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RESEARCH ARTICLE

Non-Fragile PIDA Controller Design for Time-Delayed Uncertain System

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ABSTRACT In modern power system, phaser measurement units (PMUs) have been installed for information sharing between subsystems. Due to the large installation of PMUs, the time-delay occurs between control subsystems. In the presence of time-delay, power system network shows the instability in voltage and frequency. So, this paper proposes the robust, optimal, and non-fragile controller for a perturbed automatic voltage regulator (AVR) system with measurement time-delay. The perturbed AVR dynamic model is designed by considering parametric uncertainty in time constants of AVR subsystem models. In addition, the perturbation in controller coefficients is an important problem in real-time implementation of controller for industrial applications. In this regard, this paper proposes the non-fragile PIDA controller design. The tuning of the proposed non-fragile PIDA controller is carried-out using Kharitonov's stability criterion and constrained genetic algorithm (CGA). The proposed controller is designed for the worst-case plant model, which is computed from the perturbed AVR model using Kharitonov's interval stability theorems. Further, the effect of measurement time-delay in the feedback sensor model is considered. The effectiveness and performance of the proposed controller is assessed by comparing it with the recently published control schemes in the presence of terminal voltage disturbances, parametric uncertainty, and measurement time-delay.

INDEX TERMS Automatic voltage regulator (AVR), perturbed AVR (PAVR), non-fragile PIDA controller, measurement time-delay, constrained genetic algorithm (CGA), Kharitonov's stability criterion.

I. INTRODUCTION

For the modern civilization of society, the power system is one of the most important infrastructures [1]. The penetration of renewable energy sources (RESs) in the modern power system for electrification of society and industry, is exponential growing. RESs have the intermittent nature. So, the power system networks become more complex, and there need to control the voltage, frequency, and rotor-angle in the pre-specified limits for the reliable and secure operation of it [1], [2], [3]. The voltage control in power system network is essential for reliable operation of different electrical machines, drives, and electronics appliances [1], [4], [5]. From the literature survey, it is noticed that automatic voltage regulator (AVR) system is an important part of the excitation system of synchronous generators to control the terminal voltage. The AVR system consists of an amplifier, generator, exciter and sensor sub-systems, as shown in Fig. 1 [1], [5], [6]. The AVR control design is essential to maintain a balance between the reference voltage and terminal output voltage. From the previous published work, it is found that many control approaches such as Robust control, Intelligent control, Optimal control, Adaptive control, Classical control, and Model based control, have been proposed for AVR [2], [4], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19].

PID (Proportional Integral Derivative) control design is widely preferred due to its simple structure and availability of various tuning algorithms [20]. Further, the PID controller and it's variant have been designed for controlling the

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generator terminal voltage using AVR system in power system network. The variants of PID are introduced in the literature such as cascade type (fuzzy-PID) [12], [17], fractional order type (FOPID) [21], [22], [23], and higher order type (PIDA, PIDD2) [19], [24], [25] for the AVR system. Among these Variants of PID, PIDA (Proportional Integral Derivative Acceleration) or PIDD2 (Proportional Integral Derivative Double Derivative) controller is attracted the attention of control practitioners in the field of power system operation and control due to the satisfying more design constraints [26], [27], [28], [29].

The above-discussed controllers for the AVR are very susceptible to parametric variations. The class of controllers that cause instability of the closed-loop system due to a small perturbation in their coefficients is called a fragile controller [30], [31], [32], [33], [34], [35], [36], [37], [38], [39]. Generally, a practically implementable controller must have a non-fragile nature because: (1) round off errors during the practical implementation so that the stability of the closed loop system is maintained; and (2) the tuning of controller coefficients permissible about the nominal design values [30], [31], [32], [33], [34], [35]. So, the fragile controller's are risky for practical purposes. Therefore, the non-fragile PID controller has presented for the AVR system without considering the structural parametric uncertainty in the controller designing [6]. Further, the technical deficiencies of this non-fragile PID [6] is discussed by M. Kumar et al in [39].

The tuning of PID and its variant is utmost important task for control practitioners to achieve the desired performance of the AVR system. Various tuning methods have presented in the existing literatures [2], [4], [6], [7], [8], [9], [10], [11], [12], [13], [15], [17], [18], [19], [21], [22], [23], [24], and [25]. From the aforementioned discussions, it is noticed that researchers have preferred the optimization algorithm based tuning approach. Hence, this paper also prefers the optimization algorithm based tuning method.

From the real-time power system point of view, time-delays play an important role in system stability and desired performance [3], [40], [41], [42], [43], [44], [45]. Even though time-delays exist in the wide area measurement and control (WAMAC) loops, however, mostly traditional power system controllers have been designed based on local data without considering the time-delays [3]. In WAMAC design, synchronized real-time measurements are obtained using the phasor measurement unit (PMU), which can be utilized for power system stability analysis [3]. Nevertheless, time delays are significantly presented in these PMUs measurements due to the presence of transmission channels [3]. In the presence of time-delays in measurement loops, the closed loop system sometimes shows the instability [45]. To handle parametric uncertainty and time-delays, researchers have been preferred the robust and non-fragile control design.

The robust control approach based on H_∞ and μ analysis has designed for AVR with the real structural parametric uncertainty [16]. The order of controller is high in [16], which is not desirable because the designing of controller is complex in real-time. Further, the non-fragile PID controller has presented for AVR system without considering the structural parametric uncertainty in the controller designing and time-delays [6]. Besides, the performance of designed controller in [6] has not evaluated under the real-time power system network faults and disturbances.

From the above-mentioned discussions and studies, the following important technical points can be concluded as,

- The PIDA controller performs better in comparison to the PID and FOPID for the AVR system [19], [24], [25].
- Researchers prefer the optimization algorithm based tuning approaches for PID and its variant design for AVR system in the power system network.
- The non-fragile PID control design has not been explored for AVR in the power system network with the real structural parametric uncertainty and measurement time-delay.

A. MOTIVATION

It has been found that the non-fragile PIDA control design has not been introduced in the existing literature. In [6], author has worked on the design of non-fragile PID controller for system model without any parametric uncertainty in system parameters, and its application in AVR system for voltage regulation. However, author has not been checked the non-fragility of controller using any specific parameters such as robustness fragility index [39], which shows that the design controller has the non-fragile nature.

From recently published [46], it is noticed that authors have worked on the design of non-fragile PID controller for system model with parametric uncertainty in system parameters. Similarly above-mentioned work, authors have not been checked the non-fragility of controller. In addition, authors have not been taken care of the communication time-delays or measurement delays, which is a important issue in modern power system, as discussed the above.

In [39], authors suggested the utilization of Robustness fragility index (RFI) for the non-fragile PID control design. The RFI [47] has been proposed as an attribute to show the non-fragility and robustness of the controller. The consideration of RFI in the objective function of the optimization algorithm based controller tuning can improve and confirm the non-fragility and robustness of the designed controller, which is missing in the existing literature.

B. OBJECTIVES AND CONTRIBUTIONS

The key objective of this work is to present a robust and non-fragile PIDA control design for an AVR in the power system. The controller is designed considering the presence of structural parametric uncertainty and time-delay. Further, the goal is to ensure the robustness and non-fragility through introducing RFI in the objective function of the tuning algorithm. For this purpose, the following contributions have been made in this paper:

- To introduce the non-fragile PIDA controller for the time-delayed uncertain system.
- To propose a new objective function proposes which contains the robust fragility index constraint to ensure the non-fragility of controller.
- The worst-case plant selection approach is utilized to obtain a simplified model for the proposed controller design from the interval plant.
- The proposed control design is validated on the perturbed automatic voltage regulator (AVR) to control the terminal voltage of the power system network in the presence of measurement delay.

Further, this paper utilizes the constrained genetic algorithm (CGA) and Kharitonov's stability theorem along with to satisfy the Routh-Hurwitz (RH) stability constraints, non-fragility constraint and performance specifications for the tuning of proposed non-fragile PIDA controller.

II. PRELIMINARIES AND PROBLEM FORMULATION

A. TIME-DELAYED UNCERTAIN AUTOMATIC VOLTAGE REGULATOR (UAVR) SYSTEM

The voltage control of the synchronous generator is performed using the excitation current of its flux winding. The block-diagram of the conventional AVR system with controller is shown in Fig. 1. The nominal parameters values of AVR are considered from [6]. Moreover, the time-delayed uncertain AVR system with the proposed control design is shown in Fig. 2.

