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Robust control for automatic voltage regulator system based on learning sliding mode control

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Abstract: The purpose of this study is to enhance the transient response of automatic voltage regulator (AVR) by implementing robust control strategies that optimise control parameters in a less complex manner compared to existing algorithms. The study focuses on evaluating the effectiveness of two sliding mode control (SMC) methods, namely conventional sliding mode control (CSMC) and learning sliding mode control (LSMC), and their superiority over the typical PID controller, which is better suited for the linear systems. Given the nonlinear nature of the AVR system due to external disturbances and uncertainty, SMC is deemed more appropriate. The study also utilised the Lyapunov equation to ensure stability and utilised tanh to eliminate the chattering problems and achieve a smoother control law. The findings reveal that LSMC offers improved response speed and reduced overshoot, and its learning aspect enables it to overcome external disturbances and uncertainty, making it more effective than CSMC.

Keywords: learning sliding mode control; LSMC; automatic voltage regulator; AVR; conventional sliding mode control; PID controller; SDO; chattering; MATLAB/Simulink; robust control; nonlinear system.

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Biographical notes: Ali Ahmed Mahal is a Master's student in Electronics and Communication from the University of Kufa. He received his Bachelors in Electrical Engineering in 2016. His research interest includes sliding mode control, automatic voltage regulator system control and control system.

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1 Introduction

Due to load diversity, electrical distribution systems are expanding rapidly. Many power stations linked to the distribution system supply electricity continually. The electricity flow from power stations to the loads must be regulated despite changes in this load. Two critical properties requiring regulation are the operating frequency, which depends on the generator rotor speed, and the operating voltage levels, which vary with load or generator excitation. Power plants employ controllers and measure frequency and voltage at generator terminals to ensure stability. The load-frequency-controller (LFC) is responsible for regulating the frequency, whereas the automatic voltage regulator (AVR) system is tasked with controlling the terminal voltage or reactive power. This study focuses on the problem of voltage regulation within synchronous generators that are commonly utilised in various types of power plants, including gas, thermoelectric, and hydroelectric. Verily, the nonlinearity of the load in real distribution systems doth pose a great challenge for the

AVR, fast and stable regulation is a task of great magnitude. Verily, the strategies for controlling the AVR systems hold great import for ensuring the steadfastness of the electrical power systems (Furat and Cucu, 2022), in the realm of literature, many AVR controllers have been proposed, founded upon the principles of the proportional-integral derivative (PID) controller. The PID controller has gained much renown in the realm of industry, for its simple component and the known impacts of each parameter on system output (Ekinci and Hekimoglu, 2019; Elsisi, 2020a; Modabbernia et al., 2020). The fundamental problem of standard PID tuning methods like trial and error was, the Ziegler-Nichol method, poor results against unknown systems and load disturbance, so several PID controller designs have been given to regulate the AVR system in research (Elsisi, 2020a, 2020b). For the AVR systems, the usual PID controller was presented (Çelik and Durgut, 2018; Elsisi et al., 2021) and many techniques were utilised to determine the best values for the controller's parameters (Gaing, 2004; Hasanien, 2013; Mohanty et al., 2014; Kansit and Assawinchaichote, 2016; Sahib and Ahmed, 2016; Çelik, 2018; Kose, 2020; Sikander and Thakur, 2020). The controller's performance has been evaluated and compared to previous research in the field. One of several types of conventional PID is called PID state feedback is suggested, A robust (2 degree of freedom)-2DOF state-feedback PI-controller is proposed to mitigate the steady state error using PI controller, As noted the 2DOF state-feedback PI-controller was best from the classic 1DOF state-feedback PI-controller, and using dynamic-weight-state-feedback approach to enhance the (2DOF state-feedback) PI-controller (Gozde, 2020; Eke et al., 2021). The fractional order PID controller (FOPID) is another type of PID controller and is more complex because adds an order of integral and order of derivative for the control parameter (Ayas and Sahin, 2021), However different system conditions were taken into account to test the flexibility of the proposed controller, Many controllers for AVR such as feedback controller were suggested, Where the external disturbances and limited system uncertainties, are taken into consideration in the design of this different controllers (Mary et al., 2021). To solve the AVR system's uncertainty used non-fragile PID controller with genetic-algorithm (GA) for tuning (Elsisi, 2021). To eliminate uncertainty and disturbances, different types of controllers have been found in the literature, a fractional-order-model-reference-adaptive-controller (FOMRAC) together with genetic-algorithm (GA) (Aguila-Camacho and Duarte-Mermoud, 2013).

Tuning the controllers' parameters increases with controller complexity. Optimisation methods have become popular to solve this problem. These methods aim to optimise an objective function to improve terminal voltage accuracy. The ideal parameter values are found in a limited search space, usually chosen randomly (Furat and Cucu, 2022). Avoiding complex mathematical derivations allows iterative optimisation to find the ideal value and achieve good response efficiently, and all optimisation method finds the ideal solution better than the others. Therefore, there is no ideal method for all optimisation problems (Elsisi, 2022).

Different objective functions are utilised to ascertain the optimal parameters of a controller, and they encompass specifications in both the time and frequency domains. Prominent performance indices commonly utilised in the field encompass the integral of the squared-error (ISE), integral of the -absolute-error (IAE), integral-time-squared-error (ITSE), and integral-absolute-time-error (IATE). The time domain parameters derived from step response data encompass the following variables: maximum-overshoot (M-O), percentage-overshoot (OS%), steady-state-error, settling-time, and rise-time. Frequency domain parameters commonly used in signal processing and control systems analysis encompass the concepts of phase margin (PM) and gain-margin (GM). In the research, it is common practice to formulate objective functions by amalgamating various indices alongside weighting constants. The utilisation of a singular function to handle all parameters may not yield optimal efficiency, and the process of determining the most suitable weighting constants presents a challenging task (Shayeghi et al., 2015; Jumani et al., 2020; Sikander and Thakur, 2020; Eke et al., 2021).

The variations in the terminal voltage, albeit of minor magnitude, have the potential to result in significant harm to the electrical devices linked to the distribution network. Hence, an assessment has been conducted on the efficacy of the suggested controllers for the AVR in terms of their transient and step response characteristics, and their ability to reject load disturbances (Jumani et al., 2020). The achievement of selecting the controller is contingent upon the selection of an optimisation method that effectively mitigates parameter uncertainties and ensures voltage regulation at the terminals of the generator (Bhullar et al., 2020; Jumani et al., 2020; Modabbernia et al., 2020).

