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A novel control scheme for automatic voltage regulator using novel modified artificial rabbits optimizer

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ABSTRACT

Automatic voltage regulators (AVRs) are essential components in electrical systems to maintain stable voltage output, ensuring optimal performance and equipment protection. The effectiveness of AVRs rely on key parameters such as voltage regulation, response time, stability, and efficiency. Integrating controllers with AVRs offers centralized monitoring and regulation, enhancing voltage output efficiency. This study therefore first discusses various controller types which showcase distinctive capabilities based on their tuning strategies and then introduces an intelligent optimization approach using fractional-order proportional-integral-derivative with double derivative (FOPIDD^2) controller tailored for AVRs. The study adopts the artificial rabbits optimization (ARO) algorithm, fortified with an adaptive local search (ALS) mechanism and experience-based perturbed learning (EPL) strategy. The modified version (m-ARO) enhances solution diversity and navigational efficacy, resulting in improved optimization quality. The study's core objective is to demonstrate the superior performance of the m-ARO-based FOPIDD^2 controller in addressing the multifaceted challenges of AVR control, outperforming conventional techniques in stability, speed of response, robustness, and efficiency. To validate the method's efficacy, a comparative analysis is conducted using existing controllers with different tuning algorithms. Results indicate that the proposed m-ARO-based FOPIDD^2 controller achieves superior performance metrics, demonstrating its capability. The study also includes a wider perspective by considering nineteen different controllers, reported in the literature, for comprehensive comparison. Notably, the proposed method exhibits the best stability, further affirming its effectiveness.

Introduction

Automatic voltage regulators (AVRs) play a pivotal role in maintaining stable and reliable voltage output in electrical systems, ensuring optimal performance and safeguarding equipment from potential damage [1–4]. The efficacy of an AVR lies in its ability to address key parameters, such as voltage regulation, response time, stability, and efficiency [5–7]. Achieving superior control in these aspects is crucial for maintaining a consistent and responsive power supply in the face of varying loads and input voltages. To this end, the engineering community continually seeks innovative approaches to enhance AVR control methodologies [8–10]. Using a controller with an AVR is important for several reasons. Firstly, a controller provides a centralized system for monitoring and controlling the AVR, allowing for more efficient and

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effective regulation of the output voltage. The controller can collect data on voltage, frequency, and other system parameters, and use that information to adjust the AVR as needed to maintain stable voltage levels. Secondly, a controller can provide advanced features such as remote monitoring, fault detection, and automatic shutdown in case of emergencies. These features help to prevent equipment damage, minimize downtime, and ensure the safety of personnel. Finally, a controller can improve system reliability and performance by providing real-time feedback and control over the AVR. This can help to optimize the efficiency of the generator or alternator, reduce energy consumption, and extend the life of the equipment. Therefore, different controllers such as standard proportional integral-derivative (PID) [11–14], real PID (RPID) [15], PID acceleration (PIDA) [16], fractional-order PID (FOPID) [17–19], PID plus second order derivative (PIDD^2) [20–22] and FOPID with double derivative (FOPIDD^2) [23].

All of the above-listed controllers have demonstrated certain capabilities depending on their employed tuning strategy. For example, the study in [24] explores the application of the African buffalo optimization (ABO) algorithm for tuning the parameters of a PID controller to improve the effectiveness of AVRs. By employing ABO, where each buffalo's location represents PID parameters, the study effectively addresses these concerns, yielding promising results in comparison to other metaheuristic techniques, highlighting ABO-PID's potential as a valuable addition to solving PID controller tuning challenges. The study in [25] aims to enhance control systems by applying the ant lion optimizer (ALO) algorithm to design a PID controller for AVRs, focusing on improved industrial process control and product quality. The ALO algorithm is employed to optimize PID controller parameters, with simulations conducted in Simulink/MATLAB. Comparative analysis against other nature-inspired algorithms demonstrates the superior transient and frequency domain performance of the proposed method, showcasing its robustness against disturbances and parameter variations. In another study [26], the application of FOPID controllers is explored in designing an optimal AVR. A self-regulated offline tuning method using the gradient-based optimization (GBO) algorithm is proposed. Simulations demonstrate improved dynamic response, stability, and robustness of the proposed method. The study in [15] addresses the nonlinear optimization of PID controller parameters for AVRs in electrical grids. An Archimedes optimization algorithm (AOA) is proposed to minimize settling time, rise time, and overshoot of the AVR's voltage response while adhering to PID controller parameter constraints. The study extends to optimizing FOPID and PIDD^2 controllers using AOA. Results confirm AOA's effectiveness in optimizing different versions of PID controllers, showcasing improved step response compared to other methods, and highlighting the potential of AOA-PIDD^2 controller for enhanced performance.

While existing methods have shown success, certain issues such as gain, overshoot and steady-state errors remain. In that sense, this study employs a FOPIDD^2 controller [23] which has been developed as an alternative to the other versions of the PID controller. It is a more advanced and sophisticated control method that uses a fractional order calculus approach to achieve better control performance compared to other variations of PID controller. This approach allows for more flexibility and adaptability in controlling systems that have non-linear or time-varying characteristics. Many real-world systems have non-integer order dynamics, and the FOPIDD^2 controller is better suited to handle these types of systems than other versions of PID controller. In response to this imperative, in this investigation, we aimed to employ an innovative intelligent optimization approach for crafting an efficient controller, known as the FOPIDD^2 controller, tailored for an AVR system. The path to this goal involved the adoption of the artificial rabbits optimization (ARO) algorithm [27] as the foundational optimization technique. This base methodology was then enriched by integrating an adaptive local search (ALS) mechanism and an experience-based perturbed learning (EPL) strategy. The ARO algorithm, known for its merits including ease of implementation and rapid convergence towards advantageous solutions by pinpointing the most promising contributors within the search space, became an instrumental component. However, the ARO algorithm grapples with significant hurdles when faced with intricate and multi-faceted problems, primarily in striking the delicate balance between exploration and exploitation.

A critical focal point lies in the iterative process of the algorithm, where rabbits engage in the stochastic selection of burrows. While this accelerates convergence, it may inadvertently compromise solution diversity, potentially entrapping the optimization within local optima. Additionally, the ARO methodology lacks a coherent navigational strategy to steer the search towards regions of promise, which could lead to the generation of suboptimal final solutions. Hence, there emerges a compelling necessity to enhance the efficacy of the traditional ARO algorithm to surmount these challenges. This enhancement is achieved by integrating the ALS and EPL strategies as fundamental components, thereby giving rise to an upgraded iteration known as the modified ARO (m-ARO) algorithm. The objective of this advancement is to effectively tackle the complexities posed by intricate problem landscapes and elevate the overall quality of solutions generated.

In this regard, this research focuses on demonstrating the superior performance of the proposed m-ARO-based FOPIDD^2 controller in addressing the multifaceted challenges of AVR control. By harnessing the inherent strengths of the m-ARO algorithm, this method aims to surpass conventional AVR control techniques in terms of stability, speed of response, robustness, and efficiency. Investigation has been carried out in this work by adopting different existing and widely adopted controllers of standard PID, RPID, PIDA, PIDD^2, FOPID and FOPIDD^2. In this sense, many optimizing liaisons algorithm-based PID controller [28], symbiotic organism search algorithm-based RPID controller [29], whale optimization algorithm based PIDA controller [30], cuckoo search algorithm based FOPID controller [31], opposition-based atom search optimization algorithm based PIDD^2 controller [32] and multi-verse optimizer based FOPIDD^2 controller [33] have been adopted as they present good performances. The results obtained from the comparative assessments demonstrated that the proposed method could achieve better performance metric values indicating its greater capability. Besides, the existing nineteen different controllers have also been adopted for this study for comparative presentation from a wider perspective. The proposed m-ARO based FOPIDD^2 controller has further been shown to present the best stability with the latter evaluation as well.

In conclusion, this paper presents a novel and advanced approach to AVR control through the application of the FOPIDD^2 controller and the integration of the modified ARO algorithm. The combination of these innovative elements not only addresses existing challenges in AVR control but also offers a unique and effective solution for improving stability, speed of response, and robustness. This research contributes to the field by introducing a controller tailored for the specific needs of AVRs and by enhancing optimization techniques to overcome complex problem landscapes. These original contributions underscore the novelty and significance of this study in advancing the state of the art in AVR control.