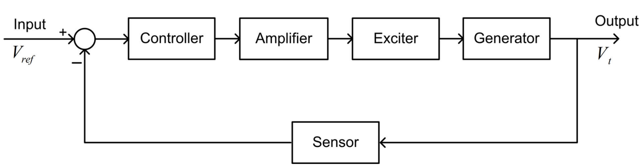


FIGURE 1. Block diagram of conventional AVR with controller [2].

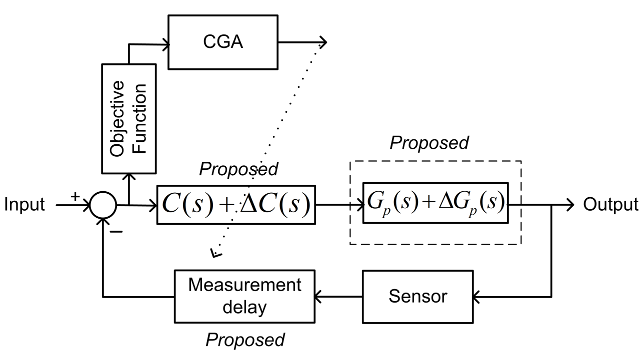


FIGURE 2. Proposed uncertain AVR system in the presence of measurement time-delay with the proposed control approach.

The open loop transfer function of AVR system without feedback (or sensor) is written as,

$$G_p(s) = G_A(s)G_E(s)G_G(s) \tag{1}$$

where, $G_A(s)$ is the amplifier dynamics, $G_E(s)$ is the exciter dynamics, and $G_G(s)$ is the generator dynamics.

The above equation (1) can be written as,

$$G_p(s) = \frac{K_A}{1+sT_A} \times \frac{K_E}{1+sT_E} \times \frac{K_G}{1+sT_G} \tag{2}$$

where, K_A, K_E, K_G are the gain parameters, and T_A, T_E, T_G are the time-constant parameters.

The uncertain time-constants based uncertain AVR system is represented as,

$$G_p(s) + \Delta G_p(s) = \frac{K_A}{1+s\left[\underline{T}_A, \overline{T}_A\right]} \times \frac{K_E}{1+s\left[\underline{T}_E, \overline{T}_E\right]_E} \times \frac{K_G}{1+s\left[\underline{T}_G, \overline{T}_G\right]} \tag{3}$$

where, $[\underline{T}_i, \overline{T}_i]$, $i \in \{A, E, G\}$ are lower and upper bounds of time-constant parameters.

B. EFFECT OF MEASUREMENT DELAY ON AVR

The terminal voltage responses of the existing control design approaches based AVR system with and without measurement delay are shown in Fig. 3. From this figure, it is observed that the terminal voltage responses for the PSO-FOPID (Particle Swarm Optimization based Fractional order Proportional Integral Derivative) [19] and PSO-PIDD2 (Particle Swarm Optimization - Proportional Integral Derivative Double Derivative) [19] controllers based AVR in the presence of measurement delay show the unstable nature. In addition, the terminal voltage responses for the non-fragile PID [6], PSO-PID (Particle Swarm Optimization - Proportional Integral Derivative) [2] and CSA-PID (Cuckoo Search algorithm based Proportional Integral Derivative) [23] controllers based AVR in the presence of measurement delay show the oscillatory nature. So, finally, it can be concluded that the existing control approaches based AVR system in the presence of measurement delay have not been satisfied the desired terminal voltage criterion.

C. KHARITONOV'S INTERVAL STABILITY THEOREM

Theorem 1 ([48]): For an interval polynomial ($p(s)$) presented in (22) having the order of $p(s)$ is 3, the family of four Kharitonov polynomial for $p(s)$ are given below

$$p_1(s, \Delta^{--}) = \underline{p}_0 + \underline{p}_1 s + \bar{p}_2 s^2 + \bar{p}_3 s^3 + \cdots \tag{4}$$

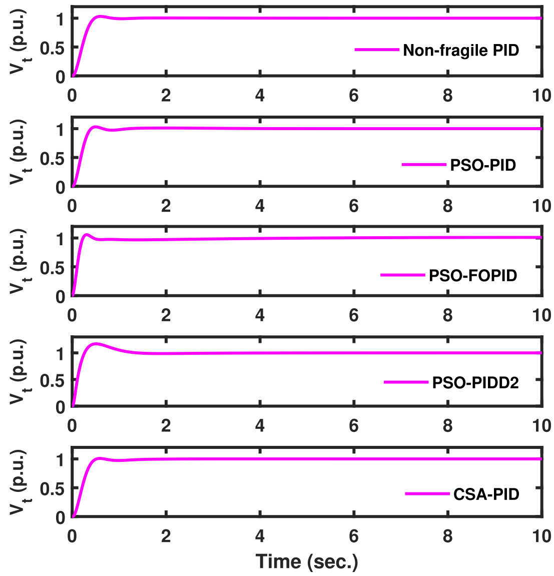
$$p_2(s, \Delta^{-+}) = \underline{p}_0 + \bar{p}_1 s + \bar{p}_2 s^2 + \underline{p}_3 s^3 + \cdots \tag{5}$$

$$p_3(s, \Delta^{+-}) = \bar{p}_0 + \underline{p}_1 s + \underline{p}_2 s^2 + \bar{p}_3 s^3 + \cdots \tag{6}$$

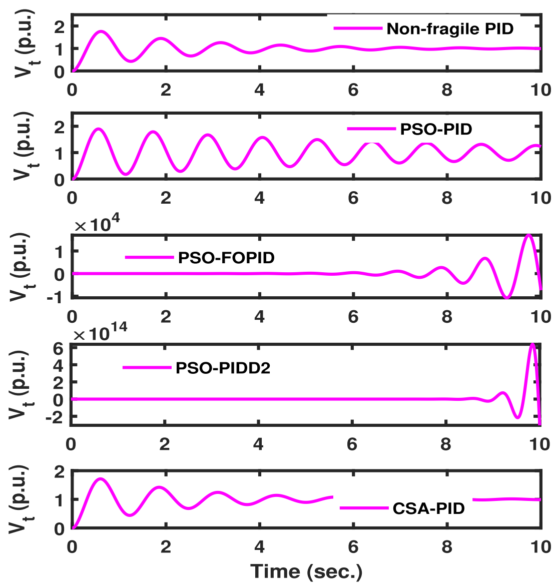
$$p_4(s, \Delta^{++}) = \bar{p}_0 + \bar{p}_1 s + \underline{p}_2 s^2 + \underline{p}_3 s^3 + \cdots \tag{7}$$

The robust stability of the complete family of polynomials in $p(s)$ is confirmed when the above mentioned four Kharitonov's polynomial are Hurwitz stable.

Proof (Proof of Theorem 1): The proof of this Theorem is discussed in [48].



(a) Without measurement delay



(b) With measurement delay

FIGURE 3. Terminal voltage responses of the existing control approaches for AVR system.

D. ROBUSTNESS FRAGILITY INDEX (RFI)

The mathematical formulation of RFI for ±20% variation in the controller parameters is given [47] as,

$$RFI_{\Delta 20} = \frac{M_{s\Delta 20}}{M_s^o} - 1 \tag{8}$$

where, $RFI_{\Delta 20}$ is the Delta 20 robustness fragility index, M_s^o is the maximum sensitivity of the control system without uncertainty in controller coefficients, and $M_{s\Delta 20}$ is the maximum sensitivity of the control system with +20% uncertainty in controller coefficients.

The nature of controllers based on $RFI_{\Delta 20}$ is categorized, as shown in Table 1.

TABLE 1. Robust fragility index (RFI) [47].

