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ORIGINAL PAPER

Optimal design of controller for automatic voltage regulator performance enhancement: a survey

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Abstract

For regulating the Synchronous Generator (SG) output voltage, the Automatic Voltage Regulator (AVR) system is a significant device. This work propounds a survey on Optimization Algorithms (OAs) utilized for tuning the controller parameters on the AVR system. A device wielded for adjusting the SG's Terminal Voltage (TV) is named AVR. A Controller is utilized for improving stability and getting a superior response by mitigating maximum Over Shoot (OS), reducing Rise Time (RT), reducing Settling Time (ST), and enhancing Steady State Error (SSE) since output voltage has a slower response and instability. The controllers utilized here are Proportional-Integral-Derivative (PID), Intelligent Controller (IC), along with Fraction Order PID (FOPID). Owing to the occurrence of time delays, nonlinear loads, variable operating points, and others, OAs are wielded for tuning the controller. (a) Particle Swarm Optimization (PSO), (b) Genetic Algorithm (GA), (c) Gray Wolf Optimizer (GWO), (d) Harmony Search Algorithm (HSA), (e) Artificial Bee Colony (ABC), (f) Teaching Learned Based Optimization (TLBO), et cetera are the various sorts of OA. For enhancing the TV response along with stability, various OAs were tried by researchers.

Keywords Automatic voltage regulator (AVR) · Fraction order proportional integral derivative (FOPID) controller · Fuzzy logic controller · Intelligent controller · Nonlinear system · Optimization technique · Proportional integral derivative (PID) controller

1 Introduction

The most vital resource to mankind after water is Electricity. The excitation system, which encompasses the AVR, is the most crucial power system control device utilized to enhance the power systems' stability [1]. AVRs are utilized to maintain a stable output voltage irrespective of the input whether there is an Under Voltage or Over Voltage in place [2]. AVR manages the SG's voltage at a specific level, where the system voltage's variation must be reduced essentially under abnormal criteria like short circuits, fault conditions, load fluctuations, and others. Exciter, generator, sensor, amplifier, and comparator are the '5' major components included in the AVR [3]. Figure 1 exhibits the AVR system's block diagram. In the AVR, every single component's transfer function is linear. Thus, every single component possesses its gain together with the time constant [4]. Every single component of AVR will be affected when an alteration occurs in the load on the SG. Hence, every single component's gains along with time constants will be changed, which affects the AVR's stability [5]. By minimizing the maximum percentage of OS, ST, RT, and SSE, better stability as well as response are gained by a controller [6].

FOPID, PID, Fuzzy P, Fuzzy I, Fuzzy D, PID-Acceleration (PIDA), and Sugeno Fuzzy Logic (SFL) are the various sorts of controllers [7]. The PID Controllers (PIDCs) are strong and provide extensive stability margin; thus, they are utilized in numerous control applications. Numerous industrial devices are non-linear along with higher-order with delay. Thus, the tuning of PIDCs to obtain an appropriate Dynamic Response (DR) is highly complex [8]. Owing to higher-order, non-linear loads, time delays, variable operating points, et cetera, OAs are wielded for tuning the controller parameters [9]. After that, to acquire the controller's optimal design, various random search methodologies like Simulated Annealing

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(SA), Ant Colony Optimization (ACO), Whale Optimization Algorithm (WOA), Gravitational Search Algorithm (GSA), Symbiotic Organisms Search Algorithm (SOSA), Chaotic Optimization (CO), and Enhanced Crow Search Algorithm (ECSA) are presented [10]. For realizing the AVR system, which possesses the finest DR, various control techniques like adaptive, optimal, robust control, et cetera have been observed by researchers until today while examining the related literature. Thus, the controller's optimal design for AVR performance improvement has been surveyed here.

2 Literature survey

In this section, the AVR system is surveyed. The optimization schemes for enhancing the AVR's performance are illustrated in Sect. 2.1. The non-linear AVR is explicated in Sect. 2.2. The parameter OA in the FOPID Controller (FOPIDC) is elucidated in Sect. 2.3. The parameter OAs in PIDC is elaborated in Sect. 2.4. The design along with the espousal of IC is detailed in Sect. 2.5. The architecture of the AVR system is represented in Fig. 1,

The AVR system's structure is displayed in Fig. 1. In an electrical power system, an AVR automatically maintains a steady voltage level. For maintaining a consistent output voltage, the AVR monitors the output voltage of the alternator or generator and modifies the excitation current to the generator's field winding. Usually, a feedback loop is used to do this by analogizing the actual output voltage to a predetermined reference value and modifying the excitation current as necessary. AVRs typically consist of a control circuit, a sensing circuit, and an output circuit. While the control circuit chooses the proper output voltage to ensure stability, the sensing circuit monitors the voltage of the system. The output circuit then adjusts the voltage of the generator or transformer to match the desired level. Overall, the use of an AVR helps to ensure that the electrical power system operates at a consistent and stable voltage level, which is essential for the reliable operation of electrical equipment and devices. In existing studies, a variety of controllers are used in the AVR system. They perform over the AVR in their own way for stabilizing the synchronous generator's output voltage. In this, the role of certain controllers in stabilizing the synchronous generator's output voltage is explained below:

a) ***Proportional-Integral-Derivative (PID) controller:*** It regulates Voltage, flow, pressure, speed, and other process variables in the AVR system. For controlling process variables, it utilizes a control loop feedback technique, and it is the most precise and stable controller.
b) ***Intelligent Controller (IC):*** It is a modular type, which comprises a module for processing transfer function identification, a module for setting the PID controller parameters, and a module for ongoing process quality monitoring. For process control, every module can be utilized independently and in other concepts. In general, the modules are designed to control a high-order system in the AVR for stabilizing the SG's output.
c) ***Fraction Order PID (FOPID):*** It is the expansion of the traditional PID controller centered on fractional calculus. It has a tunable integral and differential order, which creates the possibility to render superior control performance in the AVR system.