Artificial rabbits optimization

The ARO stands as a recent and potent metaheuristic technique, drawing inspiration from the survival tactics exhibited by rabbits, as elucidated by Wang et al. [27]. This methodology emulates the nuanced behaviors observed in rabbit populations, such as their utilization of random hiding and detour foraging strategies. The core concept of the algorithm revolves around mimicking the rabbits' foraging habits, wherein these creatures strategically approach plant consumption near neighboring burrows to outwit potential predators and safeguard their own habitats. Diverging from the conventional approach of immediate consumption, the ARO algorithm orchestrates rabbits to extend their search for sustenance to distant locales. The algorithm employs a

population size akin to a rabbit swarm, with each rabbit within the population assigned an eating zone adorned with plant life and greenery, in conjunction with several burrows. During the foraging process, rabbits engage in the fortuitous exploration of other rabbits' burrows in pursuit of sustenance. This endeavor involves not only gathering food but also perturbing the regular routine by updating their own locations in accordance with the selected rabbit, thereby introducing a level of disruption to the otherwise predictable course of action. To express this intricate foraging behavior mathematically:

$$\vec{\Delta}_i(t+1) = \vec{z}_j(t) + \rho.\left(\vec{z}_i(t) - \vec{z}_j(t)\right) + round(0.5\ .(0.05+g_1)).n_1, i, j = 1, 2\ldots\ldots, M \text{ and } i \neq j \tag{1}$$

$$E = \left(e - e^{\left(\frac{1-t}{T}\right)^2}\right).\sin(2\pi g_2) \tag{2}$$

$$c(k) = \begin{cases} 1 & if\ k == h(u) \\ 0 & else \end{cases},\ k = 1, \ldots, d\ \&\ u = 1, 2, \ldots, g_3.d \tag{3}$$

where $\rho = E.c$, $h = randperm(d)$, $n_1 \sim N(0,1)$ whereas $\vec{z}_i(t)$, $\vec{\Delta}_i(t+1)$, M,T, d, $round$, $randperm$, and E define the current position of candidate of i^{th} candidate at time t, i^{th}updated candidate at time $t+1$, population size of rabbits, the total size of iterations, the problem dimension, the rounding to the nearest integer value, random permutation function ranged from 1 to problem dimension, and running length during foraging, respectively. Here n_1 denotes normal distribution function, and g_1, g_2, g_3 define uniform random numbers inside the interval [0,1]. During the exploitation mode, rabbits employ a random hiding strategy to evade predators. They create a few burrows in close proximity to their original location. In each iteration of ARO, a rabbit consistently generates b burrows in each dimension. Then, it randomly selects one of these burrows to hide in and deceive predators. The i^{th} rabbit with j^{th} burrow can be mathematically formulated as follows:

$$\vec{BU_{ij}}(t) = \vec{z}_i(t) + H.h.\vec{z}_i(t), i = 1, 2\ldots\ldots, M \text{ and } j = 1, 2\ldots\ldots, d \tag{4}$$

$$H = \frac{1 - t + T}{T} g_4 \tag{5}$$

$$h(k) = \begin{cases} 1 & if\ k == j \\ 0 & else \end{cases},\ k = 1, \ldots, d \tag{6}$$

where $n_2 \sim N(0,1)$, H and d denote the hiding function, and formed burrows within the area of the rabbit, respectively. Primarily, a bunny's big area is where holes are generated. The size of this neighborhood shrinks as the number of iterations rises. the random hiding mode is offered as follows.

$$\vec{\Delta}_i(t+1) = \vec{z}_i(t) + \rho.(g_4.BU_{ir}(t) - \vec{z}_i(t)),\ i = 1, 2, \ldots\ldots M \tag{7}$$

$$h_r(k) = \begin{cases} 1 & if\ k == [g_5.d] \\ 0 & else \end{cases},\ k = 1, \ldots, d \tag{8}$$

$$BU_{ir}(t) = \vec{z}_i(t) + H.h_r.\vec{z}_i(t) \tag{9}$$

where $BU_{ir}(t)$ denotes the chosen burrow by the rabbit through the hiding mode, g_4 and g_5 define random numbers inside the interval [0,1]. The i^{th}rabbit's position is updated after either a detour foraging mode or a random hiding process as follows.

$$\vec{z}_s(t+1) = \begin{cases} \neg\, z_s(t) & f(\neg\, z_s(t)) \leq f(\neg\, \Delta_s(t+1)) \\ \neg\, \Delta_s(t+1) & f(\neg\, z_s(t)) \rangle f(\neg\, \Delta_s(t+1)) \end{cases} \tag{10}$$

If the s^{th} rabbit's candidate fitness is better than the position's present fitness, the bunny leaves its current location and stays in the candidate location determined by either Eq. (1) or Eq. (7). The energy of rabbits is shrinking with the progress of iteration, which helps in the transition from explorative mode to exploitative mode, which is formulated as follows:

$$EA(t) = 4\left(1 - \frac{t}{T}\right)\ln\left(\frac{1}{\alpha}\right) \tag{11}$$

where α defines a random number. When $EA(t) > 1$, the algorithm searches globally for the solution (exploration); when $EA(t) \leq 1$, the algorithm searches locally for the solution (exploitation).

Structure of proposed algorithm

In this manuscript, we present m-ARO, an enhanced iteration of the ARO algorithm. While ARO boasts merits in its straightforwardness and swift convergence, it grapples with intricacies when confronted with intricate challenges. The m-ARO algorithm confronts and mitigates these limitations by integrating adaptive local search (ALS) and experience-based perturbed learning (EPL) strategies. Through ALS, the focus narrows onto promising sectors of the problem domain, eluding the pitfalls of local optima, while EPL strikes a balance between venturing into new territories and exploiting known ground. In essence, the m-ARO demonstrates augmented efficacy in the realm of optimization tasks. The m-ARO introduces an inventive exploration approach in which rabbits trail their fellow population members. Nevertheless, this update mechanism might inadvertently trigger invasive diversification patterns. To tackle this potential issue, the algorithm incorporates the EPL methodology, designed to unearth more auspicious sectors within the feasible search expanse, thereby amplifying the exploration endeavor. The EPL procedure commences by gauging the mean (Δ^{it}_{mean}) and deviation (Δ^{it}_{dev}) of a solution chosen at random, relative to the best solution attained thus far (Δ_{best}).

Subsequently, the new solution undergoes an update grounded in these metrics, coupled with a perturbed component. This updated solution can be articulated as follows:

$$\Delta^{it}_{mean} = \left(z_{best} + z^{it}_I\right)/2 \tag{12}$$

$$\Delta^{it}_{dev} = \text{abs}\left(z_{best} - z^{it}_I\right) \tag{13}$$

$$\Delta^{it}_C = \Delta^{it}_{mean} + rand_1.\Delta^{it}_{dev} \tag{14}$$

$$z^{it}_{new} = \Delta^{it}_C + rand_2.\left(z_{best} - \Delta^{it}_C\right) + 0.95^{it}.(rand_3 - 0.5).\text{abs}\left(z_{max,j} - z_{min,j}\right),\ z_{max,j} = max_j\left\{z^{it}_i\right\},\ z_{min,j} = min_j\left\{z^{it}_i\right\}\forall \tag{15}$$

where Δ^{it}_I stand for any arbitrary solution chosen at random, $rand_1$, $rand_2$, and $rand_3$ define three random numbers elicited according to the uniform distribution inside the interval [0, 1]. Here, the third term of Eq. (15) is to perform perturbed solution within the dynamic bounders (Δ_{max} *and* Δ_{min}). By integrating EPL into the m-ARO, it effectively combines exploration and exploitation, resulting in improved search performance and better convergence to optimal solutions.