Nature of Controller	$RFI_{\Delta 20}$
Robustness Fragile	> 0.5
Robustness Non-Fragile	≤ 0.5
Robustness Resilient	≤ 0.01

E. NON-FRAGILE CONTROL ISSUE

At the real-time implementation, the controller coefficients values deviate from their actual value and due to this reason, the coefficients value of the designed controller's are changed or modified. As we know that, the controller coefficients are directly affected the closed loop system performance and stability. So, the closed loop system looses its stability as well as performance and sometimes, at worst condition, the system shows instability. Generally, the fragile type controllers are designed in the literature work. Without considering the perturbations in the controller parameters, the tuning of controller coefficients has been performed. Although, a practically implementable controller must have a non-fragile nature because: (1) round off errors during the practical (or digital) implementation so that the stability of the closed loop system is maintained; and (2) the tuning of controller coefficients permissible about the nominal design values [30], [31], [32], [33], [34], [35].

An issue of practical control system is formulated here by considering the uncertainty in controller coefficients as well as system parameters and measurement time-delays in the feedback loop, as shown in Fig. 2.

Note 1: This paper utilizes the CGA, which is explained in MATLA B Optimization Toolbox [49]. In addition, the constrained genetic algorithm is discussed in [6]. This CGA is utilized for the tuning of the proposed non-fragile PIDA controller.

III. MAIN RESULTS

This section presents the non-fragile PIDA controller design for the perturbed AVR system with measurement time-delay.

A. NON-FRAGILE PIDA CONTROLLER

The non-fragile PIDA controller is expressed as

$$C + \Delta C = c_1 + \frac{c_0}{s} + c_2 s + c_3 s^2 \tag{9}$$

where, c_0, c_1, c_2, c_3 are the coefficients of the non-fragile PIDA controller; $c_0 = [\underline{c}_0, \bar{c}_0]$, $c_1 = [\underline{c}_1, \bar{c}_1]$, $c_2 = [\underline{c}_2, \bar{c}_2]$, and $c_3 = [\underline{c}_3, \bar{c}_3]$;

$$\underline{c}_0 = k_i + \frac{\varepsilon_1}{100} k_i \tag{10}$$

$$\bar{c}_0 = k_i + \frac{\varepsilon_2}{100} k_i \tag{11}$$

$$\underline{c}_1 = k_p + \frac{\varepsilon_3}{100} k_p \tag{12}$$

$$\bar{c}_1 = k_p + \frac{\varepsilon_4}{100}k_p \tag{13}$$
$$\underline{c}_2 = k_d + \frac{\varepsilon_5}{100}k_d \tag{14}$$
$$\bar{c}_2 = k_d + \frac{\varepsilon_6}{100}k_d \tag{15}$$
$$\underline{c}_3 = k_a + \frac{\varepsilon_7}{100}k_a \tag{16}$$
$$\bar{c}_3 = k_a + \frac{\varepsilon_8}{100}k_a \tag{17}$$

where, k_p, k_i, k_d, k_a are the nominal design coefficients of PIDA controller.

From (9), the transfer functions of non-fragile PIDA controller are obtained using Theorem 1 as,

$$C_1(s) = \underline{c}_1 + \frac{\underline{c}_0}{s} + \bar{c}_2 s + \bar{c}_3 s^2 \tag{18}$$
$$C_2(s) = \bar{c}_1 + \frac{\underline{c}_0}{s} + \bar{c}_2 s + \underline{c}_3 s^2 \tag{19}$$
$$C_3(s) = \underline{c}_1 + \frac{\bar{c}_0}{s} + \underline{c}_2 s + \bar{c}_3 s^2 \tag{20}$$
$$C_4(s) = \bar{c}_1 + \frac{\bar{c}_0}{s} + \underline{c}_2 s + \underline{c}_3 s^2 \tag{21}$$

B. NON-FRAGILE PIDA CONTROLLER DESIGN APPROACH FOR UNCERTAIN SYSTEM WITH MEASUREMENT DELAY

The following subsections are discussed the design approach of the non-fragile PIDA controller for uncertain AVR system with measurement time-delay. In addition, it is presented the worst-case plant selection approach.

1) IDENTIFICATION OF WORST-CASE PLANT FROM UNCERTAIN PLANT

From (3), the uncertain AVR model is written in interval system form as,

$$G_p(s) + \Delta G_p(s) = \frac{K}{p(s)} = \frac{K}{[\underline{p}_3, \bar{p}_3]s^3 + [\underline{p}_2, \bar{p}_2]s^2 + [\underline{p}_1, \bar{p}_1]s + [\underline{p}_0, \bar{p}_0]} \tag{22}$$

Theorem 2 ([48], [50]): For an interval polynomial $(p(s))$ presented in (22) having the order of $p(s)$ is 3, the family of four Kharitonov polynomial for $p(s)$ are given below

$$p_1(s, \Delta^{--}) = \underline{p}_0 + \underline{p}_1 s + \bar{p}_2 s^2 + \bar{p}_3 s^3 + \cdots \tag{23}$$
$$p_2(s, \Delta^{-+}) = \underline{p}_0 + \bar{p}_1 s + \bar{p}_2 s^2 + \underline{p}_3 s^3 + \cdots \tag{24}$$
$$p_3(s, \Delta^{+-}) = \bar{p}_0 + \underline{p}_1 s + \underline{p}_2 s^2 + \bar{p}_3 s^3 + \cdots \tag{25}$$
$$p_4(s, \Delta^{++}) = \bar{p}_0 + \bar{p}_1 s + \underline{p}_2 s^2 + \underline{p}_3 s^3 + \cdots \tag{26}$$

Only $p_3(s, \Delta^{+-})$ examining set (as shown in (25)) is sufficient to analyze the robust stability of the complete family of polynomials in $p(s)$.

Proof (Proof of Theorem 2): The proof of this Theorem is discussed in [48].

The worst-case plant $(G_{worstcase}(s))$ of (22) using Theorem 2 is written as

$$G_{worstcase}(s) = \frac{K}{\bar{p}_3 s^3 + \underline{p}_2 s^2 + \underline{p}_1 s + \bar{p}_0} \tag{27}$$

2) CGA AND KHARITONOV'S STABILITY THEOREMS BASED PROPOSED CONTROLLER DESIGN

Using (9) and (27), the closed loop characteristic equation (Clchareq) for Fig. 2 is written as,

$$1 + (C + \Delta C)\, G_{worstcase}(s) G_S(s) e^{-\tau s} = 0 \tag{28}$$

where, $G_S(s)$ is the sensor model, which is expressed as $G_S(s) = \frac{K_S}{1+sT_S}$. In addition, K_S and T_S are the gain and time-constant of the sensor model. Further, τ is the measurement time-delay.

The above equation (28) is rewritten as,

$$1 + \left\{ \left(c_1 + \frac{c_0}{s} + c_2 s + c_3 s^2\right) \left(\frac{K}{\bar{p}_3 s^3 + \underline{p}_2 s^2 + \underline{p}_1 s + \bar{p}_0} \right) \right\} \left\{ \left(\frac{K_S}{1+sT_S} \right) e^{-\tau s} \right\} = 0 \tag{29}$$

After all-pole approximation of measurement time-delay, the above equation can be written as

$$1 + \left\{ \left(c_1 + \frac{c_0}{s} + c_2 s + c_3 s^2\right) \left(\frac{K}{\bar{p}_3 s^3 + \underline{p}_2 s^2 + \underline{p}_1 s + \bar{p}_0} \right) \right\} \left\{ \left(\frac{K_S}{1+sT_S} \right) \left(\frac{1}{1+s\tau} \right) \right\} = 0 \tag{30}$$

The simplified interval polynomial form of the above equation (30) can be written as,

$$Q(s) = \sum_{i=0}^{i=6} \left[\underline{q}_i, \bar{q}_i \right] s^i; \ \Rightarrow Q(s) = 0 \tag{31}$$

Theorem 3: Considering the perturbed AVR system model of power system network with measurement delay, the closed loop characteristic equation is given in (28). The perturbed AVR system is stabilized by the proposed non-fragile PIDA controller when the coefficients of this controller are obtained by minimizing the objective function J,

$$J = \left(1 - e^{-\beta}\right)\left(O_{M_{nominal}} - E_{ss_{nominal}}\right) + e^{-\beta} \left\{ \left(t_{s_{nominal}} - t_{r_{nominal}}\right) + RFI_{\Delta 20} + \Omega\left(\sum_{k=1}^{8} \frac{1}{\varepsilon_k} \right) \right\} \tag{32}$$

such that,

$$\tau > 0 \tag{33}$$
$$R_{ij} > 0 \tag{34}$$
$$0 < H_j < b \tag{35}$$
$$0 < RFI_{\Delta 20} \leq 0.5 \tag{36}$$

where,

$$H_j = \left(1 - e^{-\beta}\right)\left(O_{M_j} - E_{ss_j}\right) + e^{-\beta}\left(t_{s_j} - t_{r_j}\right); \quad i \in \{1, 2, 3, 4, 5\}; j \in \{1, 2, 3, 4\} \tag{37}$$

$$RFI_{\Delta 20} = \frac{M_{s\Delta 20}}{M_s^o} - 1 \tag{38}$$

Proof (Proof of Theorem 3): The proof of this Theorem is given in Appendix.