1.1 Discussion of previous studies

Highlights from AVR control literature include proposed controllers, parameter optimisation techniques, and superiority comparisons (Furat and Cucu, 2022). The literature on automatic voltage control and optimisation can be divided into two categories. The primary objective of the first group of Table 1 is to show the superiority of the proposed algorithm by comparison with other algorithms and using a conventional PID controller. The main difference between these studies is the proposed algorithms. The second group uses a controller based on a conventional PID controller with an optimisation algorithm to prove the superiority of this algorithm over others by showing its ability to improve the performance of the AVR system. As indicated in the Table 1. However, no algorithm solves all optimisation issues, although each offers advantages over the others (İzci and Ekinci, 2021). The robustness of the suggested controllers' performance is contingent upon the ability to withstand the controller uncertainties and disturbances (Modabbernia et al., 2020).

1.2 The study motivation

All of the research in Table 1 aims to improve system performance by lowering transient response characteristics such as maximum overshoot percentage (OS%), settling-time, rising-time, peak time, and steady-state error. The controller gains must be optimised to achieve this purpose. However, the absence of recommended algorithms to improve AVR system performance has delayed finding the best controller parameter improvements. These algorithms have drawbacks, including local minimum stagnation, early convergence, complicated control parameter selection, and increasing computation time depending on controller complexity (Ekinci et al., 2019).

A standard PID controller has three parameters that must be tuned, and controller complexity rises, so does the number of parameters gain to be tuned (Ayas and Sahin, 2021). Furthermore, the AVR system's PID controller parameter cannot be optimised with any degree of precision since there is no straightforward technique for doing so (Ekinci and Hekimoglu, 2019), because each algorithm has its superiority over another, as there is no specific algorithm to solve all optimisation problems. Thus, sliding mode control (SMC) solves the AVR control issue. In this work, a new SMC technique is used to create a robust learning sliding mode control (LSMC) controller that can overcome disturbances and achieve the desired system performance and compare this method with CSMC in term solve the chattering problem and obtain smoothing control law and used traditional PID to compare with them methods. And use Simulink design optimisation (SDO) to tune control parameters. The contribution of this work is as follows.

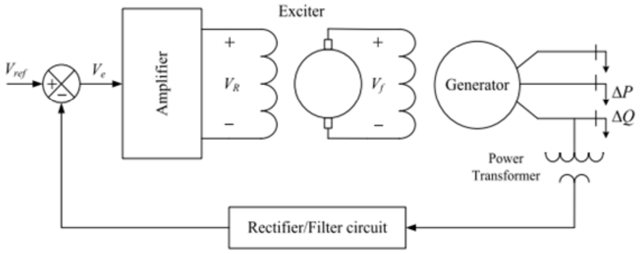
- Design a new control model for the AVR system based on SMC.
- In accordance with IEEE specifications, Moodle is used for the mathematical system.
- The suggested controller has been proved by the Lyapunov function method under uncertainty and disturbances**.**
- For the proposed control the SDO method for tuning all parameter controllers.
- Operational conditions similar to those used in previous research are analysed and compared.

The subsequent sections of the study are organised as follows: The introduction section follows the mathematical model of the parts of the system. Section 3 discusses the control methods used to improve the system. Part analyses the simulation results compares them to other research, and finally discusses all the results and future work in Section 5.

2 AVR system modelling

The output voltage of synchronous generators is often maintained by the AVR to guarantee the consistent and high quality of the electricity sent into the grid. AVR is crucial in ensuring the quality of electricity supplied to the electrical grid. It controls the field current, which in turn controls the rotor's magnetic field intensity. By regulating the field current, the AVR system is able to maintain a consistent voltage level in the electrical network, even in the presence of fluctuations or variations. The basic system architecture of an AVR is in Figure 1. The four essential parts of an AVR system are the amplifier-exciter-generator and sensor (Grainger, 1999).

Figure 1 Simple AVR system



The generation of an error signal occurs via the comparison of the output voltage of synchronous generators, which is measured by a voltage sensor, with a DC reference signal. Subsequently, the error signal is amplified and used to regulate the field windings of the generator by means of an exciter. Below, we see the transfer function of the (AVR) defined by the linearised transfer functions of its constituent parts:

2.1 Amplifier model

The T.F of this part is given as the following (Grainger, 1999):

$$G_{AMP}(s) = \frac{K_A}{1 + \tau_A s} \tag{1}$$

The amplifier gain is indicated by the symbol (K_A), while the time constant is represented by (τ_A), the range of (K_A) is between (10 to 40) and the (τ_A) between (0.02 to 0.1) second.

In this research we set ($K_A = 10$ and $\tau_A = 0.1$ second).

2.2 Exciter model

The T.F of this model is (Grainger, 1999):

$$G_{EXC}(s) = \frac{K_E}{1 + \tau_E s} \tag{2}$$

where the gain of the exciter is denoted by the symbol K_E, the time constant is denoted by (τ_E), and the values of (K_E) between (1 to 10) and τ_E between (0.4 to 0.1second)

In this research, we set ($K_E = 1$ and $\tau_E = 0.4$ second).

2.3 Generator model

Representation for this model by the T.F is (Grainger, 1999):

$$G_{GEN}(s) = \frac{K_G}{1+\tau_G s} \tag{3}$$

The generator gain is indicated by the symbol of (K_G) and the time constant is (τ_G). The range values of K_G between (0.7 to 1) and the range of (τ_G) between (1 to 2 seconds).

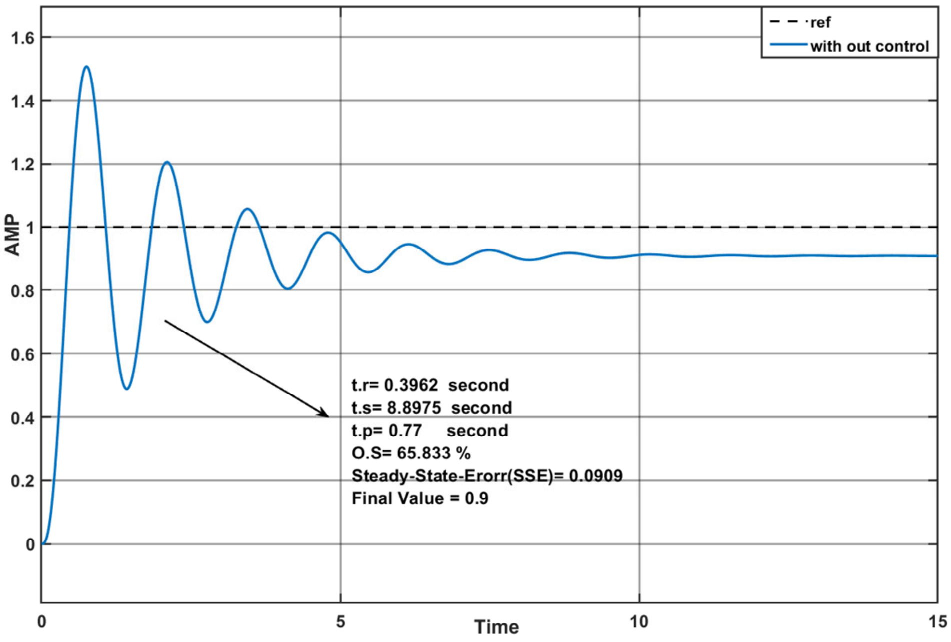
In this research, we set ($K_G = 1$ and $\tau_G = 1$ second).