2.1 Automatic voltage regulator system

Various sorts of OAs employed for tuning the controller parameters on the AVR are displayed in this survey. To illustrate a better TV response, various types of research are executed on each sort and are analogized with different approaches. The AVR system mainly depends on the optimized parameters that are optimized using the optimization algorithms. In existing works, a vast number of meta-heuristic algorithms are used, which are explained in this section. Each optimization model optimized optimal controller parameters by using their social behavior. The behaviors of each optimization model are explained clearly

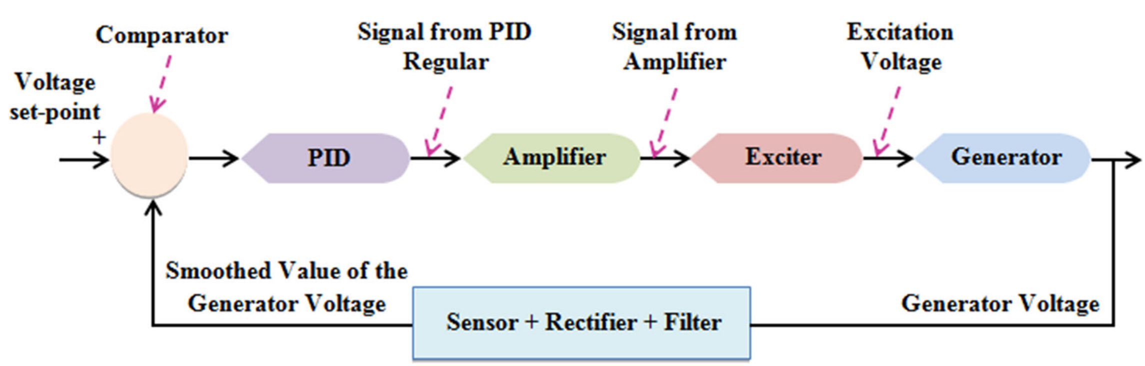

Fig. 1 Simple block diagram of the AVR system

here. Even though all the optimization models depend on different social behaviors, all these algorithms improved the optimal selection with the same strategy. In these optimization techniques, the numbers of gain parameters, namely (i) proportional gain, (ii) integral gain, (iii) amplifier gain, (iv) sensor gain, (v) derivative gain, et cetera are considered as the population. From these gain parameters, the optimal parameters are selected. By evaluating the objective function of population with the certain criteria, the optimal controller parameters are selected. In all these optimization models, the objective function is computed centered on minimizing the RT and ST. These optimal parameters help in tuning the controller in the AVR and also lead to a better output voltage of the synchronous generator.

Afzal Sikander and Padmanabh Thakur [11] introduced a Cuckoo Search (CS) approach for designing a robust PIDC of AVR. In this technique, based on the breading behavior of the cuckoo, the optimal controller parameters were selected. For this purpose of selection, the gain parameters were assumed as the number of cuckoos. By mitigating the performance indices via the CS approach, the controller gains' optimal value was achieved. For evaluating the CS-PIDC's efficacy, 2 performance indices that are directly reliant on time response features and 2 AVRs were regarded. By determining the controller's transient response features like ST, SSE, RT, along with maximum peak OS, its DR was evaluated. Via Root-Locus (RL) and bode plots, the AVR system's stability with the controller was examined. It was exposed that for a broad range of open-loop gains, the controller was not just efficient in giving an enhanced DR but also showed steady performance. However, the technique fell into the local optimal solution and the slow rate of convergence.

YazdanBatmani and HêminGolpîraan [12] established an online Adaptive Optimal Controller (AOC) for AVR design. Centered on the fault betwixt the SGs' TV and its required value, an optimal quadratic tracking issue was defined. After that, by utilizing the Adaptive Dynamic Programming (ADP) technique termed the Policy Iteration (PI) system, the optimal control issue was resolved. Also, via Single Machine Infinite-Bus (SMIB), a large-scale system was exemplified by this technique. Then, the equal SMIB system to be deployed by the control method might have linearized via modal analysis. Simulation outcomes illustrated that in a practical power system, the developed AOCs were extremely effective. Nevertheless, when the AOC was utilized, the ST of AVR was found greater than a second.

DiabMokeddem and SeyedaliMirjalili [13] presented an Improved WOA (IWOA) for tuning the controller. This technique chose the optimal controller parameters by searching the prey behavior of whales. The number of whales and prey was taken as the gain parameter for the selection process. For confirming the approach's superiority, (i) Friedman, (ii) Friedman aligned, and (iii) Quade tests were the 3 non-parametric statistical tests utilized. For designing the controller, parameters like PID plus second-order Derivative (PIDD2) for an AVR, IWOA was wielded. The results compared with the similar approaches displayed that the presented research attains better performance than the other approaches.

Soliman and Ali [14] propounded a strong design of multi-objective PIDCs for AVRs. Here, the Routh-Hurwitz Criterion (RHC) analytically calculated the set of stabilizing PIDCs. The pole placement in convex areas, which was positioned in the Left Half Plane (LHP) and bounded by the damping isoclines, guaranteed the minimum damping factors and coefficients. For guaranteeing stability as well as performance concurrently, a set of principle polynomials derived from Polyak's corollary captured the model's parametric uncertainties. For confirming the model's efficacy and simplicity, comparative simulation outcomes were rendered.

Elsisi and Soliman [15] proffered a robust non-fragile PIDC for AVR. The PID model depended fundamentally on the Kharitonov theorem along with optimization by the Future Search Algorithm (FSA). FSA imitated the performance of the people looking for the best life. Every single person sought a better life globally by emulating successful people or else changing his initial position. Based on this behavior, the controller parameters were chosen. Since the algorithm used local and global search approaches, it had less computational complexity and speed CR. To sustain the parametric fluctuations of the plant scheme and bear its gain perturbations, the PIDC was optimized by FSA; so that, strong stability and controller non-fragility were concurrently satisfied. To handle model uncertainties, an interval model was recommended; in this, only '8' extreme plants derived by the Kharitonov theorem were regarded. The Kharitonov's plant stability conditions, which were obtained using Routh–Hurwitz, constrained the FSA-based PID optimization. The outcomes exhibited the model's better response measured up to other approaches in which the robustness and non-fragility were simultaneously guaranteed. However, the proper training data availability conditioned the controller's better execution.

Leandro dos Santos Coelho [16] presented a tuning of PIDC utilizing a CO technique for AVR. Stochastic, ergodicity, and certainty were the properties of chaotic mapping, which was presented by CO by utilizing Lozi map chaotic sequences that raised its CR and resulting precision. Simulation outcomes were promising and illustrated the technique's efficacy. The CO's superior performance was demonstrated by the simulations centered on the AVR's PID control for nominal system parameters as well as step reference voltage input. Still, it was not mostly implemented for engineering issues.

EmreÇelik and RafetDurgut [17] developed an altered cost function and Symbiotic Organisms Search (SOS) approach for the AVR's performance enrichment. This design issue can be considered as an optimization task; also, via a cost function detailed here, which permitted estimating the control behavior in the time as well as frequency domains, SOS was invoked for discovering enhanced controller parameters. Distinct analysis approaches like transient response, RL, and bode were utilized for the performance assessment. Moreover, centered on the parameter uncertainties and external disturbance, a robustness assessment of the closed-loop control scheme tuned by SOS was executed. The outcomes proved that the trade-off betwixt the scheme DR and the stability margin was enhanced by the cooperation of the enhanced cost function and the SOS approach. But, the transient-time characteristics like rising time and ST were degraded by the scheme's frequency domain.