TABLE 2. Controller parameter settings.

	PSO-PID [2]	PSO-FOPID [19]	PSO-PIDD2 [19]
Controller parameters	$k_p = 0.6570$ $k_i = 0.5389$ $k_d = 0.2458$	$k_p = 1.6264$, $\lambda = 1.3183$ $k_i = 0.2956$, $\mu = 1.1980$ $k_d = 0.3226$	$k_p = 2.778$, $k_a = 0.074$ $k_i = 1.852$ $k_d = 0.999$
	CSA-PID [23]	**Non-fragile PID (K) [6]**	**Proposed Non-fragile PIDA (C)**
Controller parameters	$k_p = 0.5937$ $k_i = 0.4035$ $k_d = 0.1996$	$k_i = 0.456$, $\varepsilon_1 = 7.4\%$, $\varepsilon_2 = 9.7\%$ $k_p = 0.614$, $\varepsilon_3 = 6.1\%$, $\varepsilon_4 = 8.0\%$ $k_d = 0.195$, $\varepsilon_5 = 8.8\%$, $\varepsilon_6 = 7.2\%$	$k_i = 0.1585$, $\varepsilon_1 = 15.64\%$, $\varepsilon_2 = 30.57\%$ $k_p = 0.2534$, $\varepsilon_3 = 10.82\%$, $\varepsilon_4 = 24.32\%$ $k_d = 0.1397$, $\varepsilon_5 = 15.24\%$, $\varepsilon_6 = 30.22\%$ $k_a = 0.0332$, $\varepsilon_7 = 7.34\%$, $\varepsilon_8 = 11.76\%$

C. STEP-BY-STEP TUNING GUIDELINES FOR THE PROPOSED CONTROLLER

The following steps are required as:

Step 1: Consider a time-interval plant with 3^{rd} order as equation (22).

Step 2: Apply worst-case Theorem 2 on equation (22).

Step 3: Compute the closed-loop characteristic equation as (28) or (30) after all-pole approximation of measurement delay.

Step 4: Apply Theorem 3 to obtain the unknown gain parameters of the proposed non-fragile PIDA controller. The CGA is applied to minimize the objective function J (as equation (32)) with satisfying the constraints.

IV. RESULTS AND DISCUSSIONS

This section is presented the simulation results under practical disturbance conditions. Further, it is discussed about sensitivity, stability, robustness, and non-fragility analyses for the proposed control system design.

A. PROPOSED CONTROLLER DESIGN FOR TIME-DELAYED UNCERTAIN AVR

The values of gain and time constants for AVR system are given [2], [6], [23] as: $K_A = 10$, $T_A = 0.1\,s$, $K_E = 1$, $T_E = 0.4\,s$, $K_G = 1$, $T_G = 1.0\,s$, $K_S = 1$, and $T_S = 0.01\,s$.

Here, we have considered $\pm 20\%$ uncertainties in time-constants (T_A, T_E, T_G) of AVR sub-systems, and the equation (3) is rewritten after considering the uncertainty as,

$$G_p(s) + \Delta G_p(s) = \frac{10}{1 + s\,[0.08, 0.12]} \times \frac{1}{1 + s[0.32, 0.48]} \times \frac{1}{1 + s\,[0.8, 1.2]} \tag{39}$$

The above equation can be written after simplification as (40), shown at the bottom of the next page,

The worst case plant of the above equation using Theorem 2 is obtained as,

$$G_{worstcase}(s) = \frac{10}{0.06912s^3 + 0.3456s^2 + 1.25s + 1} \tag{41}$$

Using (41), the above mentioned closed-loop characteristic equations (28) or (30) are computed as,

$$Clchareq \Rightarrow 1 + \left(c_1 + \frac{c_0}{s} + c_2 s + c_3 s^2\right) \left(\frac{10}{0.06912s^3 + 0.3456s^2 + 1.25s + 1}\right) \left(\frac{1}{1 + 0.01s}\right)\left(\frac{1}{1 + s\tau}\right) = 0 \tag{42}$$

$$\begin{aligned} Clchareq \Rightarrow\ & (0.0007\tau)s^6 + (0.0726\tau + 0.0007)s^5 \\ & + (0.3576\tau + 0.0726)\, s^4 \\ & + (1.21\tau + 0.3576 + 10c_3)\, s^3 \\ & + (1.21\tau + 10c_2)\, s^2 + (1 + 10c_1)\, s + 10c_0 = 0 \end{aligned} \tag{43}$$

After considering the constant time-delay $\tau = 0.2$ *sec.*, the above equation can be written as,

$$\begin{aligned} Clchareq \Rightarrow\ & 0.00014s^6 + 0.0152s^5 + 0.1441s^4 \\ & + (0.5996 + 10c_3)\, s^3 + (1.41 + 10c_2)\, s^2 \\ & + (1 + 10c_1)\, s + 10c_0 = 0 \end{aligned} \tag{44}$$

The above equation (44) can be written in simplified form as,

$$\begin{aligned} Clchareq \Rightarrow\ & q_6 s^6 + q_5 s^5 + q_4 s^4 + q_3 s^3 \\ & + q_2 s^2 + q_1 s + q_0 = 0 \end{aligned} \tag{45}$$

where, $q_6 = 0.00014$, $q_5 = 0.0152$, $q_4 = 0.1441$, $q_3 = 0.5996 + 10c_3$, $q_2 = 1.41 + 10c_2$, $q_1 = 1 + 10c_1$ and $q_0 = 10c_0$.

From (9), the interval parameter form of proposed controller coefficients is written as,

$$c_i = \left[\underline{c}_i, \bar{c}_i\right];\ i \in \{0, 1, 2, 3\} \tag{46}$$

Using (46), the interval polynomial form of the above equation (45) can be written as,

$$Q(s) = \sum_{i=0}^{i=6} \left[\underline{q}_i, \bar{q}_i\right] s^i;\ \ \Rightarrow Q(s) = 0 \tag{47}$$

The parameters of proposed controller are obtained using Theorem 3 for the closed-loop characteristic equation (47) (or (45)), as shown in Table 2.

Note 2: For quantitative and qualitative analysis, we have computed the integral performance indices (ISE, IAE, ITSE and ITAE) and time-domain performance specifications (overshoot (O_M), settling time (t_s), rise time (t_r), and peak)). The minimum values of these indices and specifications are better to show the superiority of the particular control design approach.

B. PERFORMANCE ASSESSMENT UNDER NOMINAL CONDITIONS

Herein, the performance of the proposed controller is assessed in terms of the reference voltage tracking by terminal voltage under nominal conditions.

Figure 3b illustrates the terminal voltage (V_t) responses for the existing non-fragile PID [6], PSO based PID [2], PSO based FOPID [19], PSO based PIDD2 [19], and CSA based PID [23] control design approaches. In addition, Fig. 4 illustrates the terminal voltage responses for the existing non-fragile PID controllers ($K, K1, K2, K3$ and $K4$) [6] with variation in controller coefficients. Moreover, Fig. 5 illustrates the terminal voltage responses for the proposed non-fragile PIDA controllers ($C, C1, C2, C3$ and $C4$) with variation in controller coefficients.

From figs. 3b and 4, it is observed that the terminal voltage responses for the PSO-FOPID and PSO-PIDD2 controllers based AVR in the presence of measurement delay show the unstable nature. In addition, the terminal voltage responses for the non-fragile PID, PSO-PID and CSA-PID controllers based AVR in the presence of measurement delay show the oscillatory nature.

