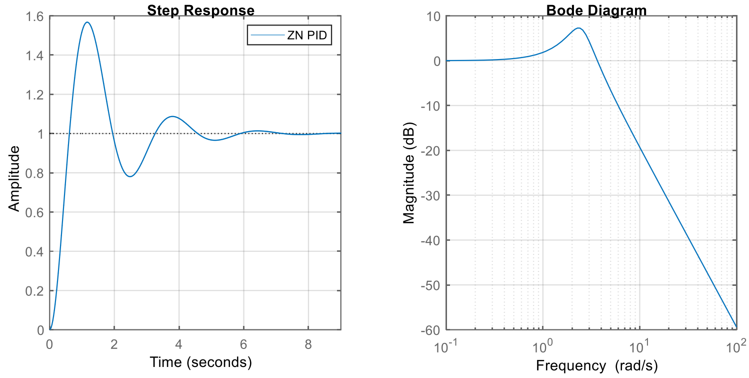

Figure 3. The time and frequency responses of the closed loop system with ZN-PID controller

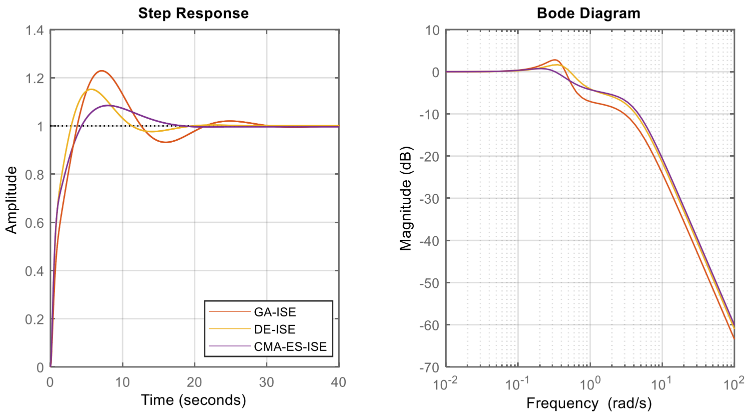

Figure 4. Time and frequency responses of the closed loop systems with controller gains obtained using GA, DE and CMA-ES by minimizing ISE

$$K_{CMAES-ISE}(s) = 7.16 + \frac{1.646}{s} + 9.91s$$

4.2 Optimal robust controller synthesis

The controllers obtained after optimization using GA, DE and CMA-ES are given by equations (13), (14) and (15), respectively. The convergence plots are shown in Figure 7. From the figure it can be observed that in both cases (when ISE is used as performance metric; and when the robustness objective is defined by equation (7)) the CMA-ES algorithm offers better convergence. The time and frequency domain responses of the closed loop systems can be seen in Figure 5. From the figure, it can be observed that these tuned PID controller offer satisfactory responses in time domain, but in frequency responses peaks are observed in the magnitude curve of the Bode plot.

$$K_{GA-R}(s) = 14.64 + \frac{1.267}{s} + 10.14s$$

$$K_{DE-R}(s) = 11.11 + \frac{0.972}{s} + 11.38s$$

$$K_{CMAES-R}(s) = 18.06 + \frac{1.251}{s} + 8.99s$$

The classical methods for tuning the PID controllers didn't offer satisfactory responses as oscillations have been observed in time domain responses and a peak can be observed in the magnitude curve of the Bode plot. So, to improve the time domain response and obtain optimal controller gains, the controller synthesis problem has been posed as an optimization problem for minimizing the ISE and has been solved using GA, DE and CMA-ES and the closed loop systems showed a good time domain behavior but not the optimal frequency domain behavior. So, to assure optimal time domain robust behavior, the optimization has been formulated as a multi-objective one, and has been solved.

The various time and frequency domain performance indices are shown in Table 1. Figures 6 and 7 show the time and frequency responses of the systems with the designed controllers. From the obtained responses in Figures 5 and 7 and Table 1, it can be observed that the CMA-ES tuned robust PID controllers offer the best response both in time and frequency domains. It can further be seen that the controllers tuned using only the time-based performance, i.e. by minimizing the ISE, offer good time response, but the frequency domain response is not optimal. The plot for control signals for all the proposed controllers is shown in Figure 8

5. Conclusions

To check the efficacy of the designed controllers, two different scenarios have been considered. In the first case,