MihailoMicev et al. [18] presented an Equilibrium Optimizer (EO) for the effective AVR evaluation. The AVR PID was considered initially for demonstrating the applicability and the algorithm's efficacy. The base of the EO algorithm used the mass balance equation that was often utilized in chemistry and physics. Based on this mass balancing, the parameters were selected. Here, the gain parameters were assumed as the sum of mass. Next, the outcomes obtained for various techniques were analogized with AVR schemes' time responses (comprising PIDC optimized by EO) with and without various forms of trouble. Moreover, the requested duration for a single iteration, the comparisons regarding the accuracy, the algorithm's entire execution time, and convergence characteristics were also executed. The outcomes illustrated that for every considered data, the EO considerably performed better compared to other techniques. However, for fluctuations in the system parameters, the system was not strong.

2.2 Non-linear and linear AVR System

The nonlinear AVR is analyzed in this part. By utilizing the feedback definite linearization of the SG dynamic equations attached to the rotor reference frame and by fixing a Linear Quadratic Regulator (LQR) for adjusting the machine field voltage, the AVR is designed.

Francisco A. Torres et al. [19] presented a nonlinear AVR for an SG supplying a passive load. Utilizing an OPAL-RT real-time simulator environment, this algorithm was examined. After that, by deploying the Hardware In Loop (HIL), an actual synchronous machine was encompassed. On a 1.2 kVA cylindrical-rotor SG, the system was executed and experimentally established in which with an SSE below 1% for load steps of 40%, the TV was synchronized by the AVR. However, the system might not work with limitations.

Kaushik Burial and P. R. Gandhi [20] presented a feedback linearization-centric non-linear AVR for Small Signal Stability (SSS) improvement. The non-linear voltage regulator replaced the joining unit of the static IEEEST1 voltage regulator along with the power system stabilizer. For the simulation of the amalgamating system along with the non-linear voltage system, synchronous machine methodology 1.1 was utilized. Via eigenvalues analysis of the combining system along with a non-linear voltage regulator, the SSS of a Single Machine Infinite Bus (SMIB) system was established. By utilizing the combining system as well as the non-linear AVR, the non-linear simulations were accomplished. But, owing to the presence of fluctuations in system parameters, there occurs a lack of robustness.

MingyangXie et al. [21] developed a control system by employing Lyapunov base finite time non-linear reactive power as well as dc-link voltage control. Here, the Lyapunov technique is employed for ensuring stability and guaranteeing strength. This system achieved superior performance when contrasted with the proportional-integral controller. Moreover, for demonstrating the model's efficacy, outcomes were provided. This technique also considered various disturbances of the system, namely faults on buses, changes in reference parameters, changes in solar insolation level, et cetera.

Davut Izci and Serdar Ekinci [22] deployed an improved RUN (iRUN) optimizer-centric real PIDD2 controller design for improving an AVR's transient response and robustness. By integrating the Pattern Search (PS) technique into the RUN optimizer's original form, the iRUN optimizer was acquired. Regarding robustness and transient response, the developed iRUN optimizer-centric real PIDD2 controller was relatively better than other available and recently reported techniques centered on PID with filter (PID-F), PID, FOPID, PIDA, and PIDD2 controllers. In addition, it was adequately robust in potential variations, which might occur in the system's parameters. Moreover, the superiority was illustrated by utilizing diverse 30 better-performing and recently reported various techniques that espoused various controllers and metaheuristic optimizers.

RenHao Mok and Mohd Ashraf Ahmad [23] presented a Modified Smoothed Function Algorithm (MSFA)-centric technique for tuning the AVR system's FOPIDC as it needed fewer function evaluations per iteration. Furthermore, the developed MSFA-centric technique could solve the unstable convergence problem in the original Smoothed Function Algorithm (SFA); hence, it can render superior convergence accuracy. For evaluating the efficiency of the AVR system's developed MSFA-FOPID controller, the simulations of step response analysis, trajectory tracking analysis, Bode plot analysis, disturbance rejection analysis, and parameter variation analysis were performed. Therefore, the outcomes acquired from the simulations showed that the developed technique was highly efficient and considerably enhanced than other prevailing FOPIDCs.

Davut Izci et al. [24] presented a control scheme for an AVR utilizing a modified artificial rabbit optimizer. The Adaptive Local Search (ALS) approach, Experience-centric Perturbed Learning (EPL) approach, and Artificial Rabbits Optimization (ARO) strategy were espoused. Navigational efficiency and solution diversity were improved by the modified version, which leads to enhanced optimization quality. Demonstrating the m-ARO-centric Fractional-Order Proportional-Integral-Derivative with Double derivative (FOPIDD2) controller's better performance to address the AVR control's multifaceted challenges is the study's main goal. It surpassed traditional approaches in robustness, efficacy, speed of response, and stability. According to the outcomes, better performance metrics were attained by the developed m-ARO-centric FOPIDD2 controller, which demonstrates its capability.

Vadan Padiachy et al. [25] established a 2 Degree Of Freedom Fractional Of Proportional Integral (2DOF FOPI) scheme for linear AVR systems. Here, for displaying an extra degree of freedom in both controller and structure, the 2DOF FOPI controller was utilized for deviating away from the standard integer order. A performance measure was modeled for the parameter tuning for enhancing the AVR performance. In disturbance interruptions and parameter perturbation, the technique attained significant robustness. The step response quality displayed that the OS and ST could be minimized by about half of the recently published scheme. Different investigations were exhibited for accepting the developed controller's dominance regarding robustness.

2.3 Various parameter optimization algorithms in FOPID controller for AVR system

For an industrial control system to get higher-quality performances, designing an effectual FOPIDC as a generalization of a standard PIDC centered on fractional order calculus is highly significant both theoretically and practically. Different parameters OAs in FOPIDC for the AVR are exhibited in Table 1.

MihailoMicevet al. [42] presented a technique for optimal tuning of an FOPIDC for an AVR. This technique was grounded on the Yellow Saddle Goatfish Algorithm (YSGA) that was enhanced with Chaotic Logistic Maps. The development of the YSGA selected the optimal parameters centered on the hunting process model by a yellow saddle goatfish group. This technique showed that the entire population of fish (gain parameters) was partitioned into sub-populations. Every single sub-population has one fish named a chaser, whereas the others are named blockers. Also, by evaluating the objective function, the optimal parameters could be attained. In this paper, the objective function was minimizing the cost function and RT. These helped to achieve optimal parameters and stabilized the output voltage. Comparing the attained FOPIDC with several FOPIDCs tuned by other metaheuristic approaches, the performance was validated. As per the outcomes, the FOPIDC tuned with the Chaotic YSGA (C-YSGA) was superior to the FOPIDCs tuned by other approaches in all tests mentioned above.