2.4 Sensor model

The T.F of the sensor model is expressed as follows. (Grainger, 1999):

$$G_{SEN}(s) = \frac{K_R}{1+\tau_R s} \tag{4}$$

Figure 2 AVR system without controller (see online version for colours)



t.r= 0.3962 second
t.s= 8.8975 second
t.p= 0.77 second
O.S= 65.833 %
Steady-State-Erorr(SSE)= 0.0909
Final Value = 0.9

Table 1 Literature study on PID controllers with optimisation techniques, and proposed controller for AVR

	Reference	*Controller used*	*Optimisation*	*Compare with*
1	Çelik and Durgut (2018)	PID	SOS	MOL, ABC, BBO
	Mustapha et al. (2015)	PID	AIA	GA
	Gaing (2004)	PID	PSO	GA
	Hasanien (2013)	PID	TCGA	GA, PSO
	Mohanty et al. (2014)	PID	LUS	PSO, ABC, DEA
	Kansit and Assawinchaichote (2016)	PID	PSOGSA	Z-N, PSO, MOL
	Çelik (2018)	PID	SFS	ABC, LUS, WCO, BBO, MOL
	Zhou et al. (2019)	PID	WWO	BA, CSA, FPA, PSO, SCA
	Kose (2020)	PID	TSA	DEA, PSO, BBO, LUS, ABC, IKA, PSA
	Sikander and Thakur (2020)	PID	CSA	PSO, GA, CAS
	Micev et al. (2021)	PID	EOA	HGA-BF, PSO, ACO-NM
	Elsisi and Soliman (2021)	PID	FSA	ABC, TLBO, MOEO, NSGA
	Sajnekar et al. (2018)	PID	Pole-zero-cancellation	……
	Bhullar et al. (2020)	PID	ECSA	ABC, MOEO, GOA, PSO
	Pachauri (2020)	PID	WCA	ABC, LUS, MOL, TLBO
	Gozde and Taplamacioglu (2011)	PID	ABCA	PSO, DEA

Table 1 Literature study on PID controllers with optimisation techniques, and proposed controller for AVR (continued)

Reference	*Controller used*	*Optimisation*	*Compare with*
2 Eke et al. (2021)	Dynamic-weighted state-feedback approach for2DOF PI-controller	SCA, WOA, MFO, SSA, GWO, WCA, VSA	PSO
Gozde (2020)	2DOF state-feedback-Controller	PSO	Classic 1DOF PI-Controller and 2DOFstate-feedback-PIcontroller-Tune by PSO
Jumani et al. (2020)	Fractional-order-proportional integral-derivative (FOPID)	AI by JOA	PID-GOA, PID-PSO, PID-DE, PID-BBO, PID-PSA, PID-ABC, FOPID-WOA, FOPID-SSA
Ayas and Sahin (2021)	Fractional_Order_Proportional_Integral_derivative with Fractional_Filter (FOPIDFF), (FOPIDF)_controller_with integer_filter, PID controller_with_fractional filter(PIDFF) (PID) with Fractional_Filter(PIDFF)	SCA	PID-GA, PID-CAS, PID-SCA, PID-ABC, PID-BBO, PID-MOEO
Alawad and Rahman (2020)	Fractional-proportional-integral derivative (FPID) controller	IWO	Classica lPID
Shayeghi et al. (2015)	A fuzzy logic-based Controller FuzzyP_FuzzyI_FuzzyD (FP+FI+FD) controller	HGAPSO	Classical PID, Fuzzy PID
Ekinci and Hekimoglu (2019)	PIDfirst-order-filter $G_{PID}(s) = K_P + \frac{K_I}{S} + \frac{K_D s}{T_f S + 1}$	IKA	PID-DE, PID-PSO, PID-BBO, PID-LUS, PID-PSA, PID-GOA, PID-ABC

The gain of the sensor is denoted by the symbol (K_R) and the time constant is indicated by the symbol (τ_R). The range values of (τ_R) between (0.01 to 0.06 seconds).

We set the $K_R = 1$ and $\tau_R = 0.01$ seconds in this research.

Here is a depiction in equation (5) of the linearised transfer function of an (AVR) without a controller.

$$\frac{V_t(s)}{V_{ref}(s)} = \frac{K_A K_E K_G (1+\tau_R s)}{(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)(1+\tau_R s) + K_A K_E K_G K_R} \tag{5}$$

Given the aforementioned, values for the system parameters, the (AVR) output response with no using a controller in Figure 2.

The response of the AVR system in Figure 2 is highly oscillatory, it can be seen that the system response characteristics are nasty. The time it takes the system to achieve a stable state (8.8975 s) and the rising time = 0.3962 seconds, as well as the fluctuation in the response, all these reasons motivate researchers to find appropriate controllers and new ways to improve performance system as mentioned above. In this study, we propose another way to solve these problems and compare with other methods in this field.

3 Control methodology

In this section, we will explore several methodologies for using controllers to enhance system performance, as shown in Figure 3. We use a method SDO to tune parameter controllers. We use MATLAB Simulink software, version R2020a because the practical application of these controllers is complex. In addition, we use IEEE standards because, it is a suitable mathematical model for academic studies ('IEEE Guide for Synchronous Generator Modeling Practices and Parameter Verification with Applications in Power System Stability Analyses', 2020).

3.1 PID controller

PID controllers are popular in process industries due to their simplicity and ability to achieve desired results under various dynamic plant conditions (Wakitani and Yamamoto, 2013). PID controller the n s-domain transfer function represented is given (Cominos and Munro, 2002):

$$\frac{U(s)}{E(s)} = K_P + \frac{K_I}{S} + K_S s \tag{6}$$

where (K_P, K_I, K_D) proportional gain, integral gain and derivative gain respectively (Panda et al., 2012). $U(s)$ is the control signal and $E(s)$ is the error between the terminal output voltage and reference. The block diagram in Figure 4 illustrates the AVR system with an added PID controller.