Table 1. Time and frequency domain performance indices

Algorithm	Rise time	Settling time	Overshoot percentage	Complementary sensitivity	Gain margin	Phase margin
Ziegler Nichols	0.41 sec.	5.53 sec.	56.76%	2.31	Inf.	25.73
GA (ISE)	2.83 sec.	25.26 sec.	22.88%	1.38	Inf.	59.52
DE (ISE)	1.99 sec.	15.49 sec.	15.22%	1.21	Inf.	85.50
CMA-ES (ISE)	2.78 sec.	14.83 sec.	8.45%	1.08	Inf.	105.42
GA (R)	1.26 sec.	2.95 sec.	0.43%	1.002	Inf..	83.17
DE (R)	2.32 sec.	4.69 sec.	0.67%	1.01	Inf.	95.14
CMA-ES (R)	0.90 sec.	1.47 sec.	0%	1.00	Inf.	72.67

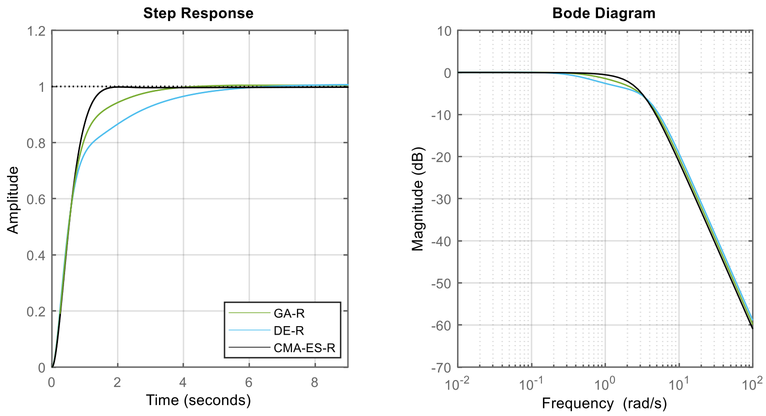

Figure 5. Time and frequency responses of the robust closed loop systems with controller gains obtained using GA, DE and CMA-ES

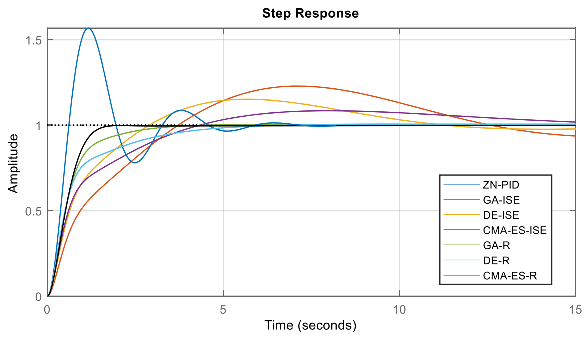

Figure 6. Time domain responses of the closed loop systems with the obtained controllers

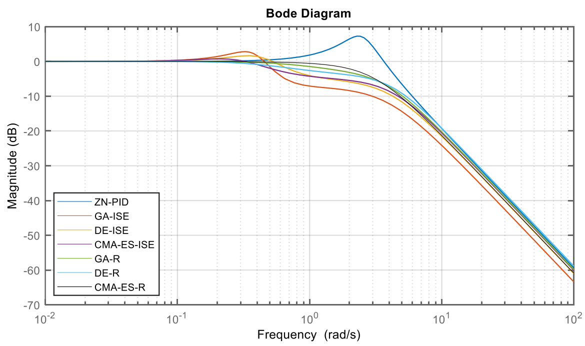

Figure 7 Frequency domain responses of the closed loop systems with the obtained controllers

the closed loop response of the system's performance has been evaluated for the plant with parametric uncertainties.

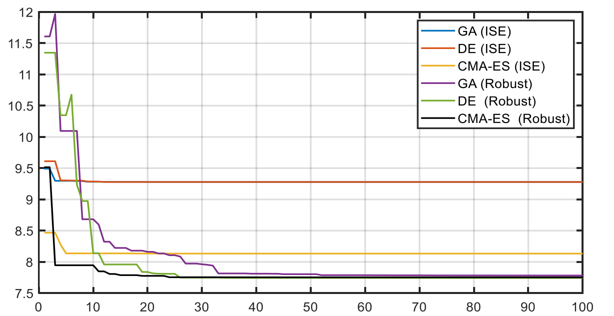

Figure 8. Plot for assessing convergence of the optimization algorithms

Secondly, the performance of the closed loop system has been evaluated whenever there is a change in the operating frequency of the hydropower system.