Nikhil Paliwal et al. [43] proffered a FOPID plus derivative with filter coefficient (FOPID-DN) controller for AVR. The EO approach optimally tuned the FOPID-DN's parameters. The system's comparative transient response assessment was performed by significant transient response indicators, namely maximum OS, RT, and ST. From the various analyzes, the presented research attained superior performance in contrast to other techniques. Also, the single objective function was considered.

HalukGozde [44] developed a controller for enhancing the mechanism's robustness toward the comparatively cruel disturbances generated as of the load side along with the set point side; also, the controller was tuned with a metaheuristic OA. By applying frequency-domain, time-domain, stability, along with 2 robustness analyzes, namely instantaneous and continuous disturbance analyzes, the controller's superiority was validated. As per the analyzes, the maximum OS as well as ST acquired as of the control structure was decreased by more than half.

Saleh Masoud Abdallah Altbawi et al. [45] proffered a self-regulated offline optimal tuning technique. By mitigating the chosen Fitness Function (FF), which was selected as Integral Time Absolute Error (ITAE), the optimal FOPID gains were attained. Concerning robustness, stability, and dynamic response, the model's performance was contrasted with the lately published metaheuristic OA-centric optimal AVR designs. As per the outcomes, the most optimal dynamic response and enriched stability among the concerned AVR designs was provided by the presented AVR designs, thus proving its efficiency.

AbdulsamedTabak [46] suggested a tilt-fractional order integral derivative with a second order derivative as well as a low-pass filter controller for augmenting the AVR's control performance. To determine the controller's eight parameters optimally, the EO algorithm was employed. A function comprising of time domain specifications was wielded as the objective function in the research. It was then analogized with the PIDA, PID, PIDD2, FOPID, and hybrid controllers for assessing the controller's performance. When analogized with the other controllers, superior performance was attained by the presented controller.

2.4 Various parameter optimization algorithms in PID controller for AVR system

Globally, the classical PIDC is a famous process among industries. Here, the diverse parameter OAs in the PIDC for the AVR system is surveyed. The AVR system is

Table 1 Optimization algorithms in FOPID controller

Author	Optimization Techniques	Number of Parameters	Description	Disadvantage
Mustafa SinasiAyasandErdincSahin [26]	Sine–Cosine Algorithm (SCA)	7	For enhancing the AVR system's performance, the optimally tuned controller termed SCA-FOPIDFF was utilized	The global search capacity was poor
Guo-Qiang Zeng et al. [27]	Improved Multi-Objective Extremal Optimization (MOEO)	10	The challenges in implementing an individual-centric iterated optimization technique along with Polynomial Mutation (PLM) were resolved by this methodology	Only the simple parameters were handled by this system
Touqeer Ahmed Jumaniet al. [28]	Jaya Optimization Algorithm (JOA)	5	For attaining an optimum amalgamation of FOPID gains, which brought about the optimum transient response and enhanced the AVR system's stability, the Artificial Intelligence (AI) model termed JOA was deployed	For unconstrained issues, the processing time was slower
Xiao Li et al. [29]	PSO	5	PSO was responsible for searching the integrated absolute error criterion's solution, that is, the FOPIDC's parameters	Implementing the fractional operators directly in the time domain as per the standard definitions of fractional differ-integral is highly complicated
Marco E. Ortiz-Quisbertet al. [30]	GA	10	To minimize non-linear along with higher dimensionality objective functions, the tuning of gains and orders of the FOPIDC along with the FOMRAC controller were focused on in this algorithm	It is highly complex to design an objective function in addition to acquiring the representation along with the operator right
HadiRamezanianet al.[31]	PSO	–	It is utilized for the optimum tuning of practical fractional PIDCs	Lower convergent rate
Jailsingh Bhookyaet al.[32]	SCA	5	By employing the time-domain objective function for the AVR, the FOPIDC was developed by the SCA optimization	Optimal solutions were not provided for continuous iterations
Santosh Kumar Vermaet al. [33]	GWO	-	Both integer and fractional-order controllers were tuned	The local search ability was poor

Table 1 (continued)

Author	Optimization Techniques	Number of Parameters	Description	Disadvantage
ZHANG Dong-Li et al. [34]	Improved ABC algorithm, which amalgamates Cyclic exchange Neighborhood with Chaos (CNC-ABC)	5	By employing this, the FOPIDC's parameters for an AVR were optimized	While addressing challenging issues, improper exploitation occurs
Yinggan Tang et al. [35]	Chaotic Ant Swarm (CAS)	5	CAS was an evolutionary algorithm inspired by the chaotic activities of an ant along with the self-organization of an ant swarm. It was utilized for searching the FOPIDC's finest parameters	Lower solution accuracy
Indranil Pan andSaptarshi Das [36]	Chaotic multi-objective optimization	–	FOPIDC was developed to look out for a variety of contradictory objective functions for an AVR	Handling the uncertainties in AVR was challenging
BachirBouroubaet al. [37]	Ant Lion Optimizer (ALO)	11	It was employed to deal with the FOPIDC tuning problem	Addressing real-world issues was highly complicated
Indranil Pan andSaptarshi Das [38]	Improved evolutionary Non-dominated Sorting GA (NSGA-II) elevated with a chaotic Henon map	–	The actual NSGA-II algorithm along with its Logistic map-assisted version was surpassed by the Henon map as the random number generator for attaining the best design trade-off with a FOPIDC	The computational cost was augmented when the number of solutions increased; similarly, simulating a great number of generations was computationally exhaustive
BettouKhalfaandCharefAbdelfateh [39]	PSO	6	It was espoused to acquire optimum fractional-order $PI^{\lambda}D^{\mu}A$ controllers against 2 real-world system models for benchmarking	The controller structure was utilized for the same condition methodologies
AbbasaliZamaniet al. [40]	Gases Brownian Motion Optimization (GBMO)	5	To address load–frequency control, the benefits of FOPIDC along with GBMO were utilized	It was very complex to tune the FOPIDCs regarding the design along with stability evaluation
Sikanderet al.[41]	CS	5	PID gains, integral, and derivative constants were the controller optimum design parameters, which were obtained by utilizing CS	For a huge amount of data, the computational cost was high

mostly dependent on parameters that have been optimized by optimization methods. This section explains many meta-heuristics algorithms that are in use. Using their social behavior, each optimization model optimized the parameters of the controller. Here is a clear explanation of each optimization model's behavior. All of these algorithms used different objective function evaluation methods to improve the optimal selection. The population in these optimization techniques is the number of gain parameters, such as derivative gain, sensor gain, amplifier gain, integral gain, and proportional gain. The optimal parameters are chosen from these gain parameters.