Figure 3 Block Diagram of AVR system (see online version for colours)

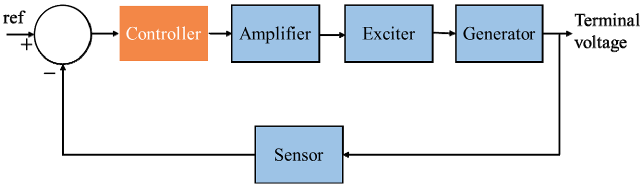
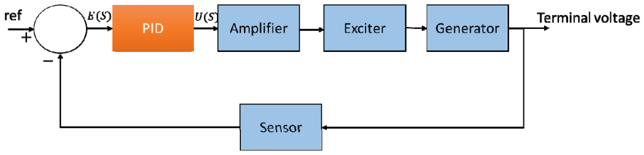
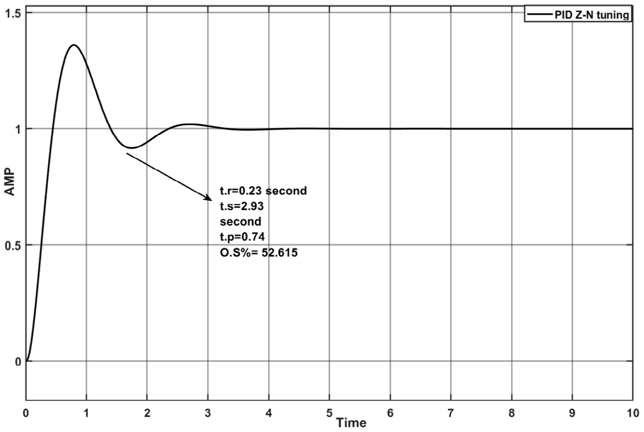


Figure 4 AVR System with PID control scheme (see online version for colours)



Trial and error and classic (Z-N) are used to tune the parameters of the PID controller. Trial and error are ineffective and unreliable because they rely on experience and monitoring the system's response. This is an easy method, but it does not give optimal performance. The classic (Z-N) is shown in Figure 5. This method is better than trial and error, however, it does not meet the system performance requirements because it causes a significant overshoot in response, and it needs to be more robust to deal with various disturbances. Therefore, in this study we proposed to use SDO.

Figure 5 Step response AVR system with (Z-N) tune



3.2 *Optimisation of simulink model parameters*

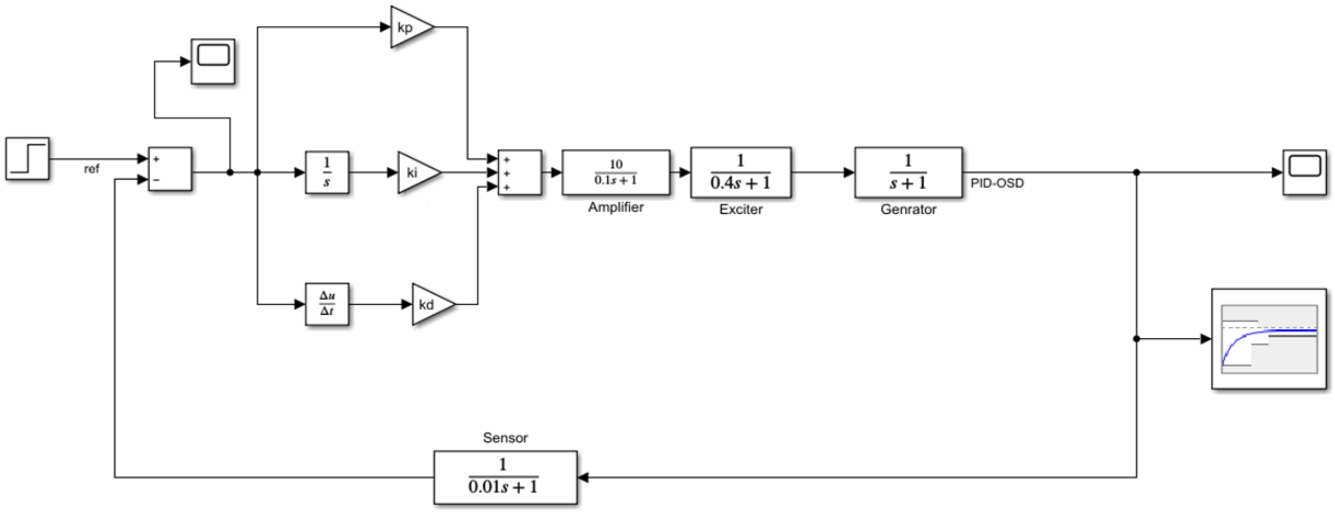
An optimisation approach to determining the optimal values for the control parameters is necessary to enhance the system's responsiveness and performance.

The SDO approach provides researchers with interactive tools that enable the examination and adjustment of parameters clearly and understandably. The toolbox uses them extensively in dynamic control units because it helps improve the system response and parameter estimation for the model.

The following procedures were used to determine the optimum controller parameter:

- Complete the model in MATLAB Simulink, by clicking on the library menu choosing the Simulation design optimisation menu, and then choosing the block (check-step-response-characteristics) and linking it to the model as is seen in Figure 6.
- Open the (check-step response-characteristics) block and start entering the specified time limits for the performance of the system properties. Settling time, rising time, overshoot, undershoot initial value, and final value. Then click (response optimisation). The region will appear under requirements and required properties.
- Through the design variables set, choose new, then define the parameters of the controller, for example (K_P, K_I, K_D), and set bounds for each of them, and then work on adding to the set of design variables to choose the values.
- To improve the response of the model, click on optimise, after the optimisation is finished, we get the optimal variables for the control parameter, to obtain the required performance.
- From Design-Vars it is possible to verify that the optimisation parameters of the controller, are obtained through the simulation interface and to observe the response of the system.

Figure 6 AVR system with check step response characteristics block (see online version for colours)



3.3 Proposed control

We need a robust controller to eliminate external disturbances and unknown uncertainties in any control system, and SMC is one of the best controllers to solve these issues.

There are two distinct categories of SMC: the first is conventional SMC, and the second is high-order SMC.

To find the control input, use the Forward path solution with the system model approximation method in traditional SMC (first-order SMC), and can be used in second-order SMC (Furat and Eker, 2014, 2016). Other types of second-order SMC include super-twisting, drift-twisting, and sub-optimal (Levant, 2007).