5.1 Response of closed loop system to parametric uncertainties

To check the efficacy of the designed controllers, the uncertain plant with variable governor inertial constant 'I_M' and damping coefficient 'D' were tested with ±10% parametric uncertainty in both of these parameters. The time and frequency domain performances of the parametrically uncertain system with the controllers designed using classical methods and the optimal controllers synthesized using GA, DE and CME-ES are shown in Figures 9 and 10, respectively, and it can be observed that the CMA-ES tuned robust PID controllers were able to offer desired response both in time

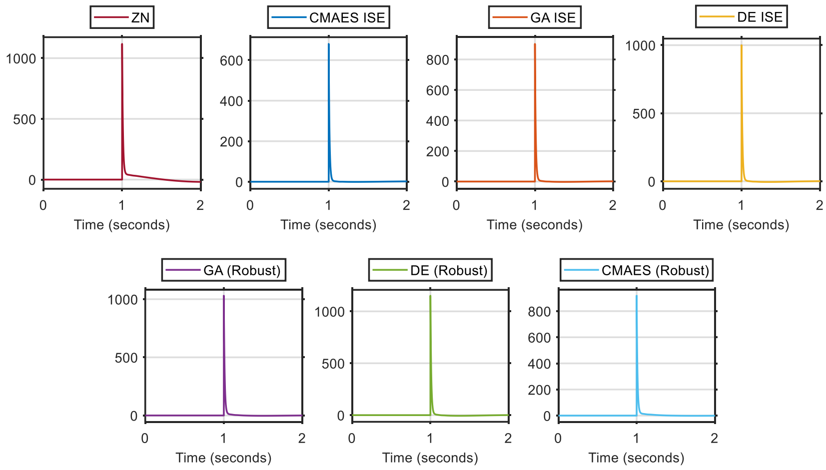

Figure 9. Control signals of the closed loop systems with the obtained controllers

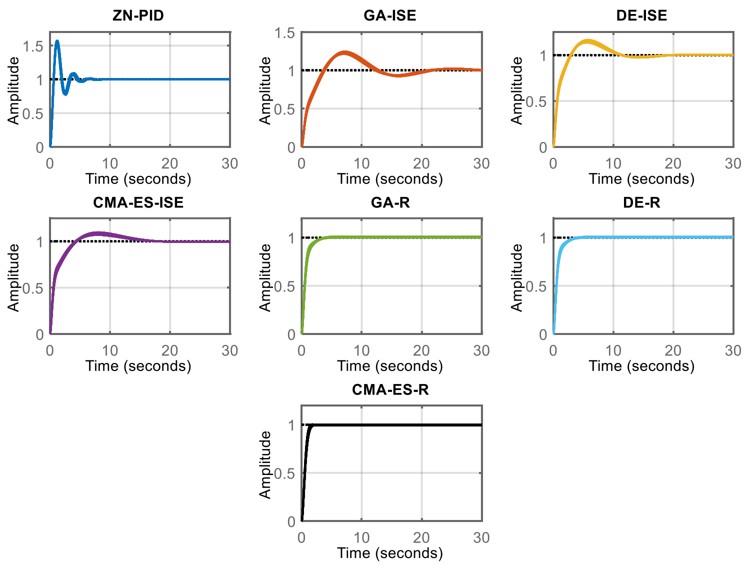

Figure 10. Time domain responses of the closed loop systems with the obtained controllers under parametric uncertainty

and frequency domain, even in the presence of parametrically uncertain plant, and that with a very tight envelope. Table 2 shows the various performance parameters for the worst-case scenario when the plant is subjected to parametric uncertainties.

5.2 Response of closed loop system to 0.02 p.u. load change

During load change a dip in the operating frequency is generally observed, and in restoring the frequency of the hydro power-system, the prime governor plays a crucial role. During such scenario, the prime governor has to either increase or decrease its speed based on the dip in the operating frequency, so that the operating frequency is restored. To analyze the response of the hydropower system with the designed controllers, a 0.02 p.u. load change has been considered. Figure 11 shows in a plot the change in frequency when there is a load change of 0.02 p.u. From the plot, it can be seen that the controller designed using CMA-ES offers the minimum frequency change and without any oscillation, thus offering and assuring a smooth operation. From Figure 11 it can be observed that the CMA-ES based controller tuned by minimizing the multi-objective formulation, as discussed in Section 3, offers the best response with minimal oscillations and the system frequency is restored within the minimum time.