Amrit Kaur Bhullar et al**.** [47] established an ECSA for AVR optimization. By addressing the CSA–PID's drawbacks, an ECSA to optimize PIDC parameters named ECSA–PID was developed. The enhanced CRs along with low values of integral indices: Integral of Absolute Error (IAE), ITAE, Integral of Squared Error (ISE), and Integral of Time multiplied by Squared Error (ITSE) were the ECSA's major features. In this model, the Crow Search Algorithm (CSA) was utilized to optimize the PID parameters, namely (a) proportional gain, (b) integral gain, and (c) derivative gain, which were minimized in the PIDC. CSA was a sort of swarm intelligence optimization algorithm built by imitating the crows' intelligent behavior of retrieving and hiding food. Centered on these characteristics, the optimal parameters were selected for fine-tuning the developed controller. Enhancing the unit step response by reducing time-domain specifications is the major goal in the developed optimized design. For attaining this aim, the objective function was established grounded on parameters like minimum RT, minimum ST, minimum IAE, and maximum control effort. Centered on 23 benchmark functions, the enriched algorithm was tested; this involved multimodal, unimodal, together with fixed dimension multimodal functions. For the entire test functions, the statistical investigation along with the capacity computation was carried out. This analysis exhibited that since global best was attained in a lesser number of iterations and time, ECSA was cost-effective and efficient. But, owing to the ineffectual exploration of its search approach, its convergence wasn't assured.

Supol Kansit and Wudhichai Assawinchaichote [48] offered an optimal PIDC design for an AVR utilizing a hybrid formulated from the PSO and GSA (PSOGSA). The PSOGSA was a low-level co-evolutionary heterogeneous hybrid approach of PSO working along with the GSA. This was motivated by combining the social thinking ability in the PSO and the local search ability in the GSA for a faster convergence speed and a superior searching capability for a global optimum. Here, the gain parameters were assumed as the number of particles. PSOGSA was utilized to search optimal parameters on the PIDC for the AVR. The parameters were (i) integral gain, (ii) derivative gain, and (iii) proportional gain. The optimized parameters were minimized in the PIDC. For optimizing the parameters, the objective function was computed grounded on the lower accumulated error signal for a reduced performance index of the developed PIDC. For displaying the design method's effectiveness, the transient response analysis along with bode analysis was regarded. Furthermore, the outcome's comparison betwixt the model and other methods like the Ziegler-Nichols (ZN) tuning technique, the PSO tuning technique, along with the Many Optimizing Liaisons (MOL) tuning technique was provided. The analysis showed that when analogized to other methodologies, the PSOGSA algorithm yielded superior outcomes for the AVR. However, the system had slow convergence along with the readiness to become trapped in local minima.

ZaferBingul et al. [49] proffered a PIDC's optimum design utilizing the CSA for an AVR. For reducing the TV's maximum OS, ST, RT, along with SSE, this performance condition was selected. Utilizing diverse objective functions, the CS-centric PIDC's performance was analogized to the PIDCs tuned by the diverse evolutionary algorithms. This technique chose the optimal controller parameters by looking at the cuckoo's breading behavior. The number of cuckoos was taken as the gain parameter for the selection process. Here, the CSA with the developed objective function was for designing the controller parameters like derivative gain, proportional gain, and integral gain to execute the controlled system's desired robust stability and response. The controller parameters were maximized over the PIDC. For optimizing the parameters, a multi-objective design optimization was calculated based on minimizing the step response characteristics. The CS-centered PIDC's DR and frequency response were evaluated in depth. Comprehensively, PIDC's energy consumption along with the PIDCs tuned PSO and ABC algorithms were evaluated. According to the extensive simulation outcomes, the CS-centric PIDC had superior control performance than other PIDCs tuned by the PSO as well as ABC systems. The PID tuning optimization method was extraordinarily enhanced by the objective function. However, the ability to seek an optimal solution was poor.

Ahmed M. Mosaad et al. [50] created a WOA for tuning PID and PIDA controllers on the AVR system. Here, for tuning the controllers' parameters, the WOA method was utilized. Here, the controller parameters of the PIDC were derivative gain, proportional gain, and integral gain, which were the design variables of the Whale Optimization Algorithm (WOA). This technique chose the optimal controller parameters by searching the prey behavior of whales. The number of whales and prey was taken as the gain parameter for the selection process. These were minimized for obtaining the AVR system's superior stability. In this designed WOA, the objective function was calculated based on minimizing the error voltage for faster response and better stability. Through comparison with numerous optimization methods, WOA utilizing PID and PIDA controllers exhibited its superiority. Subsequently, a comparison betwixt both controllers was done and exhibited that the PIDA controller was superior compared to the PIDC. Thus, WOA utilizing the PIDA controller was the finest system. For checking TV response with load variation, the robustness investigation was done, which verified again the WOA-PIDA system's superiority. But, it had slow convergence and simple localization.

Mouayad A. Sahib and Bestoun S. Ahmed [51] examined a PIDC design for an AVR application utilizing a PSO algorithm. Centered on the multi-objective Pareto front solutions, this technique exhibited a time-domain performance condition. PSO Algorithm was an intelligent way of solving tricky problems by mimicking how creatures work together. PSO utilized numerous tiny agents, which moved around to find the best answer. Every single agent remembers its own best solution and the best solution from its neighbors. Very optimal parameters were chosen using the mimicking behavior. Two categories of weights were deployed by the objective function. To maintain the equivalent contribution value of every objective term, the first category called contribution weights was accountable. For controlling the significance of every single objective term, the second category named importance weights was utilized. From the Pareto front set that was acquired utilizing the non-dominated PID solution gain parameters, the contribution weights were derived statistically. Phase Margin (PM) and Gain Margin (GM) were the gain parameters utilized for determining the control system's relative stability by minimization. As per the simulation outcomes, when analogized to the baseline objective functions, the performance criterion could greatly enhance the PID tuning optimization. But, the weighting factor's choice in the objective function wasn't a simple task.

Panda et al. [52] suggested the PIDC's design and performance evaluation for an AVR utilizing a freshly simplified PSO named the MOL algorithm. MOL was the shortened form of PSO and was derived by neglecting the particle's best position. Here, the gain parameters were considered as the number of particles and randomly initialized in the search space. Using these initialized parameters, the particles were chosen optimally based on the behavior followed in the PSO. Instead of iterating over the whole swarm, MOL simplified the actual PSO by arbitrarily selecting the particle for updating. Therefore, the particle's most prominent position was removed and it was made simpler for tuning the behavioral parameters. The PIDC's design issue was devised as an optimization issue. Then, for searching the optimal controller parameters, the MOL approach was utilized. This controller's design needs 3 major parameters, namely (i) integral gain, (ii) proportional gain, and (iii) derivative gain. The controller's gains were tuned by minimizing the controller parameters centered on the experience along with plant behavior. For the optimal selection of parameters, 4 different objective functions, namely the IAE, ITAE, ITSE, and ISE were considered. The objective function was calculated grounded on attaining the minimum value of the above-mentioned error values. These objective functions' effects on the system performance regarding maximum OS, ST, RT, and peak time were examined. Diverse analysis techniques like bode analysis, RL analysis, and transient response analysis were executed for the performance investigation. The investigation outcomes exhibited that the MOL-centered PIDC for the AVR executed superior to the other analogous currently stated population-centric OAs. However, dealing with nonlinear systems was difficult.