Further, for evaluating the performance of proposed control design approach, we have performed the quantitative and qualitative analysis. Table 3 illustrates the integral performance indices for the proposed and existing control design approaches. In addition, Table 4 reveals the time-domain performance specifications for the proposed and existing control design approaches. Finally, from the above-mentioned figures and Tables, it is found that the proposed control design approach performs better in comparison to the existing control design approaches.

C. PERFORMANCE ASSESSMENT UNDER TERMINAL VOLTAGE DISTURBANCES

The performance of the proposed controller is tested under terminal voltage disturbances. The following disturbances pattern is considered here as:

- There is a 1 p.u. change in V_{ref} at $t = 0\,s$ for analyzing the tracking performance.
- In case of short circuit faults, the generators' terminal voltage will be zero by a -1 p.u. at $t = 7\,s$ sudden disturbance at the output V_t. In such condition, the controller's must be returned from V_t to the V_{ref}.
- By a sudden change in V_t to 2 p.u., the transient over-voltage can be modeled. For this modeling a 1 p.u. at $t = 3\,s$ voltage disturbance has been added to the output V_t.

Figure 6 illustrates the terminal voltage (V_t) responses for the existing non-fragile PID [6], PSO based PID [2], PSO based FOPID [19], PSO based PIDD2 [19], and CSA based PID [23] control design approaches. In addition, Fig. 7 illustrates the terminal voltage responses for the existing non-fragile PID controllers ($K, K1, K2, K3$ and $K4$) [6]. From these figures, it is observed that V_t is not settled or reached at the steady-state in case of the existing control design approaches. So, we can conclude that the

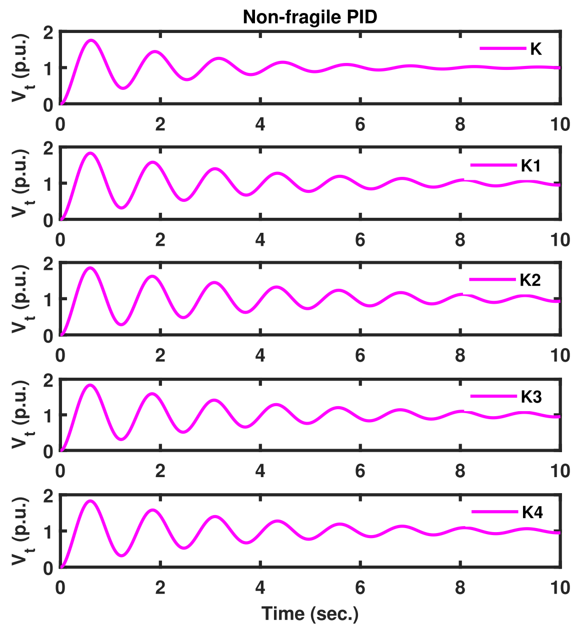


FIGURE 4. Terminal voltage responses of the non-fragile PID control design for AVR system.

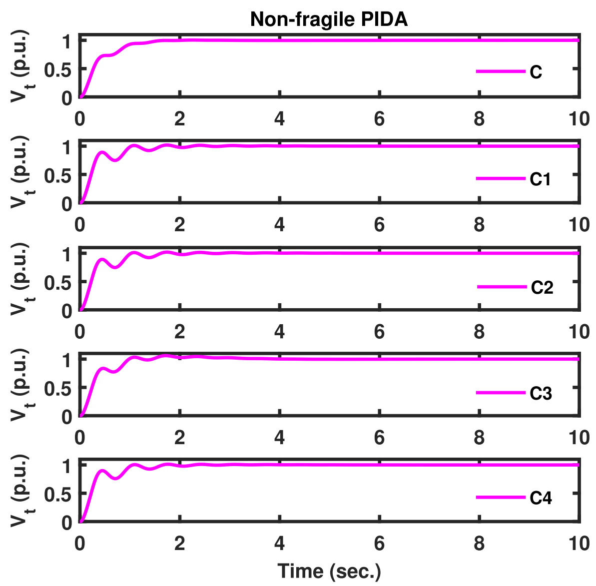


FIGURE 5. Terminal voltage responses of the proposed non-fragile PIDA control design for AVR system.

$$\Rightarrow = \frac{10}{[0.02048, 0.06912]s^3 + [0.3456, 0.7776]s^2 + [1.25, 1.85]s + 1} \tag{40}$$

TABLE 3. Integral performance indices for terminal voltage responses under nominal and disturbances scenarios.

Control design	Under nominal conditions				Under terminal voltage disturbances			
	ISE	IAE	ITSE	ITAE	ISE	IAE	ITSE	ITAE
PSO-PID [2]	1.8760	3.623	5.3800	13.96	6.190	6.814	36.40	36.93
PSO-FOPID [19]	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable
PSO-PIDD2 [19]	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable
CSA-PID [23]	0.7400	1.576	0.7136	3.202	2.383	3.958	9.817	18.01
Non-fragile PID (K) [6]	0.7869	1.663	0.8046	3.506	2.441	4.022	9.651	17.90
Non-fragile PID (K1) [6]	1.0390	2.222	1.5630	6.074	3.488	5.044	15.46	23.88
Non-fragile PID (K2) [6]	1.1510	2.442	1.9580	7.181	3.957	5.430	18.27	26.25
Non-fragile PID (K3) [6]	1.0650	2.276	1.6550	6.351	3.658	5.190	16.70	24.95
Non-fragile PID (K4) [6]	1.0390	2.222	1.5630	6.074	3.488	5.044	18.46	23.88
Proposed Non-fragile PIDA (C)	0.4385	0.634	0.1144	0.306	1.044	1.854	3.427	7.528
Proposed Non-fragile PIDA (C1)	0.3963	0.580	0.0936	0.297	1.080	1.961	3.777	8.343
Proposed Non-fragile PIDA (C2)	0.3982	0.576	0.0902	0.304	1.016	1.769	3.143	7.160
Proposed Non-fragile PIDA (C3)	0.4089	0.625	0.1004	0.400	1.060	1.874	3.604	7.616
Proposed Non-fragile PIDA (C4)	0.3948	0.575	0.0923	0.293	1.061	1.910	3.680	8.065

TABLE 4. Transient analysis for terminal voltage responses under nominal conditions.

Control Design	O_M (%)	t_s (in seconds)	t_r (in seconds)	Peak
PSO-PID [2]	54.549	9.9623	0.2147	1.8969
PSO-FOPID [19]	Unstable	Unstable	Unstable	Unstable
PSO-PIDD2 [19]	Unstable	Unstable	Unstable	Unstable
CSA-PID [23]	0.0000	9.0177	6.1816	0.9425
Non-fragile PID (K) [6]	75.426	9.0162	0.2102	1.7551
Non-fragile PID (K1) [6]	83.358	13.177	0.1991	1.8302
Non-fragile PID (K2) [6]	86.057	15.621	0.1962	1.8518
Non-fragile PID (K3) [6]	84.145	14.261	0.1974	1.8362
Non-fragile PID (K4) [6]	83.358	13.177	0.1991	1.8302
Proposed Non-fragile PIDA (C)	0.4195	1.4810	0.8257	1.0042
Proposed Non-fragile PIDA (C1)	1.9797	2.1140	0.8158	1.0198
Proposed Non-fragile PIDA (C2)	1.9797	2.1140	0.8158	1.0198
Proposed Non-fragile PIDA (C3)	6.1182	3.1112	0.7758	1.0612
Proposed Non-fragile PIDA (C4)	1.2600	2.1137	0.8241	1.0126

existing control methods are failed after consideration of measurement delays in power system networks.

Moreover, Fig. 8 illustrates the terminal voltage responses for the proposed non-fragile PIDA controllers (C, $C1$, $C2$, $C3$ and $C4$) with variation in controller coefficients.

In addition, for evaluating the performance of the proposed control design approach, we have performed the quantitative and qualitative analysis. Table 3 illustrates the performance integral indices for the proposed and existing control design approaches.

Finally, from the above-mentioned figures and Table, it is found that the proposed control design approach performs better in comparison to the existing control design approaches.