An approximate mathematical model fits the SMC-based model, providing robust input control against external disturbances and uncertainties. Whereas SMC is either a based model or a non-based mode, non-based model is used in many practical applications in a limited form (Furat and Cucu, 2022). Another advantage of SMC is its fast, accurate response and reliable stability (Elsisi and Abdelfattah, 2020). All these reasons motivated the researcher to use SMC with the AVR system.

3.3.1 CSMC

The standard procedure to design a conventional SMC of the following steps:

Step 1 Obtain a mathematical model of the system.

Step 2 Sliding surface design and its derivation.

Step 3 Calculate the equivalent control law from deriving the equation of the sliding surface and equalling it to zero.

Step 4 Choose the appropriate switching control law.

Step 5 Summing the equivalent control law and the switching control law to obtain the control input.

Step6 Apply the Lyapunov stability theorem to prove stability.

One of the most important steps in the design of the SMC is the design of the equation of the sliding surfaces

$$S = \sum_{0}^{n-1} K_i e^i \tag{7}$$

where

S sliding surface function

k_i parameter of sliding surface $k_i > 0$

e tracking error is the difference between the reference ($r(t)$) and the output ($v(t)$).

$$e(t) = r(t) - v(t) \tag{8}$$

The control input is equal to the sum of the equivalent control law (U_{equ}) and switching control law (U_{sw}):

$$U_{control} = U_{equ} + U_{sw} \tag{9}$$

The system is kept on the sliding surface by the switching control law (U_{sw}), which also addresses the transient response performance and ability to reject external disturbances.

The equivalent law (U_{equ}) drives the system to the equation of the sliding surface, and deals with the performance of the steady state.

The transfer function of the forward path of the AVR system is given as the following:

$$G_{AVR\ Forward\ Path}(S) = G_{AMP}(S) G_{EXC}(S) G_{GEN}(S)$$

$$G_{AVR\ Foword\ Path} = \frac{V(S)}{U(S)} = \frac{K_A K_E K_G}{(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)} \tag{10}$$

When designing a controller for the AVR model, the external disturbances and uncertainties must be taken into account, Therefore, the components of the AVR system, together with the system's additional uncertainties and disturbances, may be described as follows:

$$\begin{aligned} S^3 V(S) = &-\left[(A \pm \hat{a}) S^2 + (B \pm \hat{b}) S + (C \pm \hat{c})\right] V(s) \\ &+ bU(s) + D(s) V(S) \end{aligned} \tag{11}$$

where A = 13.5, B = 37.5, C = 25, b = 250, $D(s)$ is the external disturbances and $(\hat{a}, \hat{b}, \hat{c})$ is the uncertainties parameters.

$$\begin{aligned} S^3 V(S) = &-AS^2 V(S) - BSV(S) - CV(S) + bU(s) \\ &+ \hat{D}(s) V(S) \end{aligned} \tag{12}$$

The external disturbances and the uncertainties parameters can be summed in $\hat{D}(s)$.

where

$$\left|\hat{D}(s)\right| < \hat{D}_{\max}, \hat{D}_{\max} \in R^+$$

and

$$\begin{aligned} S^3 V(S) = &-AS^2 V(S) - BSV(S) - CV(s) + bU(s) \\ &+ \hat{D}(s) V(S) \end{aligned}$$

The model of AVR in equation (11) is represented in the time domain and $\hat{D}(s) = 0$, as the following:

$$\dddot{v}_g(t) = -A\ddot{v}_g(t) - B\dot{v}_g(t) - C\,v_g(t) + bu(t) \tag{13}$$

Design the sliding surface equation according to equation (7),

$$S = K_0 e(t) + K_1 \dot{e}(t) + K_2 \ddot{e}(t) \tag{14}$$

We take the first derivative of the equation for the sliding surface, and equal it to zero to calculate the equivalent control law (U_{equ}).

$$\dot{S} = K_0 \dot{e}(t) + K_1 \ddot{e}(t) + K_2 \dddot{e}(t) \tag{15}$$

where the tracking error is $e = r - v \rightarrow \dddot{e} = \dddot{r} - \dddot{v}$, substituting an equation (14).

$$\dot{S} = K_0\dot{e}(t) + K_1\ddot{e}(t) + K_2\left(\dddot{r} - \dddot{v}\right) \tag{16}$$

Now substitute equation (13) into equation (16) and make $\dot{S} = 0$ to get the equivalent control law:

$$\dot{S} = K_0\dot{e}(t) + K_1\ddot{e}(t) + K_2\left(\dddot{r} - \begin{bmatrix} -A\ddot{v}_g(t) - B\dot{v}_g(t) \\ -Cv_g(t) + bu(t) \end{bmatrix}\right) \tag{17}$$

$$U_{equ} = \frac{1}{bK_2}\left[K_0\,\dot{e}(t) + K_1\,\ddot{e}(t) + K_2\begin{pmatrix} \dddot{r} + A\ddot{v}(t) \\ +B\dot{v}(t) + Cv(t) \end{pmatrix}\right] \tag{18}$$

The equivalent control law with adding the output disturbances and uncertainties as the following:

$$\tilde{U}_{equ} = U_{equ} - \frac{1}{b}\hat{d}(t)v(t) \tag{19}$$

The control input becomes

$$U_{control} = \tilde{U}_{equ} + U_{sw} \tag{20}$$

Now substitute equation (20) into equation (17) to derive the ideal sliding mode as the following:

$$\dot{S} = K_0\dot{e}(t) + K_1\ddot{e}(t) + K_2\left(\dddot{r} - \begin{bmatrix} -A\ddot{v}_g(t) - B\dot{v}_g(t) \\ -Cv_g(t) + b\left(\tilde{U}_{equ} + U_{sw}\right) \end{bmatrix}\right)$$

Substitute for $\tilde{U}_{equ}$, and simplify the equation

$$\dot{S} = -bK_2U_{sw} + K_2\hat{d}(t)v(t) \tag{21}$$

3.3.2 *Chattering phenomenon*

The problem with the Conventional SMC is that the oscillation phenomenon occurs at a high frequency in the control input (Camacho and Smith, 2000; Thakar et al., 2013). It is due to the *sgn*(*S*) function in the switching control law part of the control input, and this phenomenon occurs around the balance point. It is called the phenomenon of chattering. If the control input contains chattering, SMC is useless in applying an AVR system. To eliminate this phenomenon, the researchers suggest that the control input is to be smooth to avoid the control unit from high frequency, such as using saturation function instead of *sgn*(*S*) or use (*tanh*) function (Eker, 2012). In addition, the use of super twisting and sub-optimal (Levant, 2007), *tanh*-based super-twisting was also offered as a means to provide a smooth control input and thereby decrease chatter (Rehman et al., 2020).