To refine precision throughout the iterative progression and foster a propensity for harnessing the potential of promising domains, we introduce the ALS strategy. This navigational framework leverages the collective insights held by the select group of top-tier rabbits, in tandem with the finest individual (z_{best}) and the weakest individual (z_{worst}). Initially, the elite group is identified by evaluating the fitness function, leading to the identification of the optimal and suboptimal individuals within this cluster (z^P and z^W respectively). Subsequently, three distinctive motion patterns come into play during the updating phase: (1) propelling z^W toward the vector pointing from z^W to z^P, (2) propelling z^W in the direction of z_{best}, and (3) propelling z^W along the trajectory bisecting z^P and z_{best}. These sequential movements unfold iteratively,

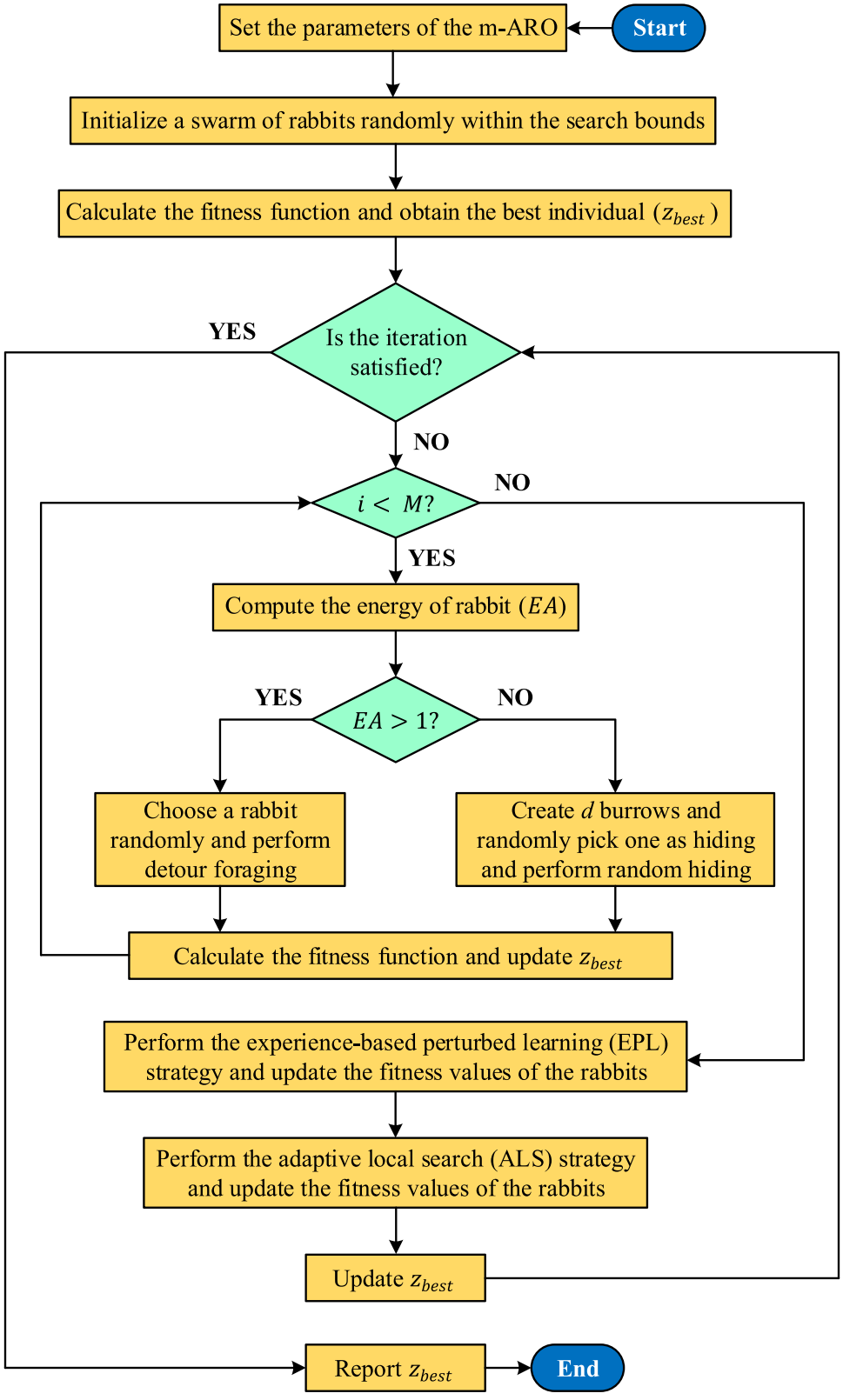


Fig. 1. Flowchart of proposed algorithm.

ceasing once any of them attains a superior fitness value. The update progression inherent in this strategy is succinctly articulated as follows:

$$z_I^{it+1} = \begin{cases} z_1^{\mathrm{ALS}} = 2 \times r_1 \times \left(z^{\mathrm{P}} - z^{\mathrm{W}}\right) + z^{\mathrm{W}} & if\, f\left(z_1^{\mathrm{ALS}}\right) \le f\left(z_I^{it}\right) \\ z_2^{\mathrm{ALS}} = 2 \times r_2 \times \left(z_{best} - z^{\mathrm{W}}\right) + z^{\mathrm{W}} & else\, if\, f\left(z_2^{\mathrm{ALS}}\right) \le f\left(z_I^{it}\right) \\ z_3^{\mathrm{ALS}} = 2 \times r_3 \times \left(\left(z^{\mathrm{P}} + z_{best}\right)/2 - z^{\mathrm{W}}\right) + z^{\mathrm{W}} & otherwise \end{cases} \tag{16}$$

where z_I^{it} and z_I^{it+1} stand for the present and updated solutions of the I^{th} solution inside the elite class. The framework of the proposed m-ARO is represented as in Fig. 1.

Automatic voltage regulator system and its parameters

An Automatic Voltage Regulator (AVR) is a device that controls and regulates the output voltage of a generator in a power system. The main function of an AVR is to maintain a stable output voltage regardless of changes in the load or input voltage [34]. The AVR receives signals from the output voltage of the generator, compares it to a reference voltage, and adjusts the field current of the alternator accordingly to maintain a constant output voltage. The AVR typically uses electronic components such as amplifiers, exciters, generators, and sensors to achieve this control [35]. Those components, their transfer functions and the adopted ranges are presented in Table 1 [28–33]. Besides, Fig. 2 provides a schematic diagram of a simple AVR system.

In a power system, the AVR plays a critical role in maintaining voltage stability and ensuring that the electrical equipment connected to the system operates within acceptable voltage limits. Without proper voltage regulation, electrical equipment can be damaged or fail to operate, leading to costly downtime and repairs. The AVR is therefore an essential component of power systems that rely on generators or alternators for electricity generation. Fig. 3 provides a block diagram of an open-loop AVR system and Eq. (17) presents the transfer function of an AVR system with open-loop [36].

$$\begin{aligned} TF_{open-loop}(s) &= \frac{G_A(s)G_E(s)G_G(s)}{1 + G_A(s)G_E(s)G_G(s)H_S(s)} \\ &= \frac{0.1s + 10}{0.0004s^4 + 0.0454s^3 + 0.555s^2 + 1.51s + 11} \end{aligned} \tag{17}$$

A novel design approach for FOPIDD^2 controlled AVR system via m-ARO algorithm

Using a controller with an AVR is critical for ensuring stable and reliable power generation in a power system. The controller provides advanced features for monitoring and controlling the AVR, improving system performance, and minimizing downtime and equipment damage.

Table 1
Parameters of the AVR system [28–33].

Component	Transfer function	Ranges of gain constant	Ranges of time constant (s)	Used values
Amplifier	$G_A(s) = \frac{K_A}{1+sT_A}$	[10, 40]	[0.02, 0.1]	$K_A = 10$ and $T_A = 0.1\ s$
Exciter	$G_E(s) = \frac{K_E}{1+sT_E}$	[1, 10]	[0.4, 1]	$K_E = 1$ and $T_E = 0.4\ s$
Generator	$G_G(s) = \frac{K_G}{1+sT_G}$	[0.7, 1.0]	[1.0, 2.0]	$K_G = 1$ and $T_G = 1\ s$
Sensor	$H_S(s) = \frac{K_S}{1+sT_S}$	[0.9, 1.1]	[0.001, 0.06]	$K_S = 1$ and $T_S = 0.01\ s$

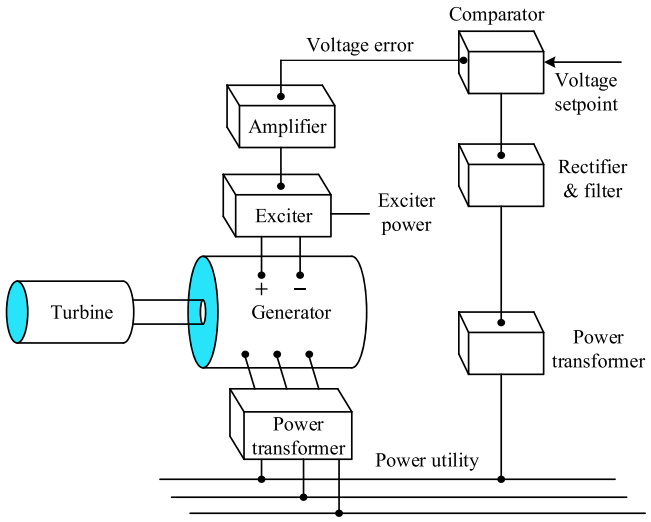


Fig. 2. Schematic diagram of a simple AVR system.