5. Conclusions

This paper proposed the design of an optimal robust controller for a single area load frequency controller. The design problem has been formulated as an optimization problem and has been solved using various evolutionary algorithms, viz. GA, DE and CMA-ES. The results show that the controller obtained using classical Ziegler-Nichols tuning, or by optimal design using time domain performance measures, offered an oscillatory response in time domain; and

Table 2. Worst case time and frequency domain performance indices

Algorithm	Rise time	Settling time	Overshoot percentage	Complementary sensitivity	Gain margin	Phase margin
Ziegler Nichols	0.44 sec.	6.01 sec.	56.49%	2.330	Inf.	25.77
GA (ISE)	3.01 sec.	26.89 sec.	23.74%	1.401	Inf.	56.64
DE (ISE)	2.15 sec.	16.37 sec.	16.07%	1.224	Inf.	80.57
CMA-ES (ISE)	2.98 sec.	15.36 sec.	8.98%	1.094	Inf.	102.93
GA (R)	1.48 sec.	3.22 sec.	0.36%	1.002	Inf..	84.78
DE (R)	2.57 sec.	5.07 sec.	0.59%	1.001	Inf.	97.38
CMA-ES (R)	1.02 sec.	1.75 sec.	0%	1.000	Inf.	74.23

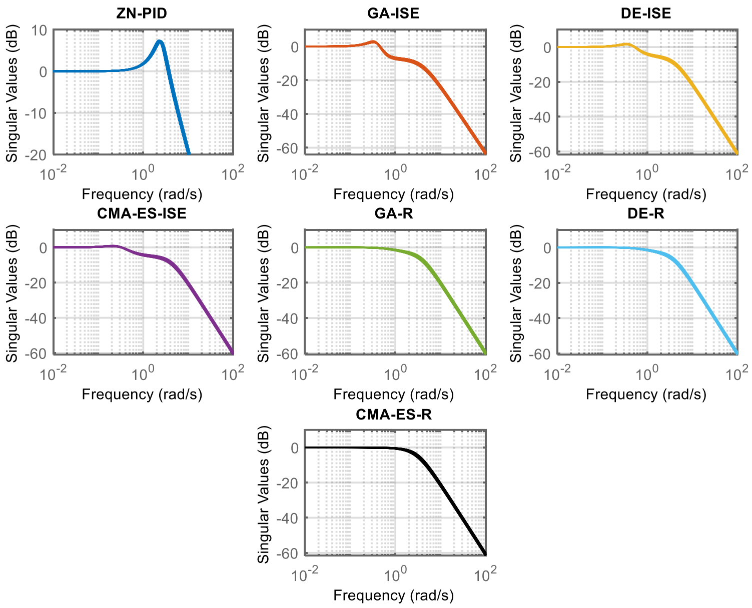

Figure 11. Frequency domain responses of the closed loop systems with the obtained controllers under parametric uncertainty

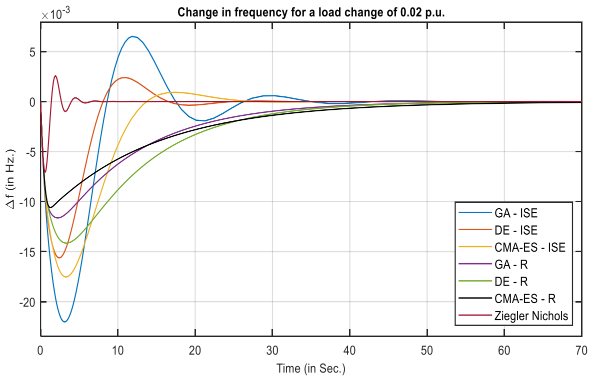

Figure 12. Time profiles of frequency after a load change of 0.02. p.u.

also the frequency domain response was not satisfactory. Thus, to assure good time and frequency domain behaviors, multiple objectives like rise time, overshoot percentage and minimization of infinity norm of the complementary sensitivity function have been targeted in the design. The results show that a robust controller designed using CMA-ES offers a satisfactory response both in time and frequency domains, and offers the minimum frequency deviation without any oscillation, thus offering and assuring a smooth operation.

Nomenclature

CMA-ES	Covariance Matrix Adaptation Evolution Strategy
GA	Genetic algorithm
DE	Differential Evolution
ZN	Ziegler Nichols Method
PID	Proportional Integral Derivate Controller
LFC	Load Frequency Control
τ_g	Governor Time Constant
τ_t	Turbine Time Constant
I_M	Governor Inertial Constant
D	Damping Coefficient

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