That's why (*tanh*) is a popular choice when it comes to smoothing the SMC's control input. In this study, we use the (*tanh*) function to reduce the phenomenon of chattering and to obtain a smooth switching control rather than the *sgn*(*S*) function, as follows:

$$U_{sw} = K_{sw}\tanh\left(K_{sf}S\right) \tag{22}$$

where K_{sw} is the gain Switching, K_{sf} is the constant of the smoothing Its value ranges $0 < K_{sf} < 1$.

In the end, we get the control input in equation (19) as the following:

$$U_{control} = \frac{1}{b\,K_2}\begin{bmatrix} K_0\,\dot{e}(t) + K_1\,\ddot{e}(t) \\ +K_2\left(\dddot{r} + A\ddot{v}(t) + B\,\dot{v}(t) + Cv(t)\right) \end{bmatrix} - \frac{1}{b}\hat{d}v(t) + K_{sw}\tanh\left(K_{sf}S\right) \tag{23}$$

3.3.3 *LSMC proposed method*

The concept of SMC has been extensively studied and effectively used in complex systems that face unpredictable external disturbance. However, obtaining a comprehensive understanding of non-model dynamics is not always feasible, making the conventional SMC design unsuitable. Even with large specified uncertainty bounds, the control input gain can exceed the operator's capabilities, and conventional SMC can lead to chattering disadvantages.

Over the years, SMC researchers have been developing new SMC technology that guarantees zero error in steady-state error and free chattering phenomenon systems (Do, 2014). A sliding mode controller with an intelligent recursive learning mechanism was built and first published by Man et al. (2011).

The objective of this segment is to create a robust LSMC controller that can overcome disturbances and achieve the desired system performance. In this study, we propose the learning sliding mode in the following manner (Man et al., 2011):

$$\tilde{U}_{control}(t) = U_{control}(t-\tau) - U_{control}(t) \tag{24}$$

where $\tilde{U}_{control}(t)$ control input τ is the time delay where always $\tau < t$, $U_{control}(t - \tau)$ is the previous sample of the control signal, and $U_{control}(t)$ is the current control signal and learning term.

The control signal $\tilde{U}_{control}(t)$ consists of the previous control signal $U_{control}(t - \tau)$ and the current control signal $U_{control}(t)$ is considered a correction term or a learning term. The control signal is updated through Lyapunov's theory and for the stability of the system. If the system is stable, the control unit adjusts the control signal continuously so that the system can be moved to the sliding surface function at a specific time and remain at it with convergence to zero. But if the system is unstable, the control unit adjusts the control signal and moves the system to the stability area continuously because the control signal has previous knowledge of the current control signal and thus is able to eliminate external disturbances and uncertainty, and this makes the control signal free of chattering, in addition to The derivative of the Lyapunov function from positive to negative pushes the system to the sliding surface with convergence to a zero line, and this ensures the stability of the system.

The use of Lyapunov stability analysis is prevalent in the demonstration of stability in nonlinear systems (Slotine and Li, 1991), applying the Lyapunov function to guarantee the stability of the system as follows:

$$V(t) = \frac{1}{2} S^2 \tag{25}$$

First derivative for equation (25) and substitute equation (21):

$$\begin{aligned} \dot{V}(t) &= S\dot{S} \\ \dot{V}(t) &= S\left[-bK_2 U_{sw} + K_2 \hat{d}(t) v(t)\right] \\ \dot{V}(t) &= -S\, bK_2 U_{sw} + S\, K_2 \hat{d}(t) v(t) \end{aligned} \tag{26}$$

Now select the switching control law (U_{sw}) and substitute in equation (26)

$$\begin{aligned} U_{sw} &= K_{sw}\,\text{sgn}(S) = K_{sw}\frac{|S|}{S} \\ \dot{V}(t) &= -S\, b\, K_2\, K_{sw}\,\text{sgn}(S) + S\, K_2\, \hat{d}\,(t) v(t) \\ \dot{V}(t) &= -S\, b\, K_2\, K_{sw}\frac{|S|}{S} + S\, K_2\, \hat{d}\,(t) v(t) \\ \dot{V}(t) &\le -b\, K_2\, K_{sw}\,|S| + |S|\, K_2\, \hat{d}\,(t) v(t) \\ \dot{V}(t) &= -|S|\left[b\, K_2\, K_{sw} - K_2\, \hat{d}\,(t) v(t)\right] \\ \dot{V}(t) &= -|S|\, K_2\left[b\, K_2\, K_{sw} - \hat{d}\,(t) v(t)\right] \\ \dot{V}(t)\Big|_{ksw > \frac{\hat{D}_{\max}}{b}} &< 0 \end{aligned} \tag{27}$$

When selected gain switching $K_{sw} > \dfrac{\hat{D}_{\max}}{b}$, then the control is stable.

The LSMC method involves creating a control signal and a learning term to adjust the stability of the closed-loop system. The learning term control signal is responsible for ensuring the system remains stable based on its latest stability state. If the closed-loop system becomes unstable, the control signal can be corrected. As shown in Figure 7.

4 Simulation results

The results were implemented using SIMULINK/MATLAB version R2020a on a computer with Core i7 and 8GB RAM. The most notable results from each of the tables are shown in bold. In the following, we present the most important results of the study in the subsections.

4.1 Transnet response analysis

In this section, we discuss three different types of controllers to improve the performance of automatic voltage regulators (AVR) as well as the use of the SDO method to tune controller parameters. We notice that the system's response improves when adding a control unit in the forward path of the system, as shown in Figure 3. We can observe the response of the AVR system when the PID control unit is added, compared to the system's response without the control unit. The addition of poles and zeros in the loop of the AVR system through the PID control unit as described in equation (6) improves the system's transient response characteristics, reducing overshoot, and increasing stability through derivative gain. The integral gain reduces steady state error (SSE), while the proportional gain increases the response speed of the system as show in Figure 9. It should be noted that the optimal values of the controller parameters were obtained using the SDO method, as shown in Table 2.