This section explains a novel design approach that adopts a FOPIDD^2 controller and m-ARO algorithm.

FOPIDD^2 controller and its application to AVR system

A FOPIDD^2 controller is a more advanced and sophisticated control method that uses a fractional order calculus approach to achieve better control performance compared to standard PID controllers [23]. This approach allows for more flexibility and adaptability in controlling systems that have non-linear or time-varying characteristics. One significant advantage of the FOPIDD^2 controller over standard PID controllers is its ability to handle fractional order systems. Many real-world systems have non-integer order dynamics, and the FOPIDD^2 controller is better suited to handle these types of systems than standard PID controllers. Therefore, in this work, the FOPIDD^2 has been adopted to maintain the terminal voltage within the desired range in the AVR system. By augmenting the fractional order PID controller with a second-order derivative gain, this novel controller has been devised to offer excellent performance in regulating the AVR system. Mathematically, the FOPIDD^2 controller can be defined with the following form:

$$C_{\mathrm{FOPIDD^2}}(s) = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} + K_{D2} s^2 \tag{18}$$

where the controller's proportional, integral, derivative, and second-order derivative gains are denoted by K_P, K_I, K_D, and K_{D2}, respectively, while λ and μ signify the fractional orders of the integral and derivative terms. The block diagram of the FOPIDD^2 controlled AVR system is illustrated in Fig. 4. Using the transfer function of the FOPIDD^2 controller given in Eq. (18) and the block diagram in Fig. 4, one can obtain the following transfer function of the AVR system with a FOPIDD^2 controller.

$$TF_{with-\mathrm{FOPIDD^2}}(s) = \frac{C_{\mathrm{FOPIDD^2}}(s)G_A(s)G_E(s)G_G(s)}{1 + C_{\mathrm{FOPIDD^2}}(s)G_A(s)G_E(s)G_G(s)H_S(s)} \tag{19}$$

Application of m-ARO algorithm to AVR system

In this study, the following procedure is adopted to describe the system under consideration as a minimization problem such that the controller parameters can be optimized. To find a feasible and efficient solution, the problem is represented as follows:

$$X = [x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6] = [K_P,\ K_I,\ K_D,\ K_{D2},\ \lambda,\ \mu] \tag{20}$$

To handle this problem an objective function is used alongside the m-

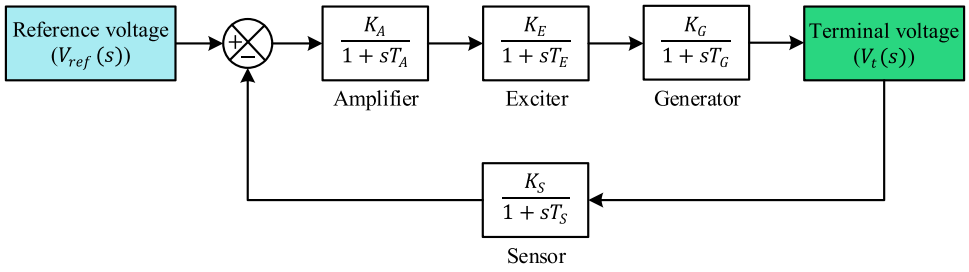


Fig. 3. Block diagram of the open-loop AVR system.

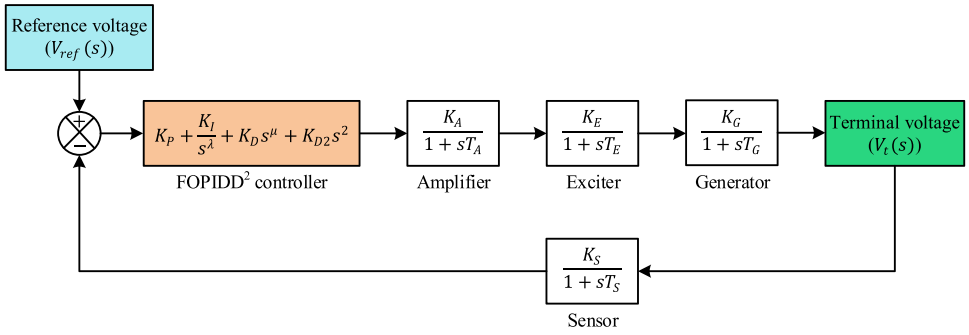


Fig. 4. Block diagram of the FOPIDD^2 controlled AVR system.

ARO algorithm for minimization. In this paper the following objective function [37] is used for minimization where φ, OS, E_{ss}, T_s and T_r respectively denote a balancing coefficient, percent overshoot, steady state error, settling time and rise time.

$$F(X)=(1-e^{-\varphi})\left(\frac{OS}{100}+E_{ss}\right)+e^{-\varphi}(T_s-T_r) \tag{21}$$

The above procedure is also subject to the constraints of $OS \leq 1\%$, $T_r \leq 0.10$ s, $T_s \leq 0.20$ s, $E_{ss} \leq 10^{-4}$ pu, $G_m \geq 100$ dB and $P_m \geq 60^\circ$ as part of the design requirements. Besides variable ranges for the controller parameters are also used as $K_P^{min} \leq K_P \leq K_P^{max}$, $K_I^{min} \leq K_I \leq K_I^{max}$, $K_D^{min} \leq K_D \leq K_D^{max}$, $K_{D2}^{min} \leq K_{D2} \leq K_{D2}^{max}$, $\lambda^{min} \leq \lambda \leq \lambda^{max}$ and $\mu^{min} \leq \mu \leq \mu^{max}$. Fig. 5 illustrates the implementation procedure of the m-ARO based tuning scheme.

Comparative simulation results and discussion

The key parameters of an AVR include the voltage regulation, response time, stability, and efficiency. Voltage regulation refers to the AVR's ability to maintain a stable output voltage over a range of load and input voltage conditions. Response time is the time it takes for the AVR to adjust the output voltage in response to a change in load or input voltage. Stability refers to the ability of the AVR to maintain a constant output voltage over time. Efficiency refers to the amount of power lost in the AVR due to its internal components and controls. In the light of these descriptions, this section provides several analyses to demonstrate the significance of the proposed method in this study.

Statistical performance

To assess the statistical performance of the proposed method, statistical analyses regarding the objective function values have initially been assessed. In this context, Fig. 6 provides the objective functions values obtained from 30 runs of the ARO and m-ARO algorithms. Besides, Fig. 7 demonstrates boxplot analysis for these algorithms. Numerical analysis is also presented in Table 2. For the assessments, 50 iterations and a population size of 30 have been used. As these figures and the table indicate, the proposed method has a more desirable

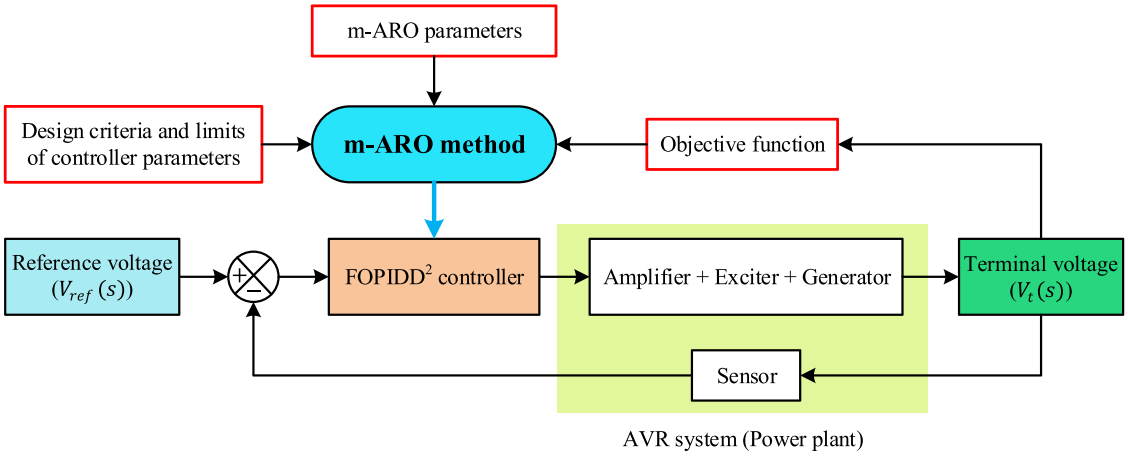


Fig. 5. System structure for FOPIDD^2 controller tuning based on m-ARO algorithm.