Shamik Chatterjee and Mukherjee [53] proffered the TLBO approach as an OA in the area of tuning the traditional controller implemented in AVR. It was implemented for finding out the PIDC gain's optimum value with a first-order low-pass filter installed in the AVR. For acquiring the studied model's online dynamic responses, the fast-acting Sugeno fuzzy logic approach was employed for online, off-nominal operating conditions. Moreover, for checking the designed TLBO-centric PIDC's performance, a robustness analysis was done. With the model parameter's variations, an analysis centered on the voltage response profile was examined. Here, the utilized TLBO was a population-centric optimization algorithm that was a meta-heuristic approach. It was centered on the classroom environment concept in which knowledge was passed on from one individual to another. Based on this knowledge-passing behavior, the optimal parameters were one by one selected. Therefore, the gain parameters were considered as the number of students. This controller's 3 parameters, namely derivative gain, proportional gain, and integral gain were regarded to be properly designed. The trial and error technique performed these parameters' tuning centered on the experience of plant behavior and designer. For choosing the parameters, the objective function was computed grounded on attaining the developed system's minimum raising time. By rendering better DRs over a broad range of system parametric variations, the benefit of utilizing this control technique might be well-known. However, huge memory space was needed.

Hany M. Hasanien [54] propounded a PIDC's optimal design in the AVR by utilizing the Taguchi Combined GA (TCGA) technique. TCGA approach was used to optimize the PIDC parameters. A higher stable AVR was acquired by reducing the parameters over the PIDC. For reducing the maximum percentage of OS, ST, RT, and SSE of SG's TV, multi-objective design optimization was established. A multi-objective function of the population was evaluated based on attaining the design variables' accurate optimal values. The search space for the optimization issue was defined by the saturation limit and PID gain. The Taguchi method utilizing analysis of means determined the design variables' approximate optimum values. For selecting the 2 most influential design variables, an analysis of variance was utilized. Subsequently, the approach's efficiency was weighed against the prior GA along with the PSO technique. The AVR system's step response could be enhanced with this TCGA technique. However, the technique had a lower number of experiments.

EmreÇelik and NihatÖztürk [55] suggested a hybrid SOS and SA (hSOS-SA) method into the PIDC's efficient model for AVR. Here, a PIDC's design included the setting of only 3 parameters, namely integral gain, proportional gain, and derivative gain. These were minimized over the controller to get a better AVR function. Initially, for optimizing PIDC parameters utilizing a cost function that regarded time-domain along with frequency-domain specifications, the SOS algorithm was considered. Initially, for optimizing PIDC parameters utilizing a cost function that regarded time-domain along with frequency-domain specifications, the SOS algorithm was considered. Through bode analysis, root locus analysis, along with transient response analysis for the identical AVR, SOS' excellence over a few baseline approaches was confirmed. The hSOS-SA algorithm's superiority was confirmed by extensive numerical outcomes calculated as of the time and frequency response specifications, such that subsequent to a minimum OS, the hSOS-SA tuned AVR system settled to the step reference quickly and followed it with the minimum SSE. However, in the local search area, SOS was not extremely performing well.

Ibrahim Eke et al. [56] suggested a robust AVR control for maintaining a persistent voltage level of SG working under various operating conditions. The controller was designed grounded on the heuristic optimization that regulated the SGs' voltage output toward severe and continuous disturbances by amplifier output as additional feedback. In this work, the Developed Optimization Algorithm (DOA) was used to optimize the controller parameter. The DOA algorithm mimics the Australian dingo dog's social behavior. The algorithm was inspired by the hunting strategies of dingoes, which are attacked by persecution, scavenging behavior, and grouping tactics. Based on this hunting process, the optimal parameters were selected by assuming the gain input parameters as the number of dingoes. The (i) proportional gain, (ii) integral gain, and (iii) derivative gain in this case were the PIDC parameters; they were the design variables of the DOA. To improve the AVR system's stability, these were minimized over the PIDC. The objective function in this constructed DOA was determined by minimizing the error voltage in order to improve stability and speed up response. In result evaluation, the system attains better performance than the other research methods.

Sultan Alghamdiet al. [57] presented an objective function to estimate Double Input Single Output-AVR (DISO-AVR) regulator parameters. Moreover, an approach termed hybrid SA and gorilla troops optimization was wielded for solving the optimization issue. For attaining the best possible response, that is, the generator voltage's desired response while the reference value changed its value from 0 to 1 per unit, the regulators' parameters were projected by reducing the respective objective function. In the experimental evaluation, the presented approach was analyzed with the existing research approaches, and the presented approach attained better performance than the existing research works. The research was not tested for multiple input problems.

AbdelhakimIdir et al. [58] developed a Low-Order Approximation (LOA) of FOPID for an AVR grounded on the altered ABC. The usage of a huge number of parameters was required by the Improved ABC (IABC) High-Order Approximation (HOA)-centric FOPID (IABC/HOA-FOPID) controller that was well-known by a considerable order approximation along with an integer order transfer function. These were reduced to augment the AVR system's stability. Also, the developed optimization model's objective function was evaluated based on reducing the error signal. As per the outcomes and comparisons with the IABC/LOA- FOPIDC along with other prevailing controllers, the IABC/LOA-FOPIDC was superior to the optimal PIDCs found by other approaches in all the above-mentioned tests.

MihailoMicev et al. [59] presented a metaheuristic technique for optimal tuning of 4 various sorts of PIDC for an AVR. The technique was grounded on the manta ray foraging OA that was amalgamated with the SA approach. Also, objective functions for the controller parameters' optimization were designed. The controller was tuned by minimizing the parameters, namely (a) proportional gain, (b) integral gain, and (c) derivative gain. The optimal parameters were obtained based on evaluating the objective function, which was centered on attaining lower steady-state error. By comparing with the controllers tuned by various approaches, the attained real PID, ideal PID, PID with second-order derivative, and FOPID controllers' performance were validated. As per the outcomes, every single sort of controller tuned with the SA-Manta Ray Foraging Optimization (SA–MRFO) approach was superior to the controllers tuned by other approaches.