Figure 7 AVR system with LSMC (see online version for colours)

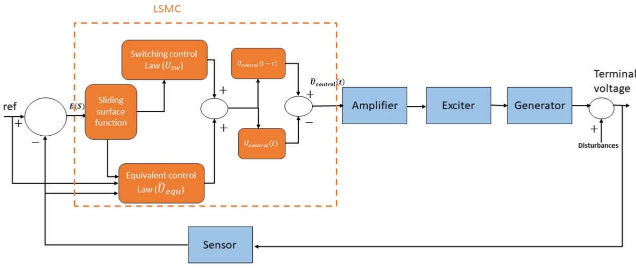


Table 2 The values of the control parameters using the SDO method

Controller	*Parameters*
PID-SDO	$K_P = 1.0104$, $K_I = 0.2789$, $K_D = 0.2358$
CSMC-SDO	$K_0 = 0.250$, $K_1 = 0.425$, $K_2 = 0.165$, $K_{sf} = 0.003$, $K_{sw} = 0.0001$
LSMC-SDO	$K_0 = 1.450$, $K_1 = 2.360$, $K_2 = 1.800$, $K_{sf} = 0.005$, $K_{sw} = 0.001$

Table 3 Performance comparison of controllers for AVR system

Controller	*O.S%*	*t.r*	*t.s*	*t.p*	*SSE*
With out controller	65.833	0.3962	8.8975	0.77	0.0909
PID-SDO	8.39	0.2783	1.48	0.82	0
CSMC-SDO	0.540	0.2511	0.80	0.45	0
LSMC-SDO	*0.505*	*0.1459*	*0.65*	*0.43*	*0*

External disturbances, uncertainty, and sudden load increases, all of these reasons make the AVR system a nonlinear system, so a controller other than the PID must be used, which is suitable for linear systems. In this study, two SMC structures were used that were proposed to improve the AVR system: (CSMC) and another approach (LSMC). Using the SDO method to tune five control parameters. The optimal control unit parameters are shown in Table 2. Figure 8 shows the system response using the conventional SMC approach, showing the significant improvement in the dynamic response of the system. Figure 9 shows a comparison of the response between traditional PID, conventional sliding mode control and the LSMC. The CSMC controller improved the system performance by taking into account external disturbances and uncertainty and generating switching controls with a slight improvement in the chattering phenomenon as shown by the Zoomed spots in Figure 8, a problem known in CSMC despite using tanh to solve this problem is as in equation (22). LSMC showed high performance efficiency and was better than using (CSMC), as it created switching control without chattering due to the use of tanh and produced smoothing switching control, as in the Zoomed spots in Figure 9, as it is responsible for the transient state of the system, while the equivalent control law drives the system to a stable state and converges to zero in the end. The presence of the learning part in the LSMC makes it have prior knowledge and thus is effective against uncertainty and external disturbances, which makes it superior to the CSMC. The stability of the controllers was ensured by Lyapunov stability theorem as equation (27). In Table 3 we notice the superiority of the proposed controller over the other controllers.

4.2 Comparison performance response with different control optimisation

In this work, we use the suggested technique to examine the responsiveness of the AVR. Moreover, the proposed approach has been compared with several methods in the literature. The comparison focuses on exploring results using different optimisation methods.

Figure 8 The AVR response with CSMC (see online version for colours)

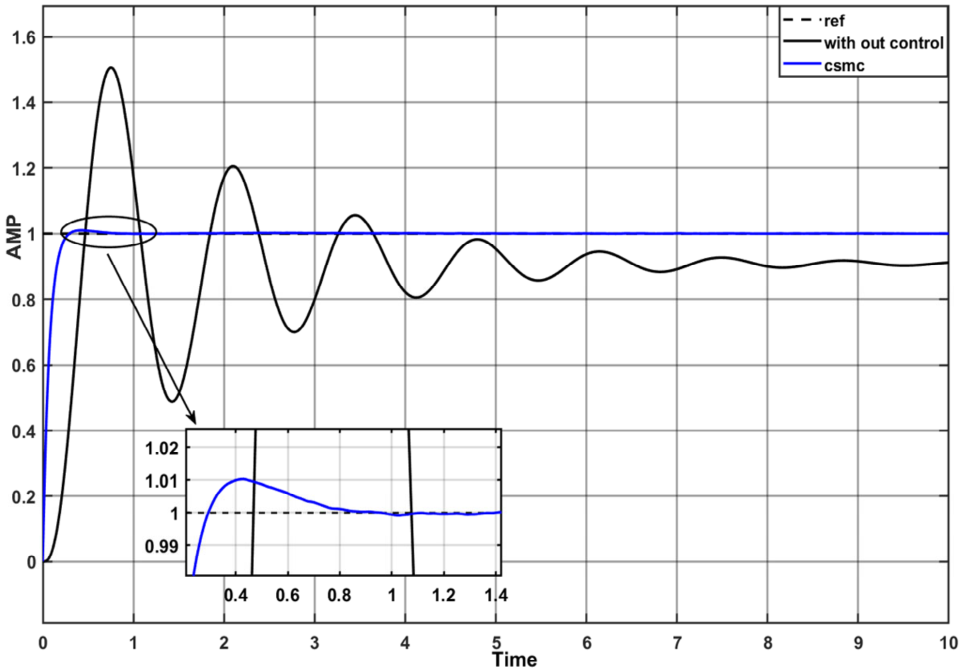


Figure 9 AVR system response with deferent controllers (see online version for colours)

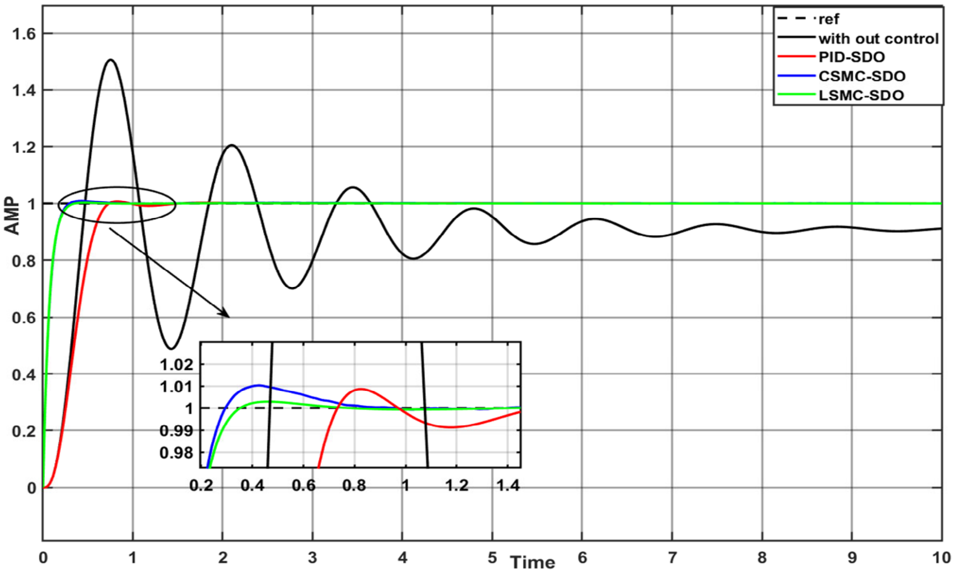


Table 4 Analysis of AVR system response performance for various controllers' methods