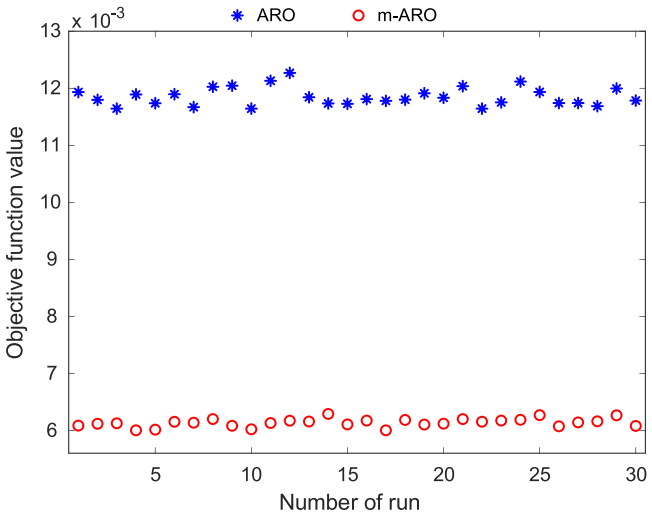


Fig. 6. The obtained F objective function values from 30 runs.

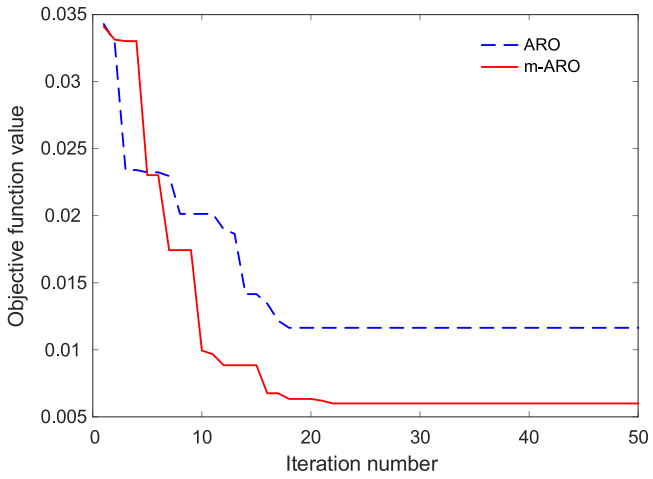


Fig. 8. Comparative convergence curves for ARO and m-ARO algorithms.

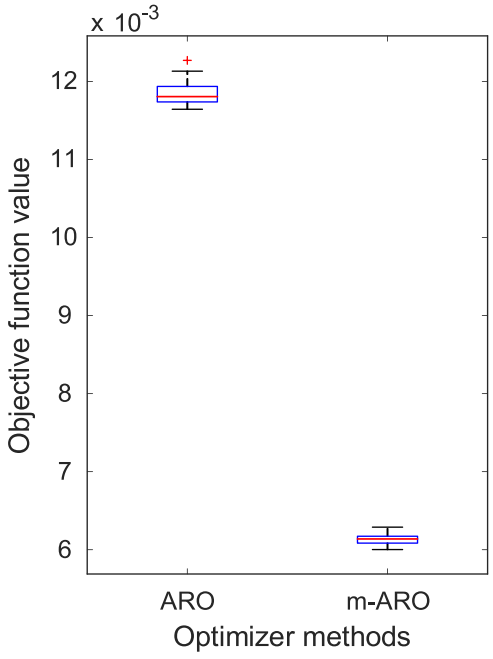


Fig. 7. Boxplots for ARO and m-ARO algorithms.

Table 3
Boundaries of FOPIDD^2 controller and obtained values for ARO and m-ARO algorithms.

Controller parameter	Search area	Tuned by ARO	Tuned by m-ARO
K_P	[0.001, 4]	2.6162	3.9125
K_I	[0.001, 4]	2.6256	2.5641
K_D	[0.001, 4]	3.0765	2.0802
K_{D2}	[0.001, 4]	0.16940	0.15857
λ	[0.5, 1.5]	0.8447	1.0492
μ	[0.5, 1.5]	0.8266	0.9801

statistical performance making it more suitable for this specific engineering problem.

Convergence profile, parameter values and transfer function

To observe how well the proposed method find the solution, a comparative convergence analysis is also presented in this study. As shown in Fig. 8, the proposed m-ARO algorithm can converge to the lowest objective function values in later iterations compared to the original ARO algorithm. This shows the more significant performance of the proposed algorithm in terms of reaching the more convenient solution. The tuned parameter values presented in Table 3 have been obtained for the ARO and m-ARO algorithms. The related table also provides the boundaries of those parameters adopted in this study. The respective parameter values are used to obtain the transfer functions provided in the following equations.

$$TF_{\text{ARO-FOPIDD}^2}(s) = \frac{0.01694s^{3.8447} + 1.694s^{2.8447} + 0.30765s^{2.6713} + 0.26162s^{1.8447} + 30.765s^{1.6713} + 0.26256s + 26.162s^{0.8447} + 26.256}{0.0004s^{4.8447} + 0.0454s^{3.8447} + 2.249s^{2.8447} + 1.51s^{1.8447} + 30.765s^{1.6713} + 27.162s^{0.8447} + 26.256} \tag{22}$$

$$TF_{m-\text{ARO-FOPIDD}^2}(s) = \frac{0.015857s^{4.0492} + 1.5857s^{3.0492} + 0.20802s^{3.0293} + 0.39125s^{2.0492} + 20.802s^{2.0293} + 39.125s^{1.0492} + 0.25641s + 25.641}{0.0004s^{5.0492} + 0.0454s^{4.0492} + 2.1407s^{3.0492} + 1.51s^{2.0492} + 20.802s^{2.0293} + 40.125s^{1.0492} + 25.641} \tag{23}$$

Table 2
Statistical values of F objective function.

Algorithm	Mean	Standard deviation	Best (minimum)	Worst (maximum)	Median
ARO	1.1852E−02	1.6107E−04	1.1643E−02	1.2269E−02	1.1805E−02
m-ARO	6.1349E−03	7.3285E−05	6.0018E−03	6.2887E−03	6.1377E−03

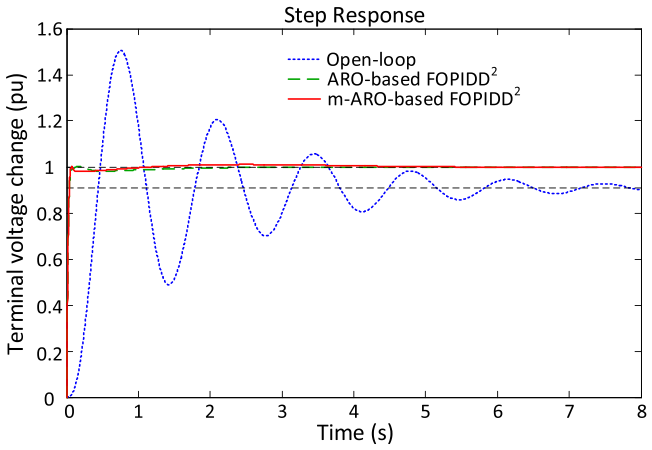


Fig. 9. Step response of open-loop and proposed FOPIDD^2 controlled AVR systems.

Table 4
Time-domain performance metrics.

Type of system	Overshoot (%)	Rise time (s)	Settling time (s)	Steady state error (pu)
Open loop	65.7226	0.2607	6.9865	0.0909
ARO-based FOPIDD^2 controlled	0.2106	0.0340	0.0620	0
m-ARO-based FOPIDD^2 controlled	0	0.0330	0.0493	0

Evaluation of stability in the time-domain for proposed controller

The time-domain based stability of the system poses a significant importance on the system and as stated earlier, it is crucial to force the system to behave within the determined constraints of $OS \leq 1\%$, $T_r \leq 0.10\ s$, $T_s \leq 0.20\ s$, $E_{ss} \leq 10^{-4}\ pu$ in order to reach a better performing system. In this context, Fig. 9 displays the step responses obtained for open-loop, ARO based FOPIDD^2 and m-ARO based FOPIDD^2 controllers.