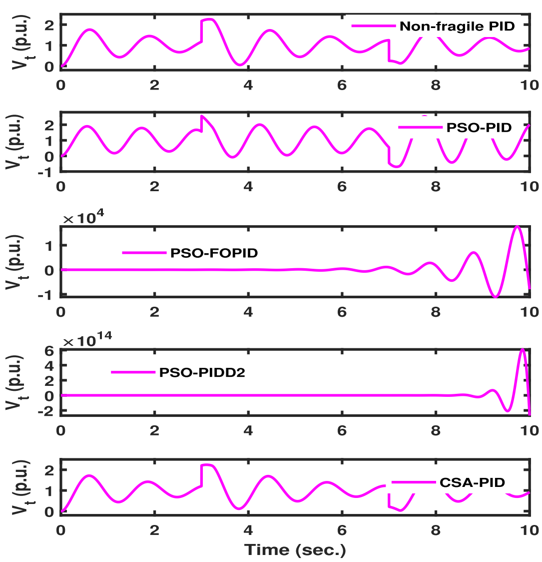


FIGURE 6. Terminal voltage responses of the existing control schemes for AVR system under terminal voltage disturbances.

D. SENSITIVITY ANALYSIS

The performance of proposed controller is assessed under ±20% parametric uncertainty in gain and time constants of amplifier, exciter and generator models. The following disturbances pattern is also considered as:

- There is a 1 p.u. change in V_{ref} at $t = 0\,s$ for analyzing the tracking performance.
- In case of short circuit faults, the generators' terminal voltage will be zero by a -1 p.u. at $t = 8\,s$ sudden disturbance at the output V_t. In such condition, the controller's must be returned from V_t to the V_{ref}.
- By a sudden change in V_t to 2 p.u., the transient over-voltage can be modeled. For this modeling a 1 p.u. at $t = 20\,s$ voltage disturbance has been added to the output V_t.

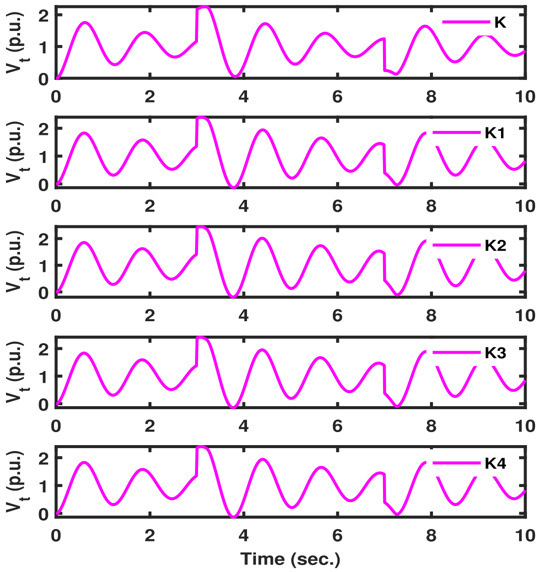


FIGURE 7. **Terminal voltage responses of the non-fragile PID control design for AVR system under terminal voltage disturbances.**

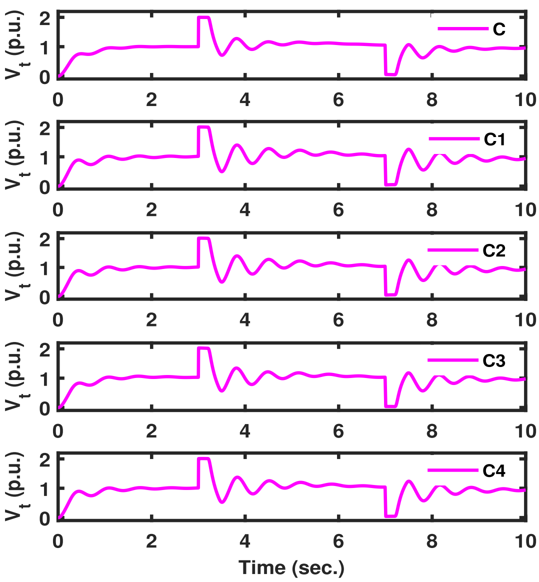
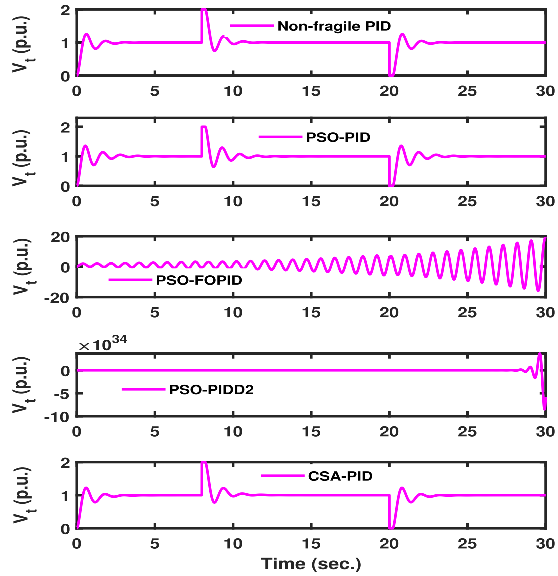
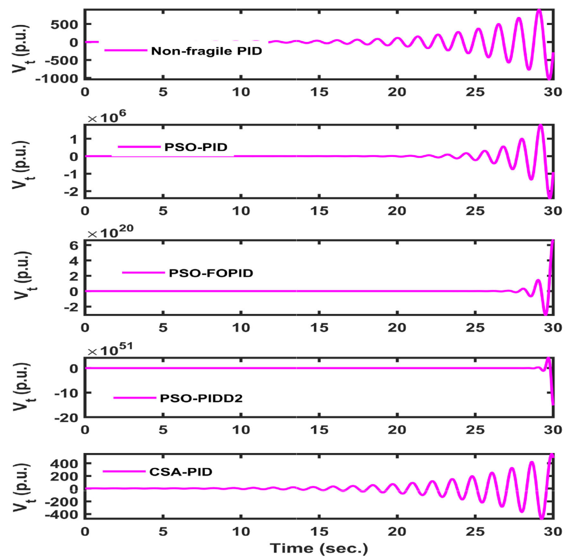


FIGURE 8. **Terminal voltage responses of the proposed non-fragile PIDA control design for AVR system under terminal voltage disturbances.**



(a) -20% parametric uncertainty



(b) $+20\%$ parametric uncertainty

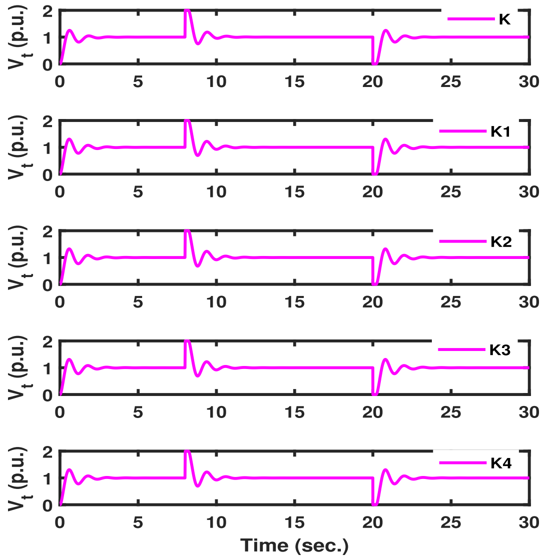
FIGURE 9. **Terminal voltage responses of the existing control design approaches for AVR system with measurement delay under terminal voltage disturbances and ±20% parametric uncertainty in gain and time constants (K_A, K_E, K_G, T_A, T_E, and T_G).**

Figure 9 illustrates the terminal voltage (V_t) responses for the existing non-fragile PID [6], PSO based PID [2], PSO based FOPID [19], PSO based PIDD2 [19], and CSA based PID [23] control design approaches. In addition, Fig. 10 illustrates the terminal voltage responses for the existing non-fragile PID controllers ($K, K1, K2, K3$ and $K4$) [6] with variation in controller coefficients. Moreover, Fig. 11 illustrates the terminal voltage responses for the proposed non-fragile PIDA controllers ($C, C1, C2, C3$ and $C4$) with variation in controller coefficients.