Reference	*Controller type-optimisation*	*O.S %*	*t.r sec*	*t.s sec*	*t.p sec*
Çelik and Durgut (2018)	PID-SOS	1.013	0.353	0.485	0.7
Sikander and Thakur (2020)	PID-CSA	5.4725	0.3370	2.145	-
Kose (2020)	PID-TSA	15.57	0.131	0.758	0.278
Ekinci and Hekimoglu (2019)	PID-IKA	15.00	0.128	0.753	0.269
Kansit and Assawinchaichote (2016)	PID-PSOGSA	-	0.431	0.691	-
Zhou et al. (2019)	PID-WWO	1.120	0.19	0.9	-
Micev et al. (2021)	PID-EQA	1.98	0.3733	0.2502	NA
İzci and Ekinci (2021)	PID-SMA	0.6071	0.3149	0.4817	0.6019
Mosaad et al. (2019)	PID-WOA	1.07	0.26	0.555	-
Hekimoğlu (2019)	PID-SCA	1.114	0.148	0.724	0.304
Gozde (2020)	2DOFstate-feedback-PIcontroller-PSO	2.224	0.690	3.442	2.279
Eke et al. (2021)	2DOF PI-dynamic-weighted state-feedback-WCA	1.7663	-	2.6614	-
Sharma et al. (2021)	PID based SMC-HHO	4.3	-	1.45	-
Furat and Cucu (2022)	CSMC-PSO	0.1	0.2969	0.8726	-
Proposed	*LSMC-SDO*	*0.505*	*0.1459*	*0.65*	*0.43*

Under the different control strategies to assess how well the AVR is functioning, we analyse the system response characteristics considering the uncertainties and external disturbances, as this proposed method aims to enhance the stability and response time of the system to achieve the optimal voltage regulation. Table 4 presents the performance of the AVR response under various strategies and different controls, highlighting the advantages and limitations of each approach and the effects of different optimisation methods.

Consequently, the suggested methodology for the AVR system demonstrates reduced oscillation, enhanced response, improved stability, and the capability to effectively counteract uncertainties and external disturbances.

5 Conclusions

The goal of this research was to enhance the functionality of the AVR, where control units were used and compared between PID, CSMC, LSMC, and SDO to tune the control parameters. The ultimate goal was to achieve stability and voltage regulation, and strength against uncertainty, and effective rejection of external disturbances through robust control.

The literature focuses on the use of PID controller or the use of a controller based on PID with different optimisation methods and a comparison between them. The control approach (CSMC) was shown as an effective strategy to improve the functionality of AVR. Furthermore, PID control is considered a suitable controller if the system is linear, as nonlinearity is a significant challenge for the AVR system. SMC is an effective way to achieve stability and in nonlinear systems. In addition to that, another challenge in SMC, which is the phenomenon of chattering, is well known in SMC as part of the switching control law and (*tanh*) has been used to reduce this phenomenon significantly and obtain a smooth control law. Another control approach derived from SMC is LSMC, which considers effective, promising, and robust strategies for improving the AVR system, considering external disturbances and uncertainty. The results of LSMC showed voltage regulation and stability, which indicates its ability to maintain voltage regulation by taking into account uncertainties and variable external disturbances, and this is what makes LSMC a convincing choice to ensure voltage regulation and a reliable and stable power supply. In our upcoming work, we will focus on applying the practical aspect of improving the AVR system, proving the effectiveness of LSMC in reality, and examining the possibility of using LSMC with artificial intelligence algorithms to obtain another hybrid controller for the AVR system capable of dealing with more complex conditions.

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Nomenclature

AVR	Automatic voltage regulator
PID	Proportional-integral-derivative
PSO	Particle swarm optimisation
ACO-NM	Ant colony optimisation and Nelder mead
Z-N	Ziegler-Nichols
HGA-BF	Hybrid genetic algorithm and bacterial foraging
ABC	Artificial bee colony algorithm
TLBO	Teaching-learning based optimisation
MOEO	Multi-objective external optimisation
NSGA	Non-dominated genetic algorithm
FPA	Flower pollination algorithm
WOA	Whale optimisation algorithm
BBO	Biogeography based optimisation
PSA	Pattern search algorithm
WCO	World cup optimisation
DEA	Differential evolution algorithm
DE	Differential evolution
LUS	Local unimodal sampling
SSA	Salp search algorithm

Nomenclature (continued)

GA	Genetic algorithm
HHO	Harris hawks optimisation
CSA	Crow search algorithm
CAS	Chaotic ant swarm optimisation
GOA	Grasshopper optimisation algorithm
SCA	Sine cosine algorithm
TSA	Tree seed algorithm
BA	Bat algorithm
IKA	Improved kidney-inspired algorithm
MOL	Many optimising Liaisons
FOPID	Fractional_order_Proportional-Integral derivative
T. F	Transfer function
t. r	Rising time
t. s	Settling time
O. S	Overshoot
SSE	Steady state error
K_P	Proportional gain
K_I	Integral gain
K_D	Derivative gain
T.p	Peak time
CSMC	Conventional sliding mode control
LSMC	Learning sliding mode control
PIDC	PID controller
SOS	Symbiotic organisms search
TCGA	Taguchi combined genetic algorithm
PSOGSA	Particle-Swarm-Optimisation-Gravitational-SearchAlgorithm
SFS	Stochastic-fractal-search
WWO	Water wave optimisation-algorithm
EOA	Equilibrium-optimiser algorithm
FSA	Future-search-algorithm
ECSA	Enhanced crow search algorithm
WCA	Water-cycle-algorithm
ABCA	Artificial bee colony algorithm
JOA	Jaya-optimisation algorithm
AIA	Intelligence of an artificial intelligence
IWO	Invasive-weed optimisation
GWO	Gray Wolf algorithm
VSA	Vortex search algorithm
HGAPSO	Hybrid of Genetic Algorithm and Particle_Swarm_ Optimisation
MFO	Moth-flame algorithm
AI	Artificial intelligence