Besides, Table 4 presents numerical values for the time-domain performance metrics. The latter figure and table signify that the proposed method can deal with the time domain related stability as it reaches zero (0) overshoot and steady state error along with the lower rise and settling times.

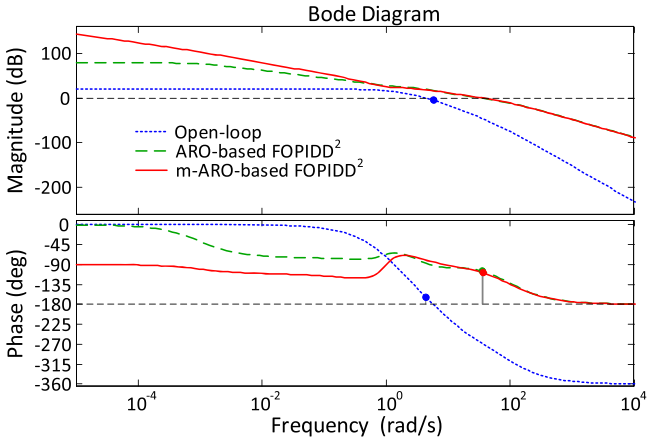


Fig. 10. Bode diagrams of open-loop and proposed FOPIDD^2 controlled AVR systems.

Table 5
Frequency-domain performance metrics.

Type of system	Gain margin (dB)	Phase margin (deg.)	Bandwidth (rad/s)
Open loop	4.6176	16.1028	6.9454
ARO-based FOPIDD^2 controlled	Infinite	75.1440	65.7095
m-ARO-based FOPIDD^2 controlled	Infinite	71.6299	65.6117

Evaluation of stability in the frequency-domain for proposed controller

Another important aspect is to construct a system that is stable in terms of frequency-domain. This can be achieved by observing the earlier stated constraints of $G_m \geq 100$ dB and $P_m \geq 60^\circ$. The Bode diagram is a powerful tool that provides critical insights into the stability of the AVR system in the frequency-domain. By analyzing the Bode diagram, we can calculate key performance metrics such as peak gain, phase and delay margins, and bandwidth. A high phase and delay margin with a low peak gain indicates a stable and reliable frequency response. Additionally, a broader bandwidth leads to a lower rise time, making it a highly desirable feature. To compare the performance of the AVR design approach presented in this work, Bode diagrams in Fig. 10 are illustrated. Moreover, the comparative performance criteria for frequency-domain stability are given in Table 5. By examining the Bode diagrams and performance criteria, we can clearly see the proposed AVR design approach performs the best in terms of frequency-domain as it performs more excellently and meets the design criteria posed by the constraints. With this valuable information at hand, we can make informed decisions and ensure that the proposed design method for the AVR system meets the required standards.

Robustness performance of proposed m-ARO-based FOPIDD^2 controller

In this study, an important aspect is to analyze the behavior of the AVR system under parameter changes, which may affect its components. To evaluate the ability of the proposed method to handle potential parameter variations, a robustness analysis has been conducted. The robustness analysis involved introducing variations within different ranges of time constant parameters (T_A, T_E, T_G, and T_S) from their nominal values. The results of the analysis are presented in Table 6, which provides numerical values for the transient response performance of the proposed method with respect to variations.

Additionally, step responses for the AVR system with the proposed method against variations of T_A, T_E, T_G, and T_S are illustrated in Figs. 11, 12, 13, and 14, respectively. It is worth noting that the step responses

Table 6
Robustness of the m-ARO-based FOPIDD^2 controller against parameter variations.

Parameter	Variation (%)	Overshoot (%)	Rise time (s)	Settling time (s)
T_A	−50	5.9785	0.0143	0.3862
	−25	0.5922	0.0235	0.3299
	+25	1.3848	0.0420	0.0615
	+50	3.3191	0.0501	0.1696
T_E	−50	14.7291	0.0130	0.5717
	−25	4.1263	0.0221	0.4232
	+25	0	0.0455	0.0772
	+50	0	0.0585	0.1009
T_G	−50	16.8816	0.0128	0.3241
	−25	5.0595	0.0217	0.1523
	+25	0	0.0465	0.0906
	+50	0.5227	0.0705	0.1422
T_S	−50	0.0939	0.0472	0.1447
	−25	0	0.0386	0.1143
	+25	3.7053	0.0298	0.1601
	+50	8.0695	0.0279	0.1763

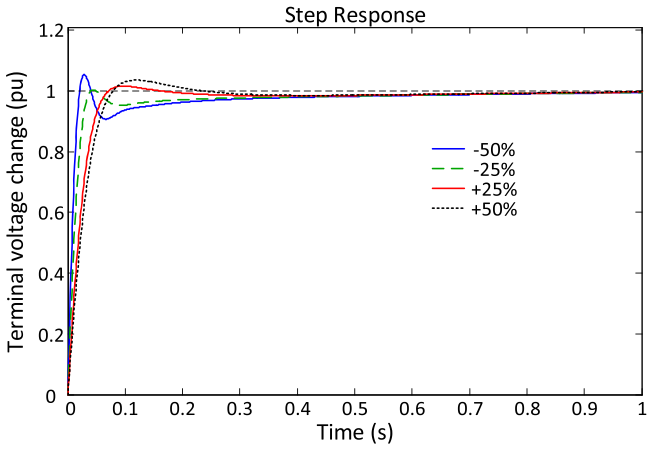


Fig. 11. Step responses of AVR system for variation of T_A parameter.

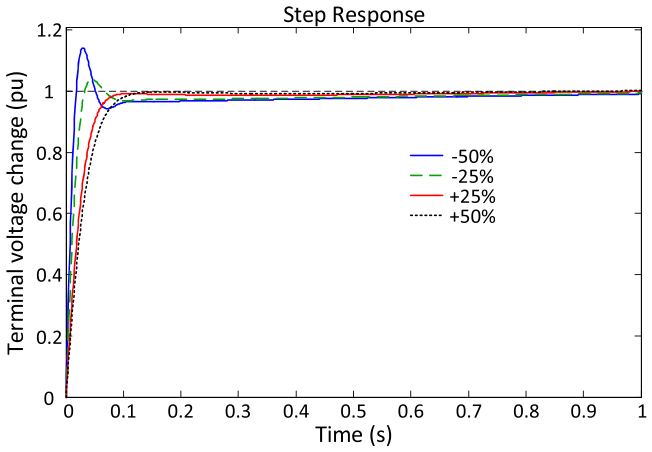


Fig. 12. Step responses of AVR system for variation of T_E parameter.

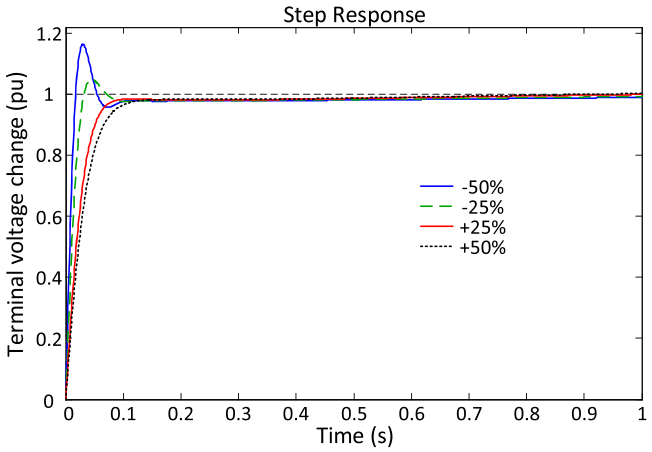


Fig. 13. Step responses of AVR system for variation of T_G parameter.

become worse with the variations compared to their nominal values, as expected. However, the proposed m-ARO based real FOPIDD^2 controller demonstrates its ability to effectively tolerate all those variations, as can be clearly observed from the presented results. It is also worth noting that the steady-state error in Figs. 11 and 12 appears due to the selected time scale. In control system analysis, steady-state error is typically assessed over an extended time period, and shorter time scales may not accurately represent the system's long-term behavior. In this context,

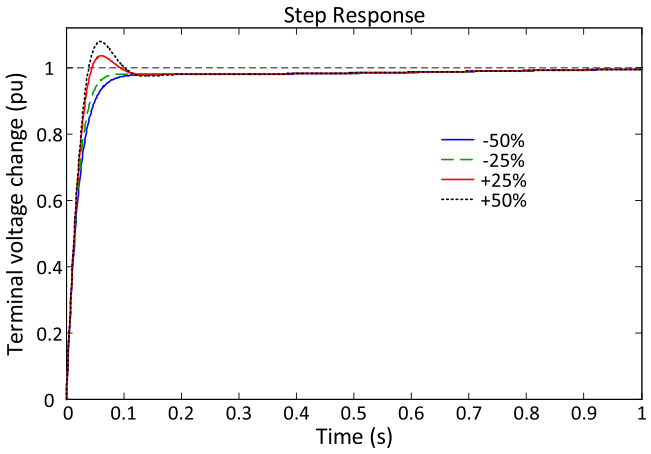


Fig. 14. Step responses of AVR system for variation of T_S parameter.

the steady-state error is actually zero in related figures. Therefore, the proposed method is sufficiently robust to deal with uncertainties caused by parameter variations, making it a reliable option for AVR applications.