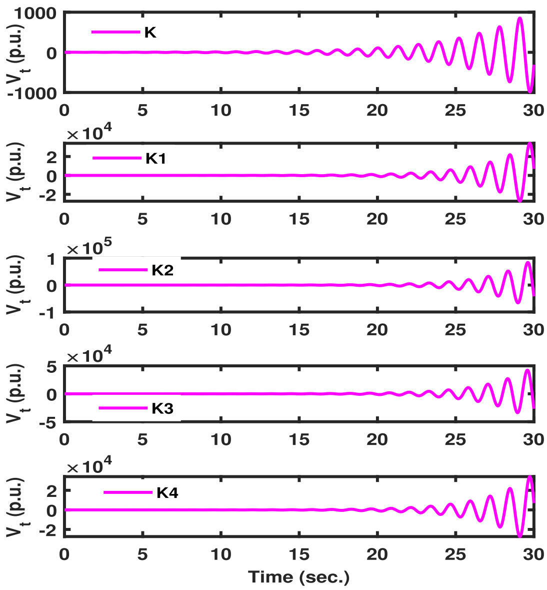
From figs. 9 and 10, it is observed that the responses of V_t show the unstable nature in the presence of $+20\%$ parametric uncertainty with the existing control design approaches. So, we can conclude that the existing control methods are failed in the presence of $+20\%$ parametric uncertainty and measurement delays in power system networks.

Further, for evaluating the performance of the proposed control design approach, we have performed the quantitative and qualitative analysis. Table 5 illustrates the performance integral indices for the proposed and existing control design approaches.

Finally, from the above-mentioned figures and Table, it is found that the proposed control design approach performs better in comparison to the existing control design approaches

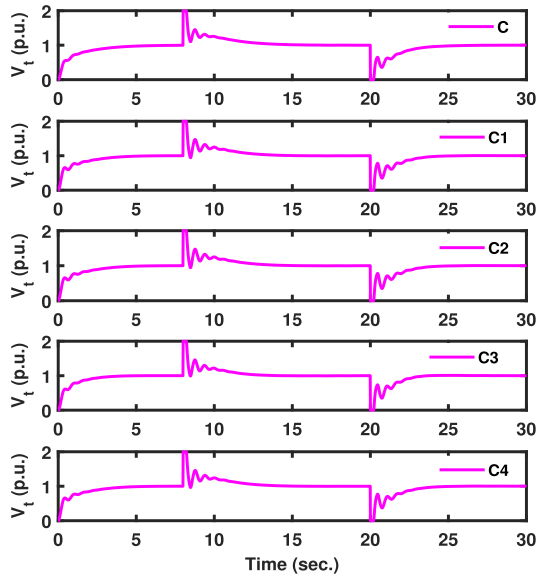


(a) -20% parametric uncertainty

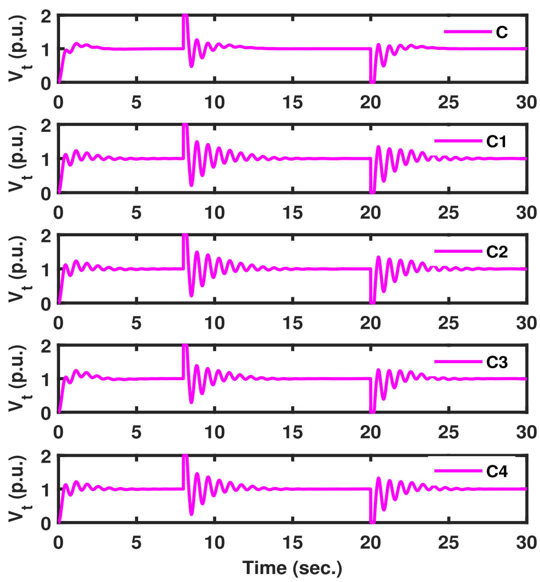


(b) $+20\%$ parametric uncertainty

FIGURE 10. Terminal voltage responses of the non-fragile PID control design for AVR system with measurement delay under terminal voltage disturbances and ±20% parametric uncertainty in gain and time constants (K_A, K_E, K_G, T_A, T_E, and T_G).



(a) -20% parametric uncertainty



(b) $+20\%$ parametric uncertainty

FIGURE 11. Terminal voltage responses of the proposed non-fragile PIDA control design for AVR system with measurement delay under terminal voltage disturbances and ±20% parametric uncertainty in gain and time constants (K_A, K_E, K_G, T_A, T_E, and T_G).

in the presence of $\pm 20\%$ parametric uncertainty in the gain and time constants of amplifier, exciter and generator models.

E. NON-FRAGILITY ANALYSIS

The Non-fragility analysis is carried out in terms of $RFI_{\Delta 20}$, as shown in Table 6. From this table, it can be observed that the proposed non-fragile PIDA control design shows more non-fragile behavior of the controller in comparison to the published control design approaches.

F. ROBUSTNESS ANALYSIS

The robustness analysis is evaluated in terms of maximum sensitivity (M_s) and parametric uncertainty in AVR system parameters. The range of M_s for maintaining the trade-off between stability and performance is considered as $[1.2, 2]$ for the stable systems [27]. The value of M_s near to a 1.2 shows the more robust behavior and vice-versa, for the specified limits. The values of M_s are given in Table 7 for the control design approaches. It can be noticed from Table 7 that the proposed control design shows robust behavior in comparison to the existing control approaches.

TABLE 5. Performance integral indices for terminal voltage response under parametric uncertainty with disturbances.

Control design	Under -20% uncertainty				Under $+20\%$ uncertainty			
	ISE	IAE	ITSE	ITAE	ISE	IAE	ITSE	ITAE
PSO-PID [2]	1.239	2.213	12.1	22.83	Unstable	Unstable	Unstable	Unstable
PSO-FOPID [19]	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable
PSO-PIDD2 [19]	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable
CSA-PID [23]	1.189	1.899	11.53	19.21	Unstable	Unstable	Unstable	Unstable
Non-fragile PID (K) [6]	1.190	1.890	11.53	19.06	Unstable	Unstable	Unstable	Unstable
Non-fragile PID (K1) [6]	1.209	2.012	11.75	20.45	Unstable	Unstable	Unstable	Unstable
Non-fragile PID (K2) [6]	1.218	2.053	11.85	20.92	Unstable	Unstable	Unstable	Unstable
Non-fragile PID (K3) [6]	1.208	2.019	11.75	20.53	Unstable	Unstable	Unstable	Unstable
Non-fragile PID (K4) [6]	1.209	2.012	11.75	20.45	Unstable	Unstable	Unstable	Unstable
Proposed Non-fragile PIDA (C)	1.660	3.689	16.84	40.58	1.248	2.286	12.36	25.23
Proposed Non-fragile PIDA (C1)	1.484	3.238	15.01	35.30	1.183	2.134	11.83	24.12
Proposed Non-fragile PIDA (C2)	1.365	2.836	13.50	30.24	1.117	1.899	10.85	21.08
Proposed Non-fragile PIDA (C3)	1.434	2.906	14.33	31.34	1.175	2.076	11.65	23.79
Proposed Non-fragile PIDA (C4)	1.478	3.234	14.91	35.24	1.169	2.121	11.62	23.95

TABLE 6. Non-fragility analysis.

Control design	$RFI_{\Delta 20}$
PSO-PID [2]	0.2304
PSO-FOPID [19]	0.2273
PSO-PIDD2 [19]	0.3732
CSA-PID [23]	0.1792
Non-fragile PID (K) [6]	0.0684
Proposed Non-fragile PIDA (C)	0.0348

G. STABILITY ANALYSIS

The stability analysis is carried out in terms of gain margin and phase margin. The positive values of gain and phase margins show the stable nature of the control system. In addition, the higher values of gain and phase margins show the more stable nature of control system. The values of gain margin and phase margin are given in Table 7 for the control design approaches. It can be noticed from Table 7 that the proposed control design shows more stable nature in comparison to the existing control approaches.