Mahmoud N. Ali et al. [60] presented a design of strong multi-objective PIDCs through the D-decomposition technique. Here, the damping factor and damping coefficient were the major parameters that were optimized using a developed optimization model and maximized over the PIDC. A Multi-Objective Extremal Optimization (MOEO) was propounded for designing an AVR system's FOPID, where 3 objective functions accounting for IAE, Absolute SSE, and ST were concerned. For pole-clustering in the open LHP, 2 regions were assigned that were defined by fixed damping isoclines. Gain along with phase margins were also considered as frequency domain specifications other than

Table 2 Intelligent controller for AVR

Researchers	Techniques	Description	Drawback
Sajjad Golshannavazet al. [61]	Fuzzy logic and Kharitonov theorem	Regarding the robust as well as intelligent methodologies, an effectual LFC technique was developed	The controllers' performance could be declined by this methodology against sudden and severe disturbances
DaniloPelusiet al. [62]	Genetic-Fuzzy Controllers (GFC)	For enhancing the timing performances, the network trained with the optimum sample was presented into the GFC	It was not ensured that rules were consistent. It was possible to encompass a variance betwixt the rules
Abdullah J. H. Al Gizi [63]	PSO, fuzzy PID (PSOFPID) controller	To gauge the optimal PIDC of generator parameters in the AVR, the PSO accompanied by the Fuzzy Logic Controller (FLC) was utilized	The controlled system's stability was not established
Mahdi Aziziet al. [64]	FLC	By exploiting the hybrid ALO along with the Jaya algorithm, the fuzzy controller's optimum design was developed	Owing to complicated operations like fuzzification along with defuzzification, the computation time was longer
Abdullah J.H. Al Giziet al. [65]	FPIDC	To enhance the system-sensitive response, the rule-centered Sugeno Fuzzy System (SFS) along with FPIDC was employed here	Human experts were required for this system
Anupam Kumar and Vijay Kumar [66]	Interval Type-2 FO-FPID (IT2FO-FPID) controller	Owing to the unit step response together with unit load disturbance, the integration of Takagi–Sugeno-Kang (TSK) type IT2FLC with the fractional controller of PID-type was examined for time response computation	To achieve an effectual performance, choosing a larger number of tuning parameters was a complicated task
Dong Hwa Kim et al.[67]	GA and BF (Bacterial Foraging) GA–BF centered intelligent PIDC	To elucidate the performance as well as performance by mutation, crossover, variation of chemotactic step, variation of step size, along with bacteria's lifetime variation in the hybrid system GA–BF, a variety of test functions was presented	An issue might occur there with local optimization or a suboptimal solution
Elsisi [68]	Neural Network Predictive Controller (NNPC)	The NNPC was centered on the GA, whereas the traditional PIDC was centered on the ZN model	Lower prediction accuracy
Azhar Ali Bhutto et al. [69]	LFC	To ameliorate the power system's transient stability limit, a Probabilistic Neural Network (PNN) was adopted	For storing the model, more memory space was desired
Vassilyevet al. [70]	Fuzzy controllers	The hierarchy levels of intellectual control were monitored; also, a comparative evaluation of various AI devices was provided	Regular update rules of an FLC system
Tripti Gupta, and Sambariya [71]	FLC	FLC-centric AVR was assessed with Triangular Membership Functions (MF)	Higher system error

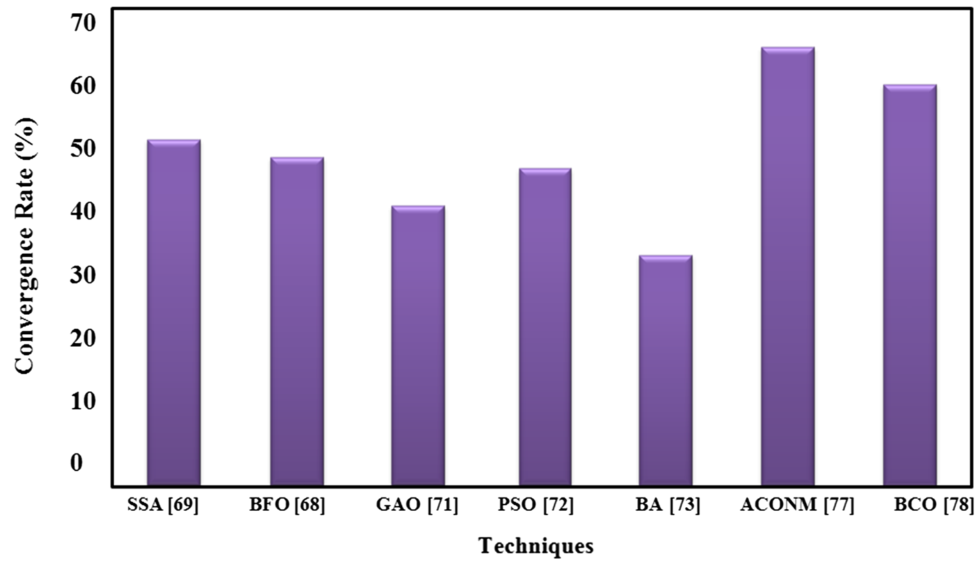

Fig. 2 Convergence rate of FOPID controller

regional pole clustering. By stabilizing a set of principle segment plants concurrently, robust stability and performance were regarded. For validating the model's efficacy in tracing Control Basins (CBs) of all permissible PIDCs, simulation outcomes were given.

2.5 Design and implementation of intelligent controllers

Here, for controlling a power-generating system's voltage and frequency, an IC was propounded. In each generator, the Load Frequency Control (LFC) and AVR are deployed for controlling the real and reactive power flows. The IC utilized for improving the AVR performance is exhibited in Table 2.

For enhancing the AVR's performance, numerous OAs are employed. The standard PIDC is generalized by the FOPID. When analogized to the PIDC, the FOPIDC has more parameters and the parameters tuning is more difficult. Regarding the system's convergence behavior, the OAs' performance is gauged. During steady-state operation, the voltage level is influenced by the AVR quality, which also minimizes the voltage oscillation during the transient periods, hence affecting the system stability. Next, regarding the system stability, IC's performance is gauged. For finding out the finest performance along with the stability of an ACR system, the outcomes are analogized with other optimization approaches. In addition, the outcomes exhibit which controller is better.

The FOPIDC's convergence behavior for AVR is exhibited in Fig. 2. The CR attained by the Salp Swarm Optimization Algorithm (SSA) [72], BF Optimization (BFO) [73], GA Optimization (GAO) [74], PSO [75], and Bat Algorithm (BA) [76] are 50%, 47.6%, 40.5%, 46%, and 33.7%, respectively. Then, the highest CR (63.4%) was attained by ACO and Nelder-Mead (ACONM) [77]. Lastly, 57.6% of CR was gained by the Bee Colony Optimization (BCO) [78].