Comparisons with widely adopted controller types

Further investigation has been carried out in this work by adopting different existing and widely adopted controllers of standard PID (SPID), real PID (RPID), PID acceleration (PIDA), PID with double derivative (PIDD^2), fractional order PID (FOPID) and FOPID with double derivative (FOPIDD^2). In this sense, many optimizing liaisons (MOL) algorithm-based SPID controller [28], symbiotic organism search (SOS) algorithm-based RPID controller [29], whale optimization algorithm (WOA) based PIDA controller [30], cuckoo search (CS) algorithm based FOPID controller [31], opposition-based atom search optimization (OBASO) algorithm based PIDD^2 controller [32] and multi-verse optimizer (MVO) based FOPIDD^2 controller [33] have been adopted as they present good performances. Those approaches and their relevant transfer functions are provided in Table 7. Using these transfer functions, a comparative assessment can be devised with the method proposed in this work.

In this regard, the step responses of each method are presented in Fig. 15 while Figs. 16, 17 and 18 displays the comparative performances in terms of overshoot, rise time and settling time, respectively. From the presented results, one can observe the more convenient of the proposed method in this work as better performance metric values are achieved.

Comparisons with other existing controller types

Apart from the controller types presented in the previous subsection, the existing different controllers listed in Table 8 have also been adopted for this study for comparative presentation of a wider perspective. As can be observed from the related table, each column lists different controller structures with a specific tuning approach. One can observe from this table that the proposed m-ARO based FOPIDD^2 controller presents the best stability as shown with the highlighted bold values. All these comparative analyses demonstrate the excellent capability of the proposed method for the AVR system control making it the best candidate for superior performance.

Discussion

This discussion section delves into the comparative simulation results and findings, shedding light on the proposed method's effectiveness in addressing the essential parameters of AVR system from a distinct angle. The m-ARO algorithm's superiority is examined through

Table 7
Transfer functions obtained for different controller structures.

Method no	Ref.	Tuning method	Proposed control scheme	Closed-loop transfer function
1	[28]	MOL	SPID	$\frac{0.01772s^3+1.831s^2+5.899s+4.189}{0.0004s^5+0.0454s^4+0.555s^3+3.282s^2+6.857s+4.189}$
2	[29]	SOS	RPID	$\frac{12.67s^3+1300s^2+3313s+2092}{0.0004s^6+0.2447s^5+23.17s^4+278s^3+2020s^2+3791s+2092}$
3	[30]	WOA	PIDA	$\frac{10.3s^4+1080s^3+5084s^2+7814s+3977}{0.0004s^7+0.2654s^6+25.9s^5+348.4s^4+2370s^3+6938s^2+8689s+3977}$
4	[31]	CS	FOPID	$\frac{0.03888s^{3.35}+3.888s^{2.35}+0.2515s^{1.97}+0.01629s+25.15s^{0.97}+1.629}{0.0004s^{4.97}+0.0454s^{3.97}+0.555s^{2.97}+3.888s^{2.35}+1.51s^{1.97}+26.15s^{0.97}+1.629}$
5	[32]	OBASO	$PIDD^2$	$\frac{0.008813s^4+1.015s^3+13.65s^2+29.4s+19.46}{0.0004s^5+0.0454s^4+1.436s^3+14.87s^2+30.21s+19.46}$
6	[33]	MVO	$FOPIDD^2$	$\frac{0.01361s^{3.8726}+1.361s^{2.8726}+0.23086s^{2.7705}+0.3s^{1.8726}+23.086s^{1.7705}+0.3s+30s^{0.8726}+30}{0.0004s^{4.8726}+0.0454s^{3.8726}+1.916s^{2.8726}+1.51s^{1.8726}+23.086s^{1.7705}+31s^{0.8726}+30}$

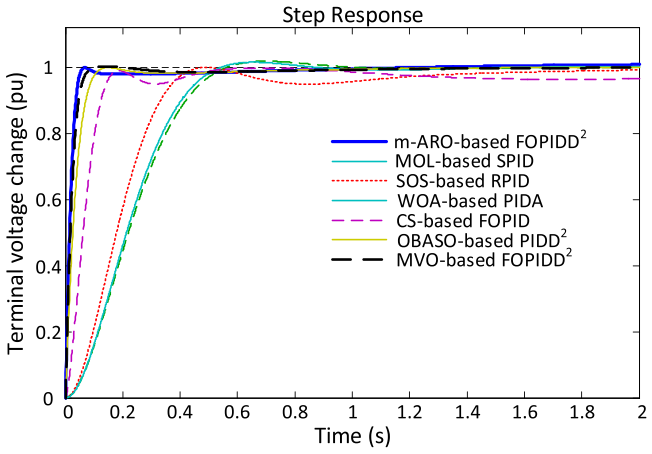


Fig. 15. Step responses of AVR system tuned by recent various approaches.

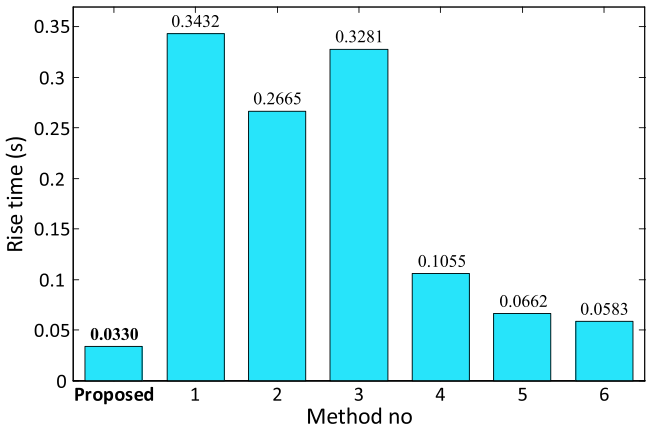


Fig. 17. Rise time for various approaches.

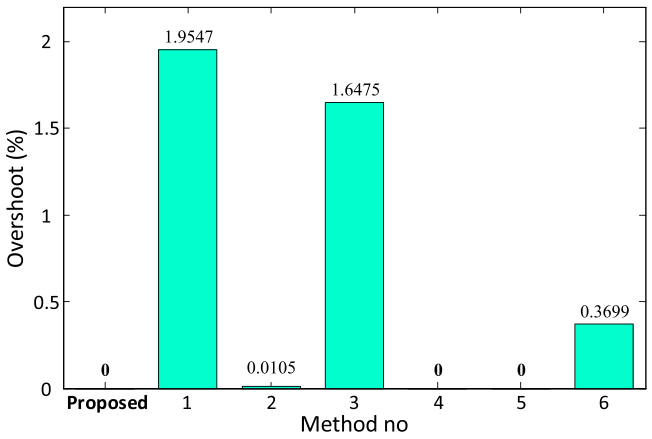


Fig. 16. Overshoots for various approaches.