V. CONCLUSION

This paper addresses the non-fragile PIDA controller design and its application in power system network under measurement delay effect. The tuning of proposed controller is carried out using CGA and Kharitonov's stability theorem. The proposed controller is designed for perturbed AVR system. The worst case plant selection approach is utilized here to find the worst case plant from the original interval system for the proposed controller design. From simulation results, it is observed that the proposed control design approach performs better in comparison to the published control approaches. The effectiveness and performance of the proposed control design are analyzed under the terminal voltage disturbances and parametric uncertainty in system coefficients. Further, the robustness and fragility analysis is carried out, and from these analyses, it is observed that the proposed control design shows the robust and non-fragile nature. Finally, it is concluded that the proposed controller design can be implementable in the real-time, and electrical engineers obtain the reference terminal voltage under the parametric uncertainty in controller and system coefficients, and terminal voltage disturbances (such as over-voltage condition and short-circuit faults). The limitation of proposed control design is to use of the CGA. The CGA has limitation such as crossover and mutation selection.

In near future, the author will adapt new optimization algorithm for the proposed controller tuning.

APPENDIX

PROOF OF THEOREM 3

From (31), it is observed that the coefficients of the polynomial (31) are changed within an interval. So, the designed controller must make the system stable at any point within the coefficient interval.

The four fixed Kharitonov polynomials for the above equation (31) using Theorem 1 can be written as

$$Q_1(s) = \underline{q}_0 + \underline{q}_1 s + \bar{q}_2 s^2 + \bar{q}_3 s^3 + \underline{q}_4 s^4 + \underline{q}_5 s^5 + \bar{q}_6 s^6 \tag{48}$$

$$Q_2(s) = \underline{q}_0 + \bar{q}_1 s + \bar{q}_2 s^2 + \underline{q}_3 s^3 + \underline{q}_4 s^4 + \bar{q}_5 s^5 + \bar{q}_6 s^6 \tag{49}$$

$$Q_3(s) = \bar{q}_0 + \underline{q}_1 s + \underline{q}_2 s^2 + \bar{q}_3 s^3 + \bar{q}_4 s^4 + \underline{q}_5 s^5 + \underline{q}_6 s^6 \tag{50}$$

$$Q_4(s) = \bar{q}_0 + \bar{q}_1 s + \underline{q}_2 s^2 + \underline{q}_3 s^3 + \bar{q}_4 s^4 + \bar{q}_5 s^5 + \underline{q}_6 s^6 \tag{51}$$

According to Kharitonov's stability theorem [51], [52], the polynomial family is robustly stable, if and only if, the above four Kharitonov polynomials are Hurwitz stable. Thus, to check the robust stability of the polynomial family, it is required to test the Hurwitz criterion for the four Kharitonov polynomials in the above mentioned equations.

Generally, Routh-Hurwitz (RH) stability criterion can be utilized to derive the set of necessary conditions for (31), as shown in Table 8 without considering the uncertainties in controller parameters.

TABLE 7. Stability and robustness analysis.

Control design	**Gain Margin** (in dB)	**Phase Margin** (in degree)	**Maximum Sensitivity** (M_s)
PSO-PID [2]	7.62	33.3	2.4434
PSO-FOPID [19]	7.03	22.8	3.0832
PSO-PIDD2 [19]	5.57	13.9	4.6238
CSA-PID [23]	8.70	36.7	2.2259
Non-fragile PID (K) [6]	8.48	34.5	2.3041
Proposed Non-fragile PIDA (C)	11.5	60.6	1.6924

TABLE 8. Routh-Hurwitz stability table for 6th order polynomial.

Row	Coefficients			
s^6	q_6	q_4	q_2	q_0
s^5	q_5	q_3	q_1	
s^4	R_1	B_1	C_1	
s^3	R_2	B_2		
s^2	R_3	B_3		
s^1	R_4			
s^0	R_5			

where, $R_1 = \frac{(q_4q_5-q_3q_6)}{q_5}$, $R_2 = \frac{(R_1q_3-q_5B_1)}{R_1}$, $R_3 = \frac{(R_2B_1-R_1B_2)}{R_2}$, $R_4 = \frac{(R_3B_2-R_2B_3)}{R_3}$, $R_5 = B_3$.
$B_1 = \frac{(q_2q_5-q_6q_1)}{q_5}$, $B_2 = \frac{(R_1q_1-q_5C_1)}{R_1}$, $B_3 = C_1$.
$C_1 = q_0$.

Similarly, the stability conditions can be applied to the four Kharitonov's polynomials in (48), (49), (50) and (51) and give four stability conditions for each Kharitonov's polynomial according to the RH stability criterion; for example as shown in Table 9 for equation (48). For this regard, the stability conditions can be concluded as follows:

TABLE 9. Routh-Hurwitz stability table for 6th order polynomial.

Row	Coefficients			
s^6	$\bar{q}_6$	$\underline{q}_4$	$\bar{q}_2$	$\underline{q}_0$
s^5	$\underline{q}_5$	$\bar{q}_3$	$\underline{q}_1$	
s^4	R_{11}	B_{11}	C_{11}	
s^3	R_{21}	B_{21}		
s^2	R_{31}	B_{31}		
s^1	R_{41}			
s^0	R_{51}			

where, $R_{11} = \frac{(\underline{q}_4\underline{q}_5-\bar{q}_3\bar{q}_6)}{\underline{q}_5}$, $R_{21} = \frac{(R_{11}\bar{q}_3-\underline{q}_5B_{11})}{R_{11}}$, $R_{31} = \frac{(R_{21}B11-R_{11}B_{21})}{R_{21}}$, $R_{41} = \frac{(R_{31}B_{21}-R_{21}B_{31})}{R_{31}}$, $R_{51} = B_{31}$.
$B_{11} = \frac{(\bar{q}_2\underline{q}_5-\bar{q}_6\underline{q}_1)}{\underline{q}_5}$, $B_{21} = \frac{(R_{11}\underline{q}_1-\underline{q}_5C_{11})}{R_{11}}$, $B_{31} = C_{11}$.
$C_{11} = \underline{q}_0$.

$$R_{ij} > 0 \tag{52}$$

where, $i \in \{1, 2, 3, 4, 5\}$ and $j \in \{1, 2, 3, 4\}$.

For the improvement in stability margins of the AVR system, it is required to minimize the maximum overshoot as well as settling time of the AVR system response. The constraints mentioned in (52) only guarantee the system stability but it is not to incorporate system performance. In this regard, the paper solves this problem by adding the value of the following function as a constraint to guarantee the system performance for each Kharitonov's polynomial,

$$H_j = \left(1 - e^{-\beta}\right)\left(O_{M_j} - E_{ss_j}\right) + e^{-\beta}\left(t_{s_j} - t_{r_j}\right); \quad j \in \{1, 2, 3, 4\} \tag{53}$$

where, j is the index for the four Kharitonov's polynomials. O_M is the maximum overshoot, E_{ss} is the steady state error, t_s is the settling time, t_r is the rise time, and β is the weighting factor. Here, the value of β to find the good performance of AVR system is chosen as 1.5 [2].

To ensure the controller non-fragility, we consider the robust fragility index ($RFI_{\Delta 20}$) in the proposed objective function. This proposed objective function has not been introduced in the literature work so far.

The following objective function is proposed,

$$J = \left(1 - e^{-\beta}\right)\left(O_{M_{nominal}} - E_{ss_{nominal}}\right) + e^{-\beta} \left(t_{s_{nominal}} - t_{r_{nominal}}\right) + RFI_{\Delta 20} + \Omega\left(\sum_{k=1}^{8} \frac{1}{\varepsilon_k}\right) \tag{54}$$

such that,

$$\tau > 0 \tag{55}$$
$$R_{ij} > 0 \tag{56}$$
$$0 < H_j < b \tag{57}$$
$$0 < RFI_{\Delta 20} \leq 0.5 \tag{58}$$

where, Ω is the constant weighting coefficient and it is chosen as 0.01, and b is the constant, which ensures the low settling time and overshoot (here, it is chosen as $b = 0.2$).

The CGA is used to minimizing the above mentioned proposed objective function J that ensures the system performance and maximizes the PIDA controller parameters limits for non-fragility.

Moreover, CGA is utilized to compute the nominal parameters of PIDA controller and the maximum permissible limits 'ε' that ensures the AVR system performance, stability, and controller non-fragility constraints.

The initialization parameters of CGA are considered as the maximum population size is set as 100 and the generations is also set as 100. In addition, CGA has the default parameters as mentioned in MATLAB toolbox.

CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

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