

Article

Participation of Renewable Energy Sources in the Frequency Regulation Issues of a Five-Area Hybrid Power System Utilizing a Sine Cosine-Adopted African Vulture Optimization Algorithm

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Abstract: In this article, a novel methodology is proposed by utilizing a technique which, in light of the change in the African vulture optimization known as Sine Cosine, adopted an African vulture optimization algorithm (SCaAVOA)-based tilt integral derivative (TID) regulator for the load frequency control (LFC) of a five-area power system with multi-type generations. At first, the execution of the Sine Cosine-adopted calculation is tried by contrasting it with the standard AVOA calculation while considering different standard benchmark functions. To demonstrate the superiority of the proposed SCaAVOA algorithm, the results are contrasted using different standard approaches. In the next stage, the proposed method is used in a five-area thermal power system and is likewise applied to a five-area, ten-unit system comprising different conventional sources as well as some renewable energy sources. The performance analysis of the planned regulator is completed for various system boundaries and loading conditions. It is seen that the said regulator is more viable in comparison to the other standard controllers.

Keywords: automatic generation control (AGC); five-area hybrid power system with multi-type generations; load frequency control (LFC); renewable energy sources; Sine Cosine-adopted African vultures optimization algorithm (SCaAVOA); tilt-integral-derivative (TID) controller



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1. Introduction

The standard undertaking of LFC is to affirm the frequency variation inside a theorized reach that is past what many would consider conceivable [1]. A fundamental issue related to LFC is how to maintain the system frequency within a certain limit [2]. The frequency regulation of a two-region interconnected power system is the focal point of research on LFC. Not many of these studies have assessed conventional energy and, incredibly, fewer have considered the effect of distributed energy sources on the LFC plan [3–5]. A three-area system is utilized to check the expansion of a two-area system [6], and a five-area power system is used to verify the extension of a three-area power system [7,8]. The application of different renewable energy sources in the AGC application is also explained in [9–11]. In any case, no exploration has considered the effect of coordinating different environmentally friendly renewable energy sources in a five-region power system. Therefore, in this work, a five-region power framework with various distributed energy sources, such as wind generators, solar generators, plug-in electric vehicles, and other sources including fuel cells,

microturbines, and diesel engine generators, are taken into consideration in different areas of the system.

It is obvious from the literature that the Proportional-Integral (PI) regulators are generally utilized in AGC because of their basic executive strategy, while simultaneously giving satisfactory system responses. In any case, the presentation of a basic PI regulator decays as far as the overshoots and the settling time of the system response [12]. The PID regulator is an exceptionally famous construction because of its simple execution. However, it is not efficient to control a non-linear system that leads to unbounded responses [13]. Therefore, researchers have focused on the improvement of the PID controller such that the stability region and the application can be extended to highly nonlinear, dynamic, and complex systems [14–16]. In the TID regulator, the comparable part to the PID regulator is displaced with a shifted part having a transfer function s^{-1}/n , thus achieving an upgraded feedback controller [17]. This paper uses a TID regulator associated with the frequency control issue of the five-region power system. In the proposed TID regulator, the comparable part to the PID regulator is displaced with a shifted part having a transfer function s^{-1}/n , thus achieving an upgraded feedback controller.

Involving an evolutionary algorithm as an answer for the LFC issue is one choice (EA). The essential objective of involving an EA is to have the option of overseeing non-linear capabilities [18]. EA applications incorporate the genetic algorithm [19], artificial bee colony algorithm [20], particle swarm optimization [21], butterfly optimization algorithm [22], biogeography-based optimization [23], satin bowerbird algorithm [24], grasshopper optimization algorithm [25], gravitational search algorithm [26], coyote optimization algorithm [27], whale optimization algorithm (WOA) [28], novel COVID-19-based optimization [29], equilibrium optimization [30], etc.

Although these strategies give a strong execution and deal with a reasonable LFC structure, their convergence rate is very sluggish and they are oftentimes caught in local optima. In recent years, another calculation known as the African vulture optimization algorithm (AVOA) has grown in prevalence and has been comprehensively used in various optimization issues. The AVOA is inspired by the foraging and navigational behaviours of African vultures and aids in improvement measures through an optimization procedure [31]. Although the said calculation has been, by and large, used, it has a couple of limitations. The most concerning issue related to the AVOA is that it effectively falls into local optimum [32]. In light of the previously mentioned issue, this paper proposes a clever methodology by bringing some scaling factors into the first AVOA calculation, known as the sine cosine-adopted AVOA algorithm, for the LFC of five-area hybrid multi-type generations.

2. Research Gap, Inspiration, and Paper Organization

2.1. Research Gap, Inspiration, and Paper Organization

The principal perceptions acquired from a review of the above studies are as follows:

- Almost no exploration has considered the effect of coordinating different renewable power sources into an AGC.
- Again, the significance of different important disturbances, such as solar irradiation, wind power change, and load change, on an AGC system has not been examined in previous studies.
- To the best of the authors' knowledge, an execution of a tilt-integral-derivative control in an AGC five-area renewable energy integrated hybrid power system for LFC applications is missing.

2.2. Inspiration and Paper Organization

Under typical operating conditions, the governor, which is in primary control, may attenuate small frequency deviations, while the LFC, which is in charge of the secondary control, is in charge of big frequency deviations. Control techniques, such as optimization, and intelligent controllers, such as fuzzy, have been applied in power system control to improve the function and performance of a system during normal and abnormal conditions.

The HVDC components and their placement in the power system can also improve the operation of the AGC. The key contributions of this study are as follows:

- The SCAVOA algorithm's advantages over a few alternative tactics are analyzed in terms of execution time and objective function.
- A five-area power system's response to the coordination of various distributed energy sources is examined.
- For the aforementioned hybrid five-area system, a TID controller is set up using the newly introduced SCAVOA computation, and by differentiating it from some other existing regulators/controllers, it is shown to provide a better frequency regulation.

3. Proposed System under Study

Figure 1 shows a one-area interconnected thermal power system. The single-line diagram of an interconnected five-area hybrid power system comprising some conventional, non-conventional, and other distributed generation (DG) sources is shown in Figure 2. Table 1 shows the gains (K) and time constant (T) of the system parameters for the above-mentioned five-area system.

Table 1. Parameters used for the simulation of the power plant model under study.

Components	Gain (K)	Time Constant (T)
Wind turbine Generator (WTG)	$K_{WTG} = 1$	$T_{WTG} = 1.5$
Hydro-Aqua Electrolyzer (AE)	$K_{HAE} = 0.002$	$T_{HAE} = 0.5$
Fuel Cell (FC)	$K_{FC} = 0.01$	$T_{FC} = 4$
Battery Energy Storage System (BESS)	$K_{BESS} = -0.01$	$T_{BESS} = -0.1$
Diesel Energy Storage System (DEG)	$K_{DEG} = 0.003$	$T_{DEG} = 2$
Micro-Turbine	$K_{MTG} = 1$	$T_{MTG} = 1.5$
Thermal Power System	$T_g = 0.08, T_t = 0.3, T_{12} = 0.0866, B = 0.425,$ $K_r = 0.5, T_r = 10.0$	
Damping Coefficient	$D = 0.03$	
Inertia Constant	$M = 0.4$	

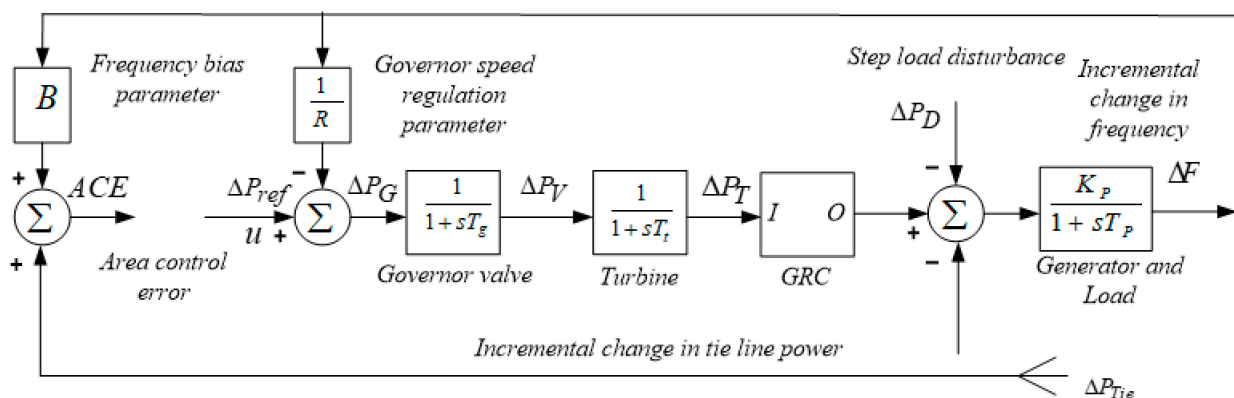


Figure 1. One area of an interconnected power system.

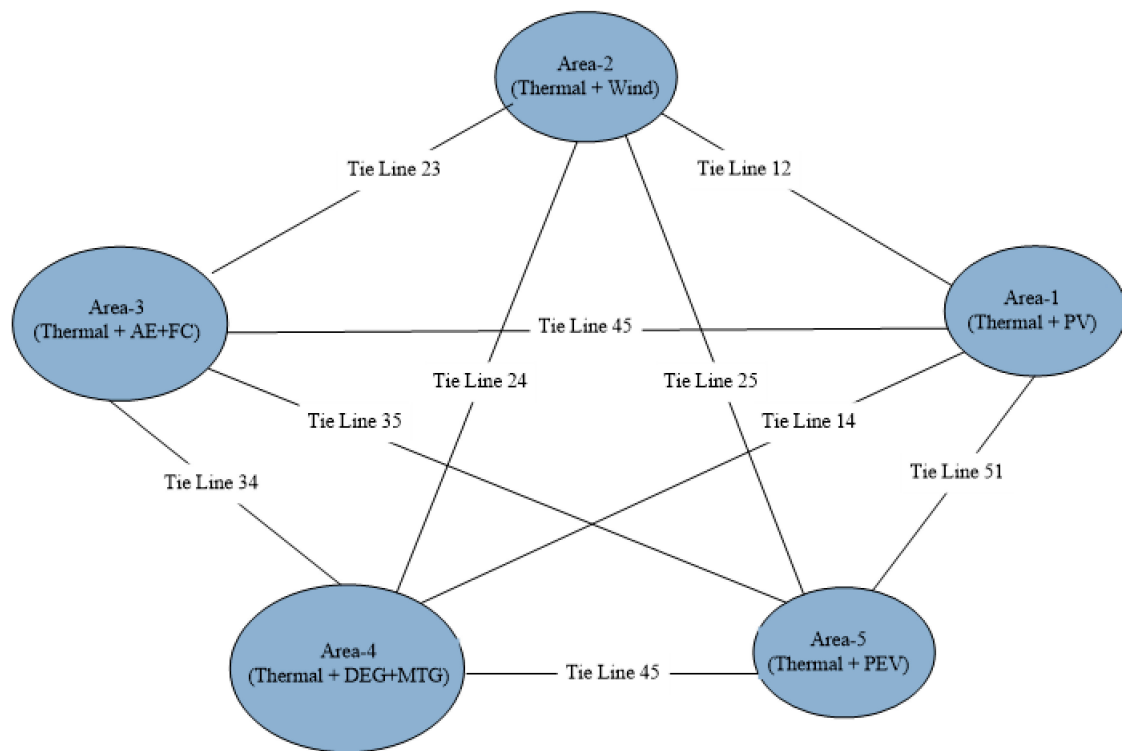


Figure 2. Proposed structure of a five-area hybrid power system.

3.1. Power System Component Modelling

3.1.1. Photovoltaic (PV) System

The basic components of a PV system are the PV module, the MPPT tracker, the converter, and the filter circuit, which can be represented as follows [12]:

$$G_{PV}(s) = \frac{K_{PV}}{1 + sT_{PV}} \quad (1)$$

3.1.2. WTG System

The wind turbine system is a non-linear system [33], and it can be addressed in low-frequency oscillation as follows:

$$G_{WTG}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} \quad (2)$$

3.1.3. Plug-in Electric Vehicle

A PEV can be characterized as a vehicle that draws power from a battery and is good for being charged from an external source. PEVs are, at present, expected to account for the reasonable power control intended to deal with the issues resulting from the significant emergence of renewable energy. In this manner, PEV can be addressed as follows [34]:

$$G_{PEV}(s) = \frac{K_{PEV}}{1 + sT_{PEV}} = \frac{\Delta P_{PEV}}{\Delta U} \quad (3)$$

3.1.4. Hydrogen Aqua Electrolyzer

A HAE is one of the renewal energy sources which can be represented as follows:

$$G_{HAE}(s) = \frac{K_{HAE}}{1 + sT_{HAE}} \quad (4)$$

3.1.5. Fuel Cell

A fuel cell utilizes the compound energy of hydrogen or different fuels to produce electric power neatly and productively. Its power device is comparably a critical part, considering its diminished contamination level and extended efficiency, which can be expressed as follows [35]:

$$G_{FC}(s) = \frac{K_{FC}}{1 + sT_{FC}} \quad (5)$$

3.1.6. DEG System

Diesel motor generators are fit for addressing the shortfall of power and can limit power awkwardness, among other generators, in the power market. The transfer function for a DEG system can be expressed as follows [34]:

$$G_{DEG}(s) = \frac{K_{DEG}}{1 + sT_{DEG}} \quad (6)$$

3.1.7. BESS System

As a prerequisite, a BESS goes about as a source or a load according to the necessity of the system and can be expressed as follows [36]:

$$G_{BESS}(s) = \frac{K_{BESS}}{1 + sT_{BESS}} \quad (7)$$

3.1.8. Thermal Power System

A non-reheat thermal system is considered for the proposed study where the value of the GRC is taken as 12% p.u. MW/minute, which can be communicated as follows:

$$\text{Turbine } G_t(s) = \frac{K_t}{1 + sT_t} \quad (8)$$

$$\text{Generator } G_p(s) = \frac{K_p}{1 + sT_p} \quad (9)$$

$$\text{Governor } G_g(s) = \frac{K_g}{1 + sT_g} \quad (10)$$

$$\text{Reheater } G_r(s) = \frac{1 + sK_rT_r}{1 + sT_r} \quad (11)$$

3.1.9. System Modelling

To represent the system with load, the following transfer function can be used:

$$G_p(s) = \frac{K_p}{1 + sT_p} \quad (12)$$

4. Tilt-Integral-Derivative (TID) Controller

A TID regulator is fundamentally a tunable compensator having K_P , K_I , and K_D as the three control boundaries with the tuning boundary as n . The construction of a TID controller is like that of a PID regulator: the proportional behaviour is replaced by a shifted comparable way of behaving having a transfer function $1/S^{1/n}$ or $s^{-1/n}$. The tilted conduct gives an input gain as a part of the frequency, which is shifted, concerning the gain of the common compensator which is insinuated as the TID compensator, as shown in Figure 3. Mathematically, it can be stated as follows [16]:

$$U_{TID} = G_{TID}(s, \theta) E_{TID}(s) \quad (13)$$

$$E_{TID} = R_{TID}(s, \theta) - Y_{TID}(s) \quad (14)$$

where $G_{TID}(s, \theta)$ shows the transfer for the TID controller, $S \in \mathbb{C}$ and $\theta \in \mathbb{R}^4$. The $G_{TID}(s, \theta)$ can be expressed as follows [17]:

$$G_{TID}(s, \theta) = \frac{K_T}{s^n} + \frac{K_I}{s} + K_D s \quad (15)$$

where $\theta^T = [K_T \ K_I \ K_D \ n]$ and $\theta \in \mathbb{R}^4$, $n \in \mathbb{R}$, and $n \neq 0$

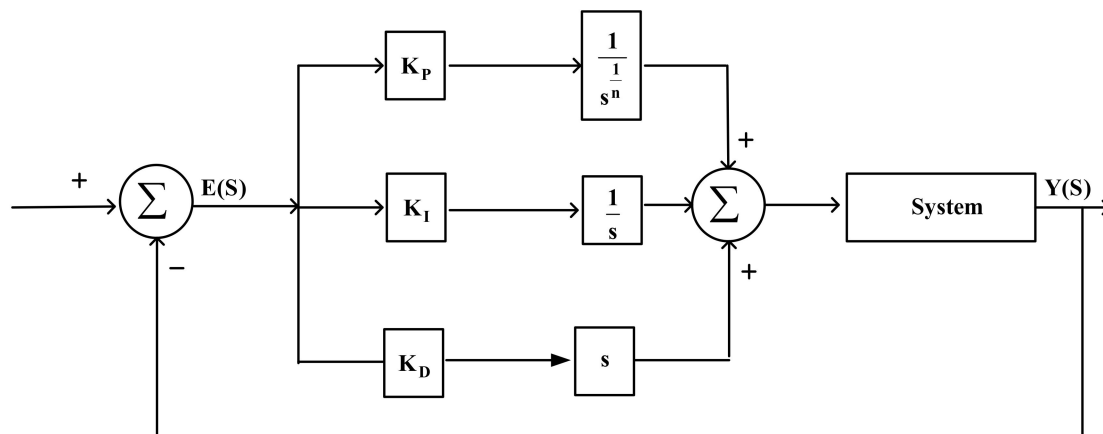


Figure 3. Structure of a TID controller.

5. Optimization Problem

In the proposed work, the goal is the minimization of frequency deviation by considering an ITAE objective function, which can be expressed as follows [35]:

$$J = \text{ITAE} = \int_0^{t_{\text{sim}}} (|\Delta F_i| + |\Delta P_{\text{Tie}-i-k}|) \cdot t \cdot dt \quad (16)$$

where ΔF_i , $|\Delta P_{\text{Tie}-i-k}|$, and t_{sim} show the i^{th} area frequency deviations, tie-line power deviation between the i^{th} and k^{th} areas, and simulation time, respectively.

The fitness function and constraints for this formulated optimization problem are given as follows:

$$\text{Minimize } J \quad (17)$$

$$\text{Subject to } K_P^Y \leq K_x \leq K_P^Z$$

$$\begin{aligned} K_I^Y &\leq K_x \leq K_I^Z \\ K_D^Y &\leq K_x \leq K_D^Z \end{aligned} \quad (18)$$

where K_X is the constant for controller gains, K_X^Y denotes the smallest estimation, and K_X^Z is the highest value of the controller parameters. To improve control performance, four controller parameters, or twelve (20) parameters for five sections of TID, should be obtained or correctly tuned. The controller parameters' range is taken to be between -2 and $+2$, and n is kept between 1 and 10 [25].

6. Proposed Sine Cosine-Adopted African Vultures Optimization Algorithm

6.1. African Vultures Optimization Algorithm

The AVOA is inspired by the foraging and navigational behaviours of African vultures. The biological nature of vultures regarding searching and competing for food is described in four different steps here [31].

6.1.1. Findings of the Best Solution

Let there be N vultures in the environment which indicates the number of population s.t $n = \{1, 2, \dots, N\}$. Then, the fitness function of each position is calculated. Let p_n be the probability of selecting the first or second group, which is calculated as follows:

$$p_n = \frac{F_n}{\sum_{n=1}^N F_n} \quad (19)$$

where F_n is the fitness function of the n th position. Then, the formation of the first and second groups in each iteration is obtained by the following equation:

$$R(it) = \begin{cases} \text{first group, } p_n = L_1 \\ \text{second group, } p_n = L_2 \end{cases} \quad (20)$$

where the ranges of L_1 and L_2 are $0 \leq L_1, L_2 \leq 1$ and $L_1 + L_2 = 1$.

6.1.2. The Rate of Starvation

The satiated vultures with enough energy can move a long distance to search for food while the hungry one cannot fly longer. The rate of being satiated or hungry describes the movement from the exploration phase to the exploitation phase, which is given as follows [32]:

$$A = (2 \times \text{rand}_1 + 1) \times x \times \left(1 - \frac{it}{IT_{\max}}\right) + y \quad (21)$$

$$y = h \times \left(\sin^z\left(\frac{\Pi}{2} \times \frac{it}{IT_{\max}}\right) + \cos\left(\frac{\Pi}{2} \times \frac{it}{IT_{\max}}\right) - 1\right) \quad (22)$$

where A denotes the vultures with high energy; it and $IT_{\max}$ denote the current and maximum iteration, respectively; x , h , and rand_1 are the random numbers varying between -1 to 1 , -2 to 2 , and 0 to 1 , respectively; and z defines the probability of entering the exploration stage.

6.1.3. Exploration

The process of finding food by African vultures describes the exploration phase, in which the parameter p_1 , $0 \leq p_1 \leq 1$ decides the selection of strategy. Hence,

$$P(it+1) = \begin{cases} (6), & p_1 \geq \text{rand}_2 \\ (8), & p_1 < \text{rand}_2 \end{cases} \quad (23)$$

$$P(it+1) = R(it) - D(it) \times A \quad (24)$$

$$D(it) = |q \times R(it) - P(it)| \quad (25)$$

where $P(it+1)$ represent the vultures' position vector in the next iteration. A and $R(it)$ are obtained from (3) and (2), respectively. $q = 2 \times \text{rand}_3$, where rand_3 is a random number between 0 and 1 .

$$P(it+1) = R(it) - A + \text{rand}_4 \times ((u_b - l_b) \times \text{rand}_5 + l_b) \quad (26)$$

u_b and l_b are the upper and lower bounds of the variable, respectively. rand_4 and rand_5 are the random numbers between 0 and 1 .

6.1.4. Exploitation

The exploitation stage has two phases with two different strategies. The selection of any strategy depends on the parameters p_2 and p_3 . The values of p_2 and p_3 are between 0 and 1 . When $|F|$ lies between 0.5 and 1 , the exploitation stage enters the first stage which

describes two different strategies, such as rotating flight and siege fight. Hence, the next position is updated as follows:

$$P(it+1) = \begin{cases} (10), p_2 \geq \text{rand}_6 \\ (11), p_2 < \text{rand}_6 \end{cases} \quad (27)$$

where rand_6 is a random number between 0 and 1. The solutions to (27) are given as follows:

$$P(it+1) = D(it) \times (A + \text{rand}_7) - d(it) \quad (28)$$

$$D(it) = R(it) - P(it) \quad (29)$$

Then, the rotational flight of vultures is modelled as follows:

$$P(it+1) = R(it) - (M_1 + M_2) \quad (30)$$

$$M_1 = R(it) \times \left(\frac{\text{rand}_8 \times P(it)}{2\pi} \right) \times \cos(P(it)) \quad (31)$$

$$M_2 = R(it) \times \left(\frac{\text{rand}_9 \times P(it)}{2\pi} \right) \times \sin(P(it)) \quad (32)$$

where rand_8 and rand_9 are two random numbers between 0 and 1.

The exploitation phase enters the second phase when $|F| > 0.5$, which explains the two different strategies of vultures, such as accumulation and aggressive siege and fight to find food. The selection of any strategy is based on the following condition:

$$P(it+1) = \begin{cases} (16), p_3 \geq \text{rand}_7 \\ (19), p_3 < \text{rand}_7 \end{cases} \quad (33)$$

where

$$P(it+1) = \frac{B_1 + B_2}{2} \quad (34)$$

$$B_1 = \text{Best}_{\text{vulture1}}(it) - \frac{\text{Best}_{\text{vulture1}}(it) \times P(it)}{\text{Best}_{\text{vulture1}}(it) \times P(it)^2} \times A \quad (35)$$

$$B_2 = \text{Best}_{\text{vulture2}}(it) - \frac{\text{Best}_{\text{vulture2}}(it) \times P(it)}{\text{Best}_{\text{vulture2}}(it) \times P(it)^2} \times A \quad (36)$$

$\text{Best}_{\text{vulture1}}(it)$ and $\text{Best}_{\text{vulture2}}(it)$ represent the best vultures of the first and second groups, respectively, in the current iteration. The aggressive competition among the vultures is represented as follows:

$$P(it+1) = R(it) - |d(it)| \times A \times \text{Levy}(d_1) \quad (37)$$

where d_1 represents the dimension of the optimization problem. $\text{Levy}(d_1)$ is calculated as follows:

$$\text{Levy}(x) = 0.01 \times \frac{u \times \sigma}{|v|^{1/\beta'}}, \sigma = \left(\frac{\gamma(1+\beta) \times \sin\left(\frac{\Pi\beta}{2}\right)}{\gamma(1+2\beta) \times \beta \times 2\left(\frac{\beta-1}{2}\right)} \right)^{1/\beta} \quad (38)$$

6.2. Sine Cosine-Adopted African Vultures Optimization Algorithm (SCaAVOA)

In the beginning phases of the AVOA calculation, the best solution is not known. Consequently, utilizing large steps at first might bring about the moving of the calculation far away from the optimal position. Subsequently, scaling variables can be utilized to change the situations during the beginning phases of the calculation. In the proposed

SCaAVOA strategies, at the end of each iteration, the vultures are repositioned using the sine and cosine adopted scaling factors, as given below:

$$P(it + 1)_{New} = P(it + 1) \times SCaSF$$

where SCaSF shows the scaling factors as

$$SCaSF = \begin{cases} \sin(W_1 - W_2 \frac{it}{Max_it}) & \text{if } RND1 < 0.5 \\ \cos(W_1 - W_2 \frac{it}{Max_it}) & \text{if } RND1 \geq 0.5 \end{cases} \quad (39)$$

where RND1 shows a random number; W_1 and W_2 are the weighting factors; and it and Max_it are the present and maximum iteration. The scaling factors are utilized to control the development of the vultures during the beginning phases of the calculation. For the appropriate choice of W_1 and W_2 , various upsides of W are appointed and tried. It is seen that the best outcomes are acquired when W_1 and W_2 are chosen as 10 and 9, respectively. The consideration of the scaling factor stage changes the vultures' positions during the underlying periods of the pursuit interaction in this manner, further developing the hunting capacity of the algorithm. For the legitimate exploitation of search space, the calculation ought to have the option to track down a better position between two positions. For the exploration of the search space, the arrangement can look past the space. This cycle can ensure a better exploitation and exploration capacity of the calculations.

7. Discussion on the Simulation Results

7.1. Performance Evaluation of the Proposed Sine Cosine-Adopted AVOA

As a first step, the performance of the proposed SCaAVOA technique has been investigated with some benchmark test functions [35]. The following algorithm parameters are chosen while executing the hybrid algorithms: the search agents are 30, the maximum iterations are 500, and the iteration is 30. Table 2 shows the statistical results for several unimodal (f1 to f7) and multimodal (f8 to f10) functions. To authenticate the supremacy of the said technique, GSA [26], MWOA [28], ASO [29], AVOA [31], and a published hybrid hGGSA-PS algorithm [37] results are also given in Table 2. It can be seen that, for almost all test functions, the proposed hybrid technique is very competitive compared to other algorithms.

The computing time for 30 runs for all the benchmark capabilities for the SCaAVOA and AVOA computations is also shown in Table 3. Table 3 shows that the proposed SCaAVOA tends to take less time to compute than the initial AVO calculation for each of the capabilities. According to the study mentioned above, the modified algorithm performs better than the normal calculation; hence, we will use it for our proposed study.

Table 2. Cost function comparison of the proposed SCAVOA considering standard benchmark functions.

Function	DE [20]		PSO [21]		GSA [26]		MWOA [28]		ASO [29]		hGGSA-PS [34]		AVOA [31]		Proposed SCAVOA	
	Avg.	Std. Dev	Avg.	Std. Dev	Avg.	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev
f_1	8×10^{-14}	5.9×10^{-14}	0.00014	0.000202	3.985×10^{-8}	6.671×10^{-18}	2.986×10^{-10}	6.21×10^{-39}	2.687×10^{-21}	3.652×10^{-21}	2.795×10^{-9}	9.63×10^{-10}	0.696×10^{-293}	0	0	0
f_2	1.5×10^{-9}	9.9×10^{-10}	0.04214	0.045421	4.196×10^3	2.601×10^{-9}	2.123×10^3	2.98×10^{-25}	3.332×10^{-10}	1.892×10^{-10}	3.978×10^3	3.69×10^2	0.028×10^{-152}	0.153×10^{-152}	0.113×10^{-164}	0.445×10^{-164}
f_3	6.8×10^{-11}	7.4×10^{-11}	70.1256	22.11924	3.567×10^{-14}	41.96643	4.653×10^{-15}	3.78×10^{-10}	1.983×10^{-2}	79.7024	3.567×10^{-14}	6.39×10^{-19}	0.421×10^{-223}	0	0.859×10^{-249}	0
f_4	0	0	1.08648	0.317039	2.964×10^{25}	7.531×10^{-9}	6.523×10^{-28}	0.02514	3.245×10^{-9}	6.142×10^{-9}	8.567×10^{-27}	3.25×10^{-32}	0.145×10^{-136}	0.794×10^{-136}	0.406×10^{-159}	0.221×10^{-159}
f_5	0	0	96.7183	60.11559	1.674	11.29836	0.059	1.23×10^{-10}	24.8388	0.515853	0.901	0.0025	0.8674	4.7508	0.2891×10^{-3}	0.447×10^{-3}
f_6	0	0	0.0001	8.28×10^{-5}	9.865×10^{-4}	0	5.023×10^{-6}	0.00219	0	0	6.758×10^{-6}	4.36×10^{-19}	0.526×10^{-6}	0.328×10^{-6}	0.332×10^{-5}	0.3101×10^{-5}
f_7	0.00463	0.0012	0.12285	0.044957	2.486	0.007716	1.956	2.12×10^{-5}	0.035641	0.019498	2.486	0.007716	0.182×10^{-3}	0.256×10^{-3}	0.153×10^{-3}	0.192×10^{-3}
f_8	−11080.1	574.7	−4841.29	1152.814	8.456×10^{-27}	341.6006	4.565×10^{-28}	3.65×10^{-30}	−7428.17	422.3977	6.787×10^{-27}	2.65×10^{-35}	1.239×10^{-4}	$0.036 \times 10^{+4}$	1.251×10^{-4}	$0.016 \times 10^{+4}$
f_9	69.2	38.8	46.7042	11.62938	8.986×10^{-11}	4.439862	0.021×10^{-12}	0	0	0	6.787×10^{-11}	4.25×10^{-17}	0	0	0	0
f_{10}	9.7×10^{-8}	4.2×10^{-8}	0.27602	0.50901	2.546	3.961×10^{-10}	0.896×10^{-10}	8.36×10^{-15}	3.001×10^{-11}	2.151×10^{-11}	0.901	0.00256	0.888×10^{-15}	0	0.888×10^{-15}	0

Table 3. Comparison of computational time between the SCaAVOA and AVOA algorithms for the considered standard benchmark functions (f_1 – f_{10}).

Functions	% Reduction in Execution Time	SCaAVOA Elapsed Time (s)	AVOA Elapsed Time (s)
f_1	10.031	3.459	3.845
f_2	6.235	3.549	3.785
f_3	7.945	7.612	8.269
f_4	6.835	3.448	3.701
f_5	2.247	3.915	4.005
f_6	8.025	3.312	3.601
f_7	6.101	5.494	5.851
f_8	5.086	4.012	4.227
f_9	7.016	3.525	3.791
f_{10}	7.763	3.564	3.864

7.2. Statistical Test of the Proposed Sine Cosine-Adopted AVOA

A nonparametric statistical test known as Wilcoxon's test is used here to test the significance of the proposed SCaAVOA procedure with that of the standard AVOA methods. The outcomes (p esteem) are displayed in Table 4 for pairwise correlation of the SCaAVOA vs. AVOA. An algorithm is significant when the p esteem returns a worth under 0.05. It can be seen from Table 3 that, for most of the functions, the p esteem is noticeably under 0.05. This suggests that the SCaAVOA is significant in accomplishing the best encouraging answers for the standard benchmark functions [38].

Table 4. p test for pairwise comparison of the SCaAVOA vs. AVOA algorithm.

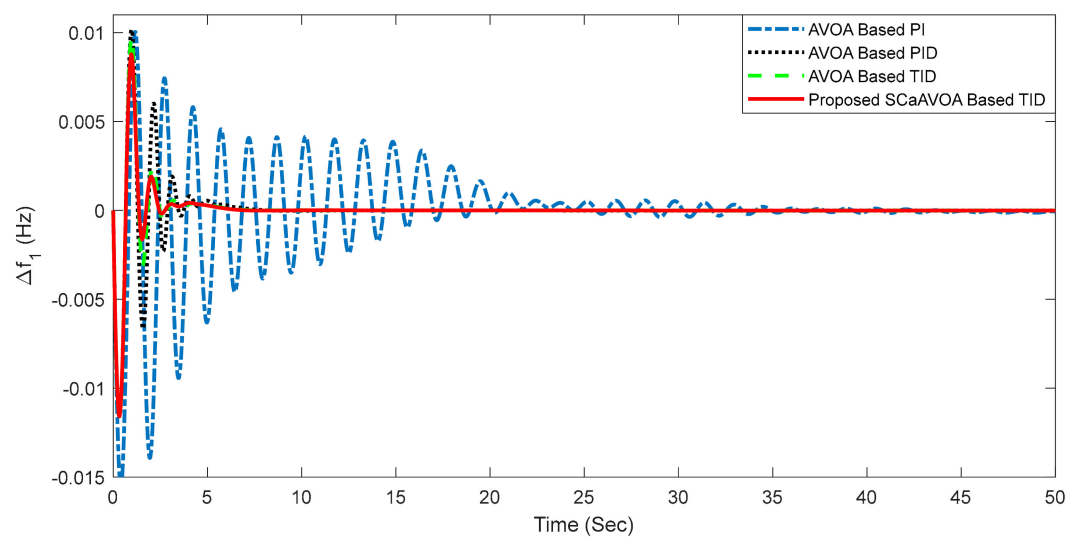
SCA-AOA vs. AOA			
Functions	Values	Functions	Values
f_1	2.213×10^{-6}	f_6	1.2118×10^{-12}
f_2	1.2118×10^{-12}	f_7	1.2118×10^{-12}
f_3	1.2118×10^{-12}	f_8	1.2118×10^{-12}
f_4	1.2118×10^{-12}	f_9	NA
f_5	1.2118×10^{-12}	f_{10}	1.6853×10^{-14}

7.3. Implementation of the Proposed SCaAVOA Algorithm

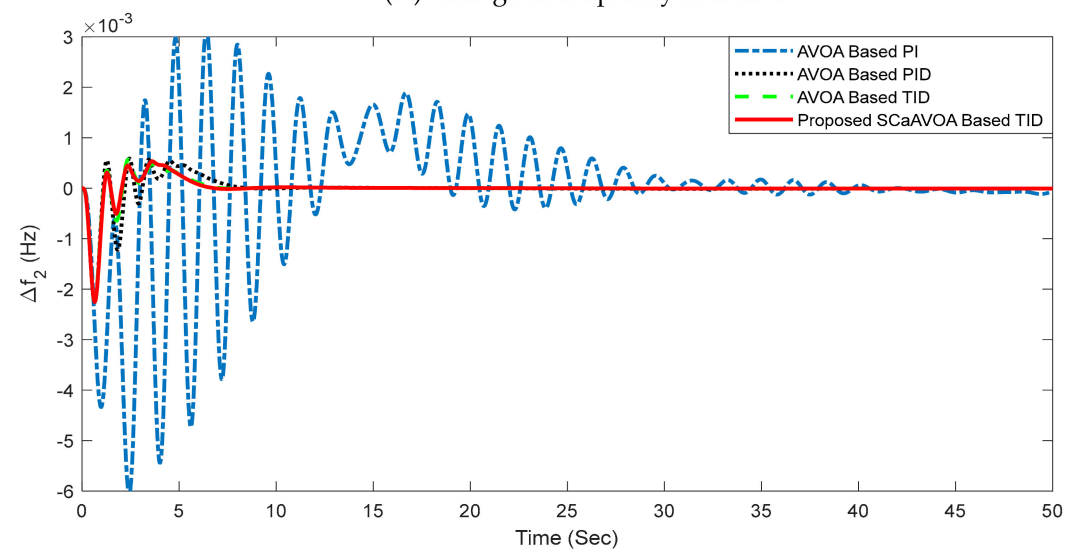
When the simulation is complete, the limits of the TID, PID, and PI regulators can be found by using Equation (18) to calculate the goal function for the five-area thermal system. Table 4 displays the regulator boundaries that contrast the current tactic with other conventional methods. Table 4 also shows that, when compared to the AVOA-based TID and the AVOA-based PI regulator, the Sine Cosine-adopted AVOA-based TID controller produces the best results. In a similar manner, it shows that, overall, the proposed plan with the proposed Sine Cosine-adopted AVOA-based TID system gives improved results when compared to the AVOA.

7.4. Testing on Five-Area Thermal Power System

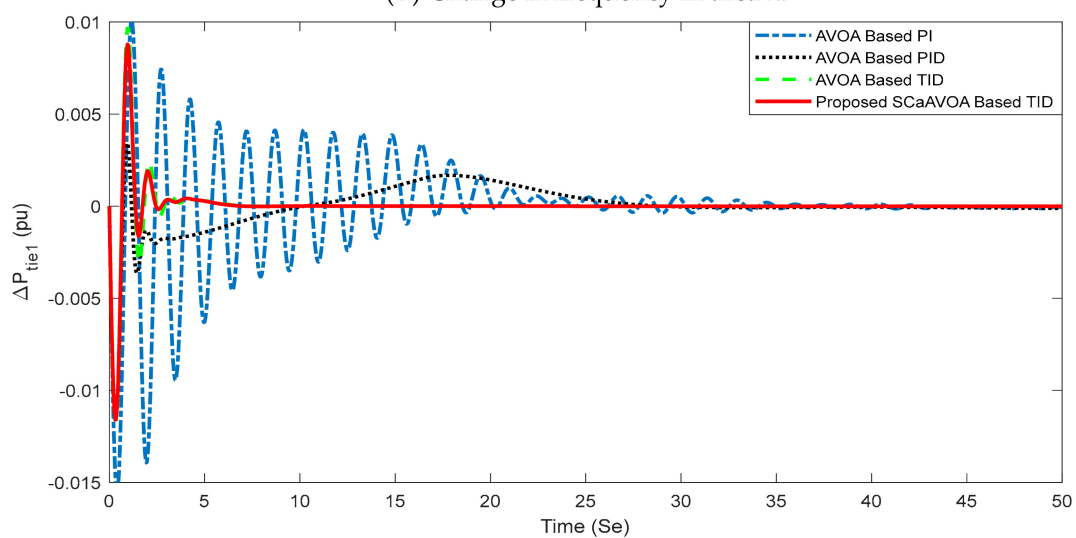
The system response is shown in Table 5 for a 1% step load expansion in area 1 at $t = 0$ s. The results using the PID controllers are also shown in Table 5 and Figure 4 for comparison (A–C). It is clear from Figure 4 that the proposed SCaAVOA-based TID structure achieves improved system response when compared to the simple PID structure. Additionally, Table 5 provides the performance list for the said scenarios. The table shows that the proposed TID structure performs better than the traditional PID structure in terms of lower ITAE values and faster settling times for Δf and P_{tie} .



(A) Change in frequency in area 1.



(B) Change in frequency in area 2.



(C) Tie-line power

Figure 4. (A–C) System response for the five-area power system.

Table 5. Controller parameters for the five-area power system.

Component Parameter	Proposed SCaAVOA Tuned TID Controller	AVOA Tuned TID	AVOA Tuned PID	AVOA Tuned PI
Controller-1	$K_{P1} = 1.7995, K_{I1} = 1.9958, K_{D1} = 1.0127, n_1 = 2.5109$	$K_{P1} = 1.9954, K_{I1} = 1.9011, K_{D1} = 0.9092, n_1 = 2.6816;$	$K_{P1} = 1.9372, K_{I1} = 1.9958, K_{D1} = 1.0350$	$K_{P1} = 0.0089, K_{I1} = 0.2184$
Controller-2	$K_{P2} = 1.9952, K_{I2} = 1.9956, K_{D2} = 1.9942, n_2 = 9.9192$	$K_{P2} = 1.9317, K_{I2} = 1.9030, K_{D2} = 1.9793, n_2 = 9.9800;$	$K_{P2} = 1.9952, K_{I2} = 1.6493, K_{D2} = 1.9878$	$K_{P2} = 0.0011, K_{I2} = 0.2516$
Controller-3	$K_{P3} = 1.9946, K_{I3} = 1.9938, K_{D3} = 1.9858, n_3 = 9.5630$	$K_{P3} = 1.4228, K_{I3} = 1.9938, K_{D3} = 1.4069, n_3 = 5.1143;$	$K_{P3} = 1.9946, K_{I3} = 1.8576, K_{D3} = 1.9858$	$K_{P3} = 0.1462, K_{I3} = 0.2022$
Controller-4	$K_{P4} = 1.9946, K_{I4} = 1.9938, K_{D4} = 1.9558, n_4 = 4.2015$	$K_{P4} = 1.9946, K_{I4} = 1.9938, K_{D4} = 1.9558, n_4 = 8.0693;$	$K_{P4} = 1.9186, K_{I4} = 1.9938, K_{D4} = 1.9858$	$K_{P4} = 0.0921, K_{I4} = 0.2291$
Controller-5	$K_{P5} = 1.9946, K_{I5} = 1.9938, K_{D5} = 1.9858, n_5 = 9.9192$	$K_{P5} = 1.9575, K_{I5} = 1.9938, K_{D5} = 1.2533, n_5 = 9.9800;$	$K_{P5} = 1.9104, K_{I5} = 1.9938, K_{D5} = 1.6359$	$K_{P5} = 0.2236, K_{I5} = 0.2227$
ITAE	0.1001	0.1045	0.1651	2.795

7.5. Extension to Five-Area, Ten-Unit Hybrid System

To show the capacity of the proposed plan to deal with systems using various sources of generations, a five-area, ten-unit system is examined. The hybrid system is composed of a non-reheat type of thermal power system in each area and a photovoltaic system in area 1, a wind system in area 2, an aqua electrolyzer and fuel cell in area 3, a diesel engine generator and microturbine in area 4, and a plug-in electric-vehicle in area 5, respectively. The TID structures are accepted for every area and the proposed Sine Cosine-adopted AVOA calculation is utilized to tune the regulator boundary. The following disturbance is taken into consideration:

7.5.1. Case 1: Solar Variations

For the primary occurrence, a test is performed by thinking about adjustment to solar irradiation, as shown in Figure 5A. Table 6 shows the regulator boundaries for the said disturbance. Figure 5B–D outline the frequency response bend of the hybrid power system for the TID-based planned regulators. A conclusion can be made that the TID-based hybrid power system offers better framework execution when it is contrasted with other standard regulators.

Table 6. Controller parameters for the five-area, ten-unit hybrid power system.

Component Parameter	Proposed SCaAVOA Tuned TID Controller	AVOA Tuned TID	AVOA Tuned PID	AVOA Tuned PI
Controller-1	$K_{P1} = 1.1381, K_{I1} = 0.3380, K_{D1} = 0.8155, n_1 = 3.0131$	$K_{P1} = 0.7316, K_{I1} = 0.3577, K_{D1} = 0.2553, n_1 = 2.3491$	$K_{P1} = 0.7935, K_{I1} = 0.5885, K_{D1} = 0.4888$	$K_{P1} = 0.0089, K_{I1} = 0.2184$
Controller-2	$K_{P2} = 1.8385, K_{I2} = 0.1870, K_{D2} = 1.3267, n_2 = 5.1948$	$K_{P2} = 0.8843, K_{I2} = 0.2229, K_{D2} = 0.3843, n_2 = 3.6644$	$K_{P2} = 1.9952, K_{I2} = 0.1775, K_{D2} = 0.4528$	$K_{P2} = 0.0011, K_{I2} = 0.2516$
Controller-3	$K_{P3} = 1.2227, K_{I3} = 0.9752, K_{D3} = 1.3722, n_3 = 8.6644$	$K_{P3} = 0.9090, K_{I3} = 0.575, K_{D3} = 0.7078, n_3 = 1.4077$	$K_{P3} = 0.2463, K_{I3} = 1.9931, K_{D3} = 1.9858$	$K_{P3} = 0.01462, K_{I3} = 0.2022$
Controller-4	$K_{P4} = 1.5446, K_{I4} = 0.5303, K_{D4} = 0.9427, n_4 = 9.9800$	$K_{P4} = 0.7742, K_{I4} = 0.3660, K_{D4} = 0.6315, n_4 = 3.5428$	$K_{P4} = 0.5474, K_{I4} = 1.8711, K_{D4} = 1.9815$	$K_{P4} = 0.0092, K_{I4} = 0.0229$
Controller-5	$K_{P5} = 1.1889, K_{I5} = 0.6183, K_{D5} = 0.001, n_5 = 3.0732$	$K_{P5} = 1.1007, K_{I5} = 0.1775, K_{D5} = 0.7676, n_5 = 3.2820$	$K_{P5} = 0.5022, K_{I5} = 1.9576, K_{D5} = 0.3243$	$K_{P5} = 0.0023, K_{I5} = 0.0022$
ITAE	18.99	19.72	24.38	37.69

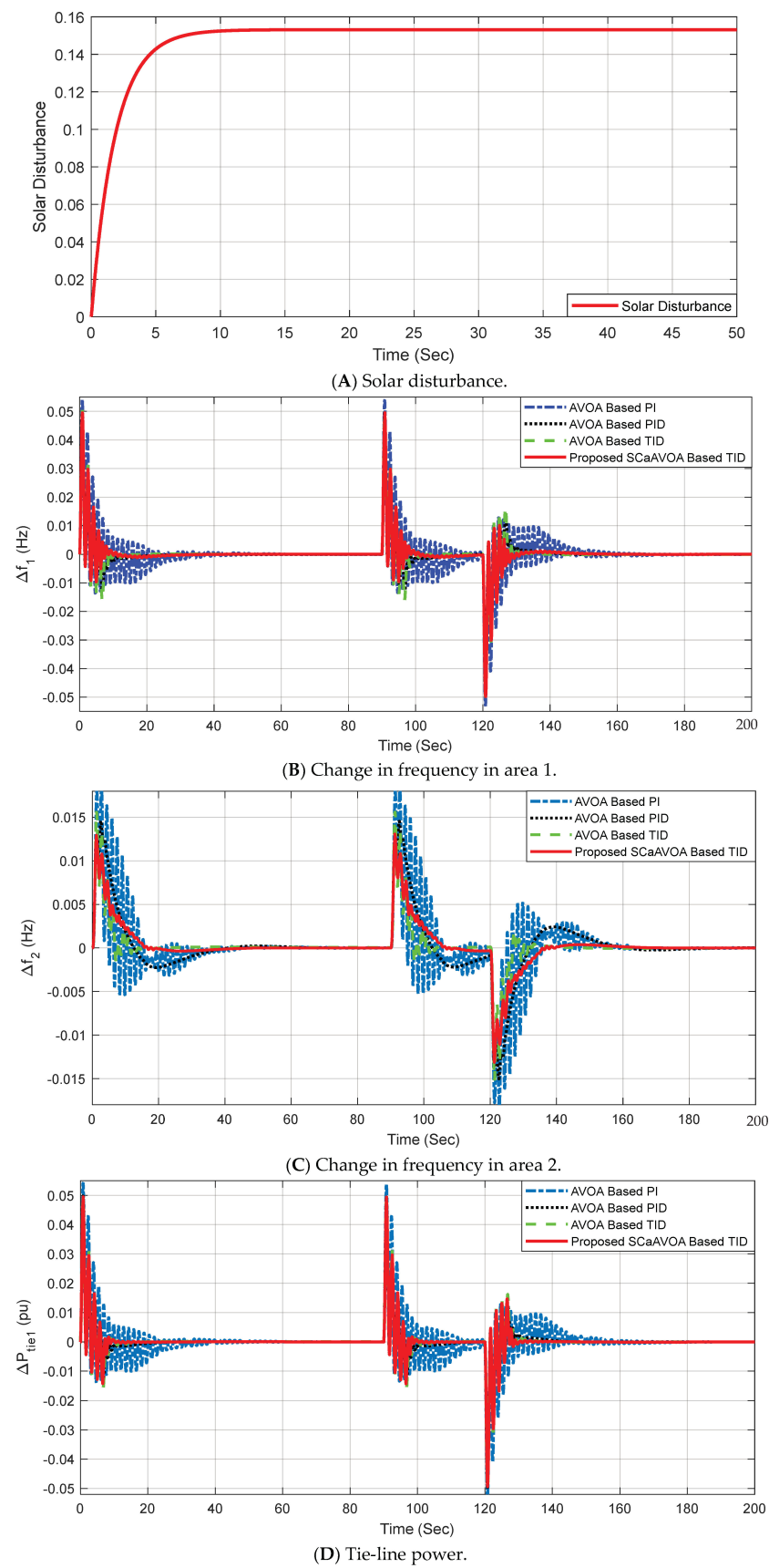
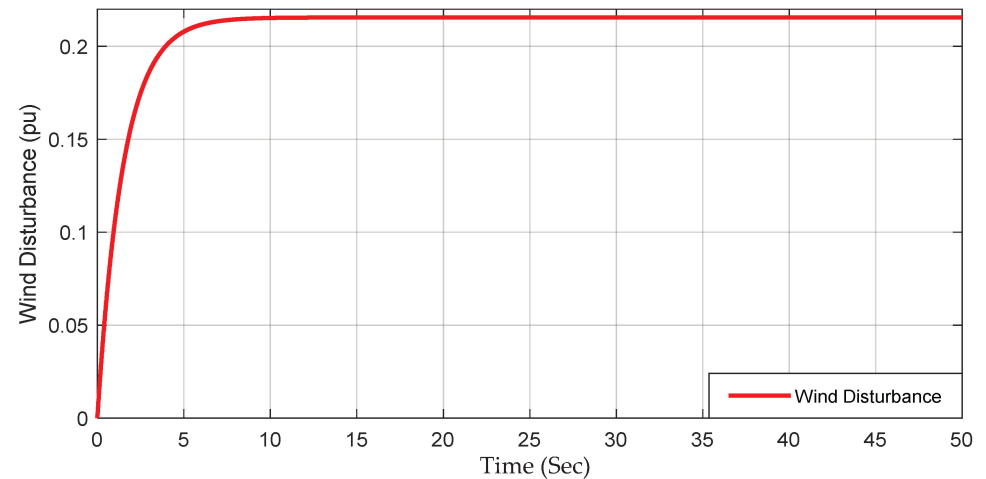


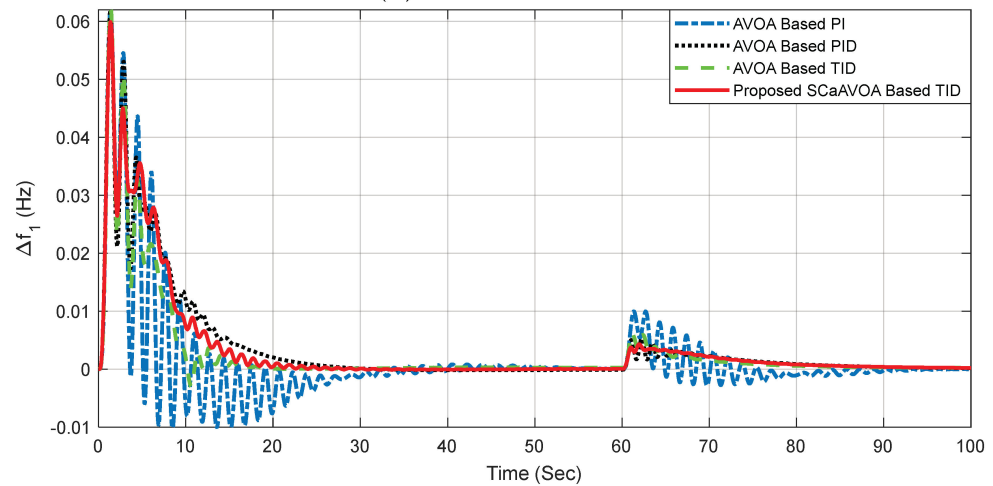
Figure 5. (A–D) System response for the five-area, ten-unit system with solar disturbance.

7.5.2. Case 2: Wind Penetration Variations

At the same time, one more certified test is performed by an adjustment of wind power variation, as shown in Figure 6A. Figure 6B–D outline the system reaction showing the examination of the proposed and the regular regulators. A similar conclusion can be drawn as in case 1.

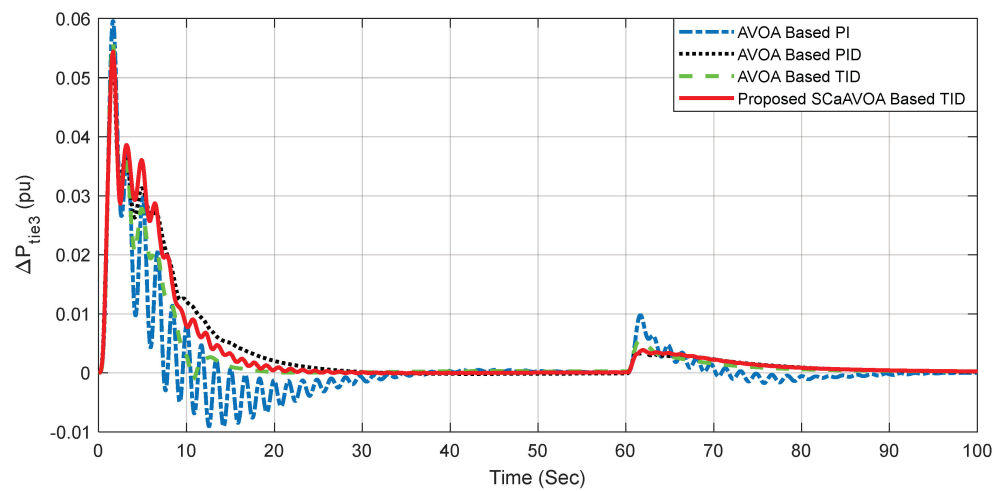


(A) Wind disturbance.

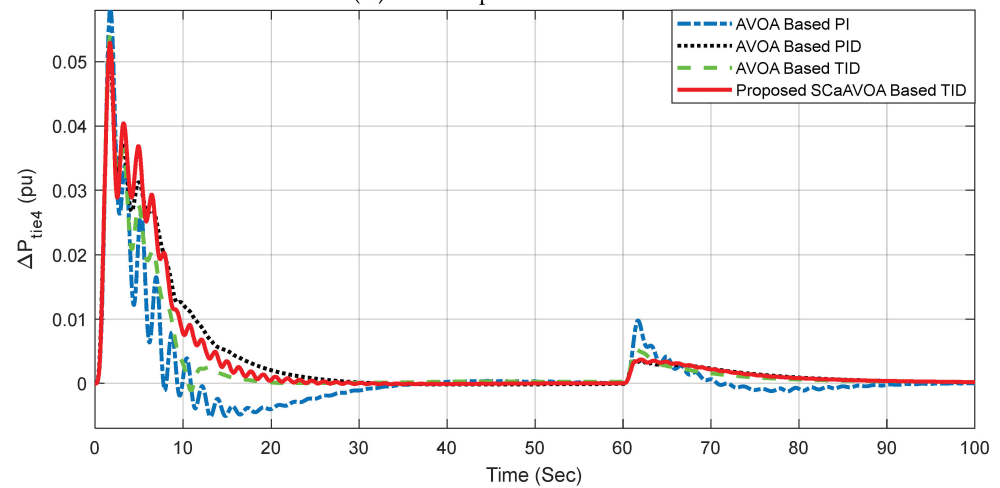


(B) Change in frequency in area 1.

Figure 6. Cont.



(C) Tie-line power in area 3.

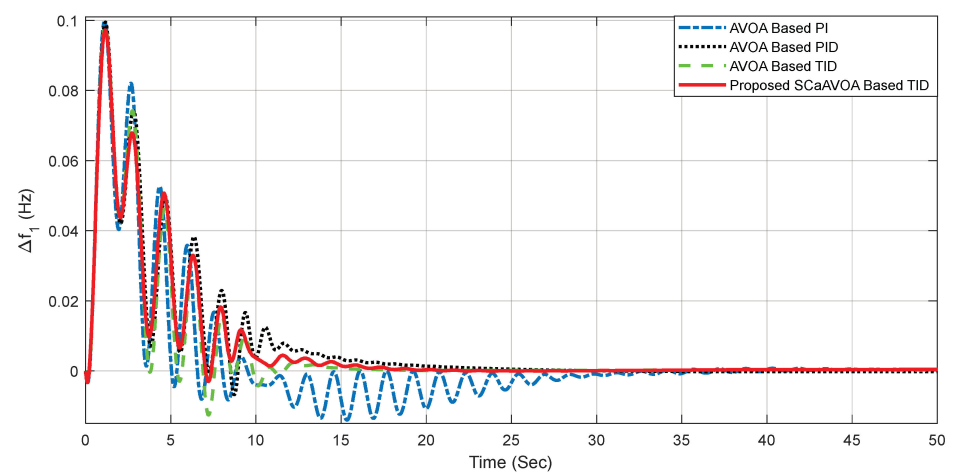


(D) Tie-line power in area 4.

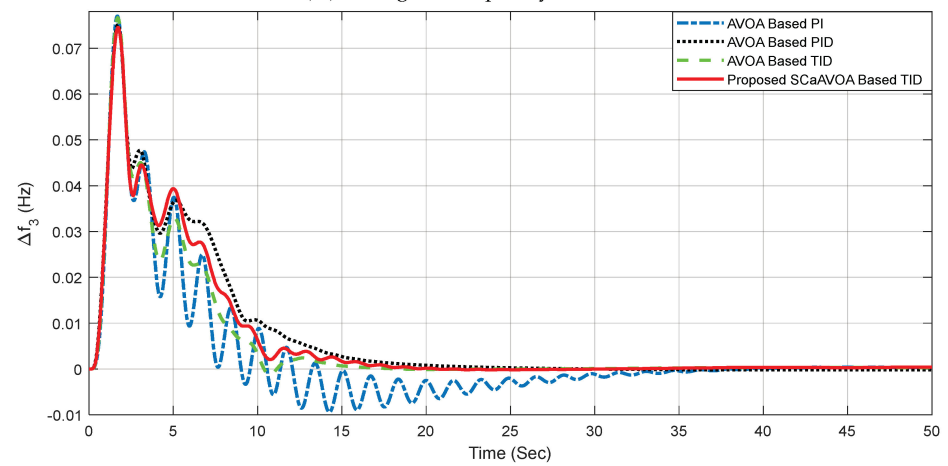
Figure 6. (A–D) System response for the five-area, ten-unit system with wind disturbance.

7.5.3. Case 3: Simultaneous Variation of All Disturbance

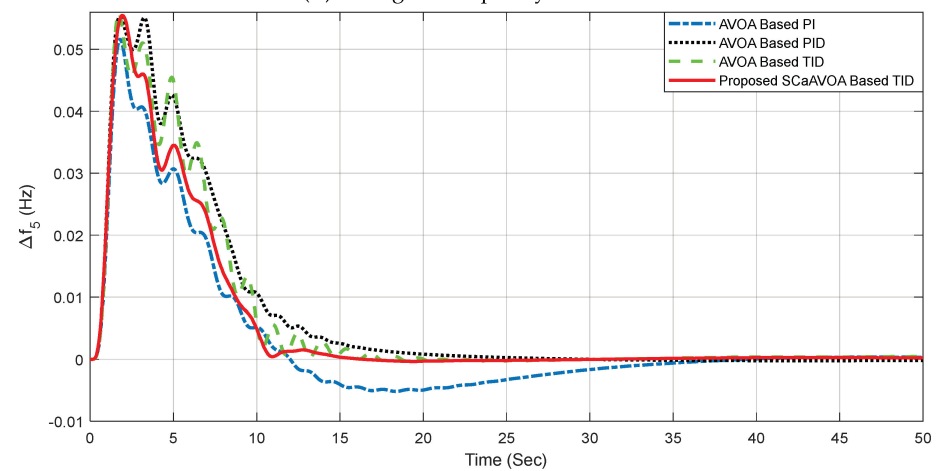
For this situation, a simultaneous change in the different system parameters, including sun irradiation change, wind power change, and a step change of 1% load in locale 1 at $t = 0$ s, is considered. Figure 7A–F exhibit the frequency reaction of the AGC five-area power system and a conclusion can be made that, for each disturbance, the system frequency maintains a steady state of equilibrium.



(A) Change in frequency in area 1.

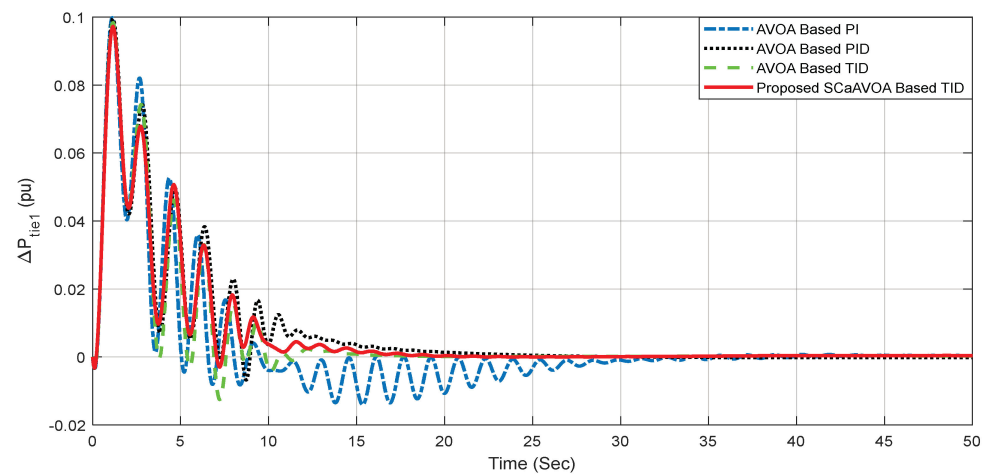


(B) Change in frequency in area 3.

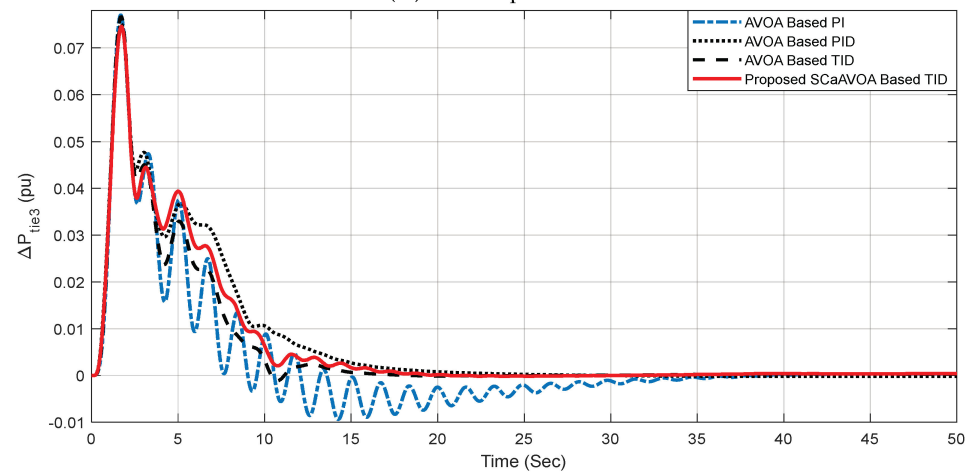


(C) Change in frequency in area 5.

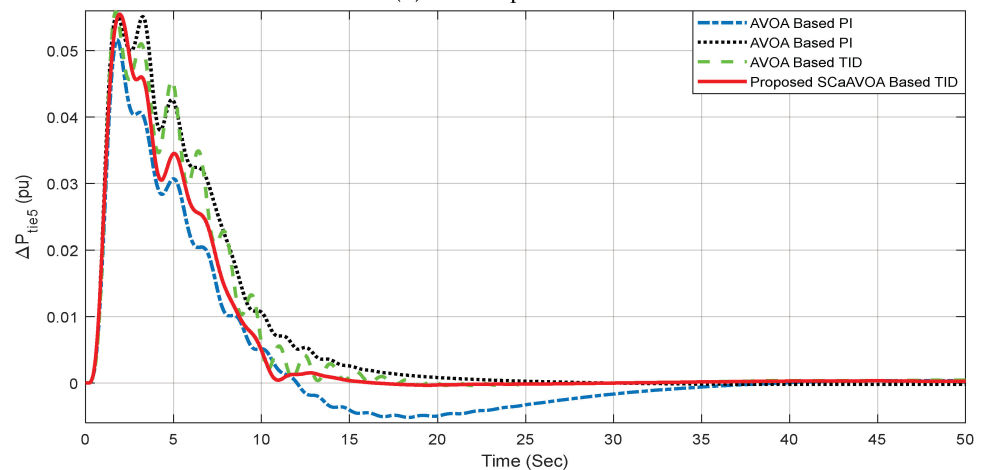
Figure 7. Cont.



(D) Tie-line power in area 1.



(E) Tie-line power in area 3.



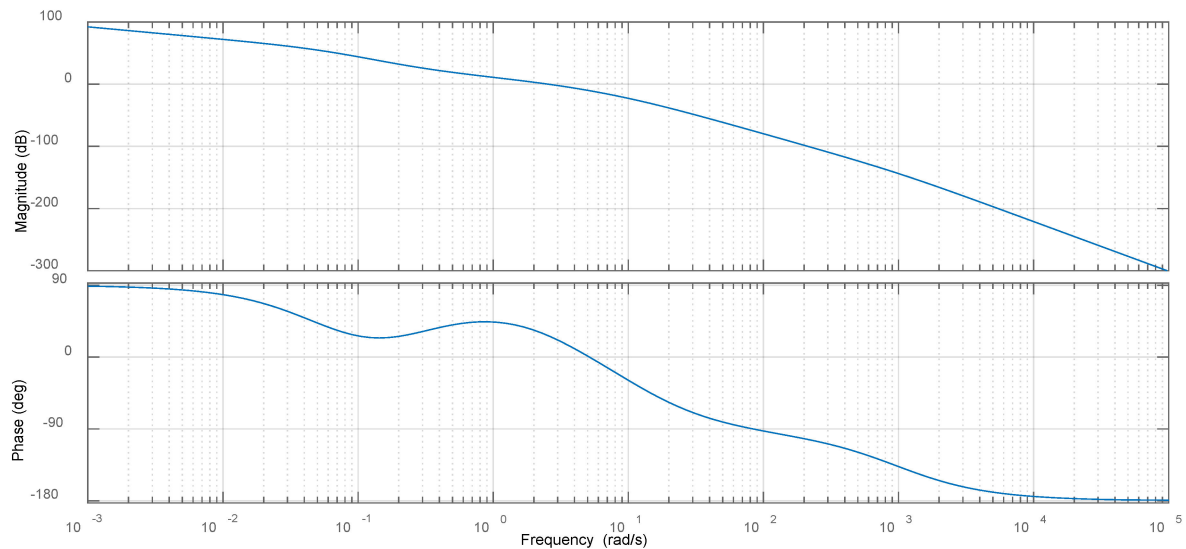
(F) Tie-line power in area 5.

Figure 7. (A–F) System response for the five-area, ten-unit power system with all disturbances.