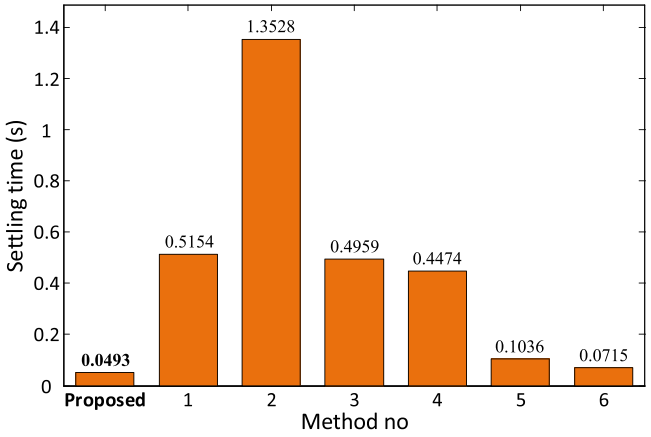


Fig. 18. Settling time for various approaches.

a comprehensive analysis encompassing voltage regulation, response time, stability, and efficiency.

The statistical performance evaluation, as presented in Fig. 6, Fig. 7, and Table 2, offers a compelling view of the m-ARO algorithm's superiority. The consistency displayed across the 30 runs of the m-ARO algorithm reveals its remarkable ability to consistently converge to optimal solutions. The boxplot analysis visually accentuates the stability and reliability of the m-ARO approach in contrast to the ARO algorithm. This observation aligns with the engineering need for consistent performance in AVR systems, thereby positioning the m-ARO algorithm as a robust and reliable choice.

Fig. 8 provides a captivating illustration of the m-ARO algorithm's distinct advantage in terms of convergence speed. The m-ARO algorithm exhibits accelerated convergence to lower objective function values, underscoring its efficiency in navigating complex solution spaces. This acceleration hints at the algorithm's inherent adaptability and optimization capabilities, rendering it a potent tool for achieving rapid and accurate AVR control adjustments. The m-ARO algorithm's superiority is further emphasized by its capacity to fulfill stringent performance criteria in the time domain. Fig. 9 and Table 4 exhibit the proposed method's prowess in minimizing overshoot, achieving rapid rise times, and settling within shorter timescales. These attributes denote the m-ARO algorithm's profound ability to efficiently stabilize the AVR system, culminating in superior transient responses and enhanced control precision.

Table 8
Performance comparison with other existing controller types.

Reference	Tuning method	Proposed control scheme	Overshoot (%)	Rise time (s)	Settling time (s)
Proposed	m-ARO	FOPIDD^2	**0**	**0.0330**	**0.0493**
[38]	ICA	Neural network predictive	0.6	NR	1.9067
[39]	COA	PI$^\lambda$DND^{2}N^2	1.596	0.0400	0.0617
[40]	EO	FOPID-DN	**0**	0.076	0.144
[41]	ICA	Gray PID	1.23	0.2305	0.3193
[42]	GA	Radial basis function neural network	0.168	1.0024	1.3766
[43]	AOA	Model predictive	1.2862	NR	0.2444
[44]	iRUN	Real PIDD^2	**0**	0.0399	0.0626
[45]	GA	Fuzzy PID	1.0407	0.1857	0.2963
[46]	Nonlinear SCA	Sigmoid-based PID	2.2	0.498	0.579
[47]	PSO	Reference model + FOPID	1.08	0.1592	0.2114
[48]	PSO	FHODFC	0.001	0.373	0.685
[49]	PSO	2DOF state-feedback PI	2.224	0.690	3.442
[50]	Ziegler-Nichols	Conventional tuning	51.50	0.237	3.052
[51]	SCA	FOPID with fractional filter	0.1262	0.1230	0.1670
[52]	WOA	2DOF fractional PI	1.17	1.12	1.74
[53]	FSA	Robust non-fragile PID	1.0	NR	0.4417
[54]	Rao	MFOPID	0.01	0.0965	0.170
[55]	DDPG	Reinforcement learning	0.2064	0.34	0.55
[56]	Hybrid learning	ANFIS	1.3206	1.1994	1.8818

NR: Not reported.

In the frequency-domain stability analysis (Fig. 10 and Table 5), the m-ARO algorithm shines brightly as it consistently satisfies critical performance metrics. The profound gain and phase margins achieved underscore the algorithm's adeptness in maintaining robust and dynamically stable AVR responses. Furthermore, the proposed method's capacity to achieve broader bandwidths through its skillful frequency-domain manipulation showcases its prowess in adapting to varying load conditions swiftly.

The m-ARO algorithm's exceptional robustness against parameter variations is particularly noteworthy. As evidenced in Table 6 and Figs. 11–14, the algorithm maintains a remarkable level of control performance even in the face of parameter uncertainties. This aspect is pivotal in real-world scenarios where fluctuations and changes are inherent. The m-ARO algorithm's resilience aligns with industrial demands for adaptable and consistent AVR control, setting it apart as a reliable and enduring choice.

The m-ARO algorithm's supremacy becomes even more evident when benchmarked against established controller types. Figs. 15–18 poignantly illustrate the algorithm's consistent outperformance across various performance metrics. This versatility in surpassing multiple well-established methods underscores the m-ARO algorithm's adaptive nature and its unparalleled ability to optimize AVR performance across diverse scenarios.

Expanding the analysis to include a broader range of controller types serves as the final testament to the m-ARO algorithm's supremacy. Among the array of existing controllers listed in Table 8, the m-ARO-based FOPIDD^2 controller consistently emerges as the most stable option, confidently surpassing its peers in stability benchmarks. This exhaustive comparative analysis underscores the m-ARO algorithm's unwavering capability to deliver superior AVR control even in the presence of complex controller structures.

In summary, the comprehensive evaluation conducted across statistical performance, convergence, stability, and comparative analyses collectively highlight the m-ARO algorithm's exceptional suitability for AVR control. The algorithm's consistency, rapid convergence, stability achievements in both time and frequency domains, robustness, and superiority over existing methods converge to define it as an unrivaled choice in achieving superior AVR performance.

Conclusion

In this study, the pivotal role of AVRs in ensuring optimal performance while safeguarding equipment from potential damage was highlighted, along with the key parameters of voltage regulation, response time, stability, and efficiency that govern their effectiveness. The integration of controllers with AVRs emerged as a vital strategy for centralized monitoring and regulation, leading to improved voltage output efficiency. The advanced features offered by controllers, such as remote monitoring, fault detection, and automatic shutdown, contribute to enhanced system safety, reduced downtime, and personnel security. Furthermore, controllers provide real-time feedback and control over AVRs, optimizing generator or alternator efficiency, minimizing energy consumption, and extending equipment lifespan.

Among various controller types explored, the FOPIDD^2 controller stood out as a sophisticated alternative to other PID controller versions. Leveraging fractional order calculus, the FOPIDD^2 controller exhibited superior performance in handling non-linear and time-varying systems, addressing the complexities often encountered in real-world applications. The research's primary objective was to introduce an innovative intelligent optimization approach, the m-ARO algorithm, tailored specifically for the FOPIDD^2 controller in AVR systems. By integrating ALS and EPL strategies into the ARO algorithm, the m-ARO algorithm demonstrated enhanced solution diversity and navigational efficacy. This upgrade aimed to overcome challenges related to exploration-exploitation balance and solution quality in intricate problem landscapes.

The experimental results, involving comparative assessments with various existing controllers, provided evidence of the superiority of the proposed m-ARO-based FOPIDD^2 controller. Its superior performance metrics in terms of stability, speed of response, robustness, and efficiency showcased its capability in addressing the complex challenges of AVR control. In conclusion, this study successfully presented an intelligent optimization approach, the m-ARO-based FOPIDD^2 controller, as an effective solution for AVR control systems. The integration of ALS and EPL strategies into the ARO algorithm addressed existing limitations and demonstrated improved optimization quality. The research contributes to the advancement of AVR control methodologies, offering a promising avenue for enhancing the stability and efficiency of electrical systems in the face of varying loads and input voltages. Further research could explore additional applications of the m-ARO algorithm in other control systems, ultimately contributing to the ongoing evolution of optimization techniques and control strategies in the field of electrical engineering. Furthermore, it's worth noting that future research in the field of AVR control could explore the integration of multi-objective optimization algorithms to achieve a trade-off between different control performance metrics. These algorithms could enable control systems to balance competing objectives, such as minimizing settling time, reducing overshoot, and optimizing energy efficiency simultaneously. Such an approach holds promise for achieving more adaptable and versatile AVR systems capable of meeting diverse operational requirements.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.
Data is available from the authors upon reasonable request.

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Not Applicable

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