The IC's system stability is exhibited in Fig. 3. Various methodologies like SFL, Fuzzy logic, SFS, FLC, FRM (Fuzzy Rule Matrix), and TLBO have 65.6%, 44.7%, 43.7%, 63%, 56.2%, and 68.2% of stability, respectively. The gain parameters are tuned to the controller in this literature review of the comparative study. Only percentage adjustments can be made to any of these gain parameters. Consequently, the controller's stability is expressed as a percentage. Additionally, the objective function is utilized for choosing the optimal parameter value based on achieving the ideal peak time, RT, and ST, all of which are expressed as percentages. As a result, the convergence rate is expressed in percentage terms.

2.6 Discussion

Various OAs to augment the AVR performance via tuning the controller parameters are displayed in this survey. The performance analysis utilizing RL and Bode diagram, which were precise presentations to the system, are not considered in most of the research. Additionally, in most of the literature, several fresh OAs like the Whale optimization approach are not utilized. Lastly, in most of the literature, numerous fresh controllers like PIDA controllers aren't utilized. The survey showed that the AVR system performance's stability could be elevated by an IC.

2.7 Discussion

Figure 4 displays the OS analysis of the traditional controller with the advanced controllers. Here, the advanced controllers attain superior performance analogized to the baseline controller. The LOA-FOPID attains a better result than the

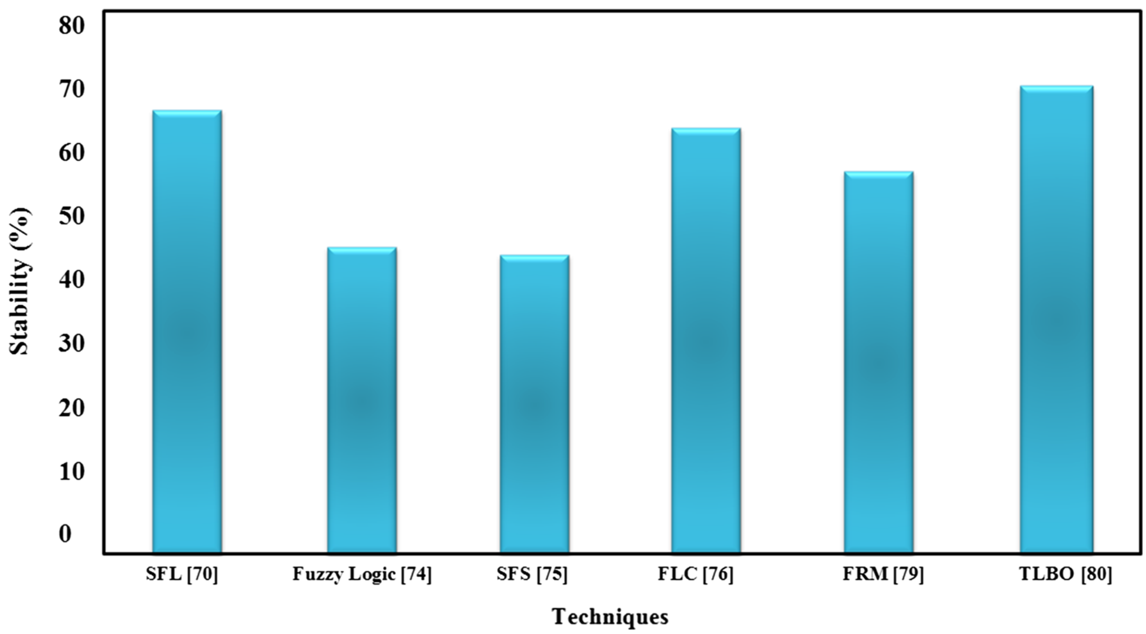

Fig. 3 System stability of the intelligent controller

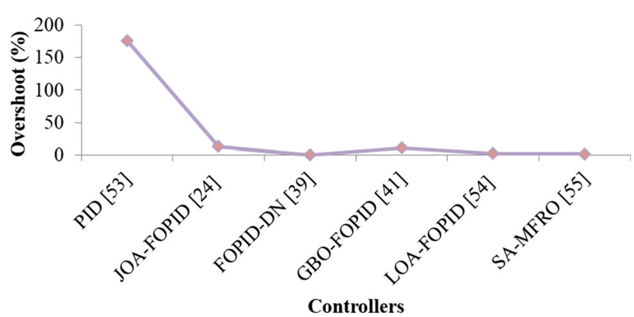

Fig. 4 Overshoot analysis of the traditional controller with the advanced controllers

advanced controllers. Thus, the discussion defines that better tuning of the traditional controller attains superior performance when contrasted with the conventional controllers.

Table 3 Rise time and Settling time analysis of traditional and advanced controllers

Controllers	Rise time (s)	Settling time(s)
PID [57]	0.023681675214101	0.247536364709054
JOA-FOPID [28]	0.0827	0.453
FOPID-DN [43]	0.076	0.144
GBO- FOPID [45]	0.0885	0.653
LOA-FOPID [58]	0.14	0.24
SA—MFRO [59]	0.2540	0.382

2.8 Discussion

Table 3 depicts the RT and ST analysis of the traditional controller with the advanced controllers. Attaining lower RT and ST during the parameter tuning shows better performance. Here, the advanced controllers take lower RT and ST than conventional controllers. The reason behind attaining better performance by the advanced algorithms is the optimal selection of parameters like derivative gain, integral gain, and proportional gain. The optimal parameters are selected using advanced and efficient algorithms. Therefore, the controller is tuned by adjusting these parameters. Here, the advanced PID [57] takes 0.023681675214101 s as RT and 0.247536364709054 s as ST. Likewise, the RT and ST of the FOPID-DN [43] are 0.076 s and 0.144 s, respectively. But, traditional controllers like JOA-FOPID [28], GBO-FOPID [45], and SA-MFRO [59] take higher RT and ST. Thus, the discussion defines that better tuning of the advanced controller attains superior performance when contrasted with the conventional controllers.

3 Conclusion

For regulating the SG's TV, the AVR system is wielded. The AVR system model has a slower response (larger SSE, longer ST, and larger OS). This model exhibits a lower time response (lower damping ratio) and lower-frequency response (higher peak margin, lower delay margin, lower bandwidth, along with lower phase margin). In this survey, several OAs, which enhance the TV DR in the SG's AVR system, are exhibited. By reducing maximum OS, minimizing ST, minimizing RT, and enhancing SSE, OAs are utilized for tuning the controller parameters along with enhancing the response. This survey presents diverse OAs along with the comparison betwixt diverse types of controllers to acquire a superior response for improving the AVR system's performance. It is observed that PID is the most utilized controller in prior studies; however, other controllers like PIDA, FOPID, and Fuzzy logic have superior performance. It is evident that the most utilized optimization is PSO, and as exhibited in the prior sections, modification versions of PSO like APSO, MOL, TLBO, and GAO offer superior outcomes compared to PSO. However, this survey exposed the optimization selection's low speed and accuracy. For overcoming these problems, further research will concentrate on ICs.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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

Consent of publication Not applicable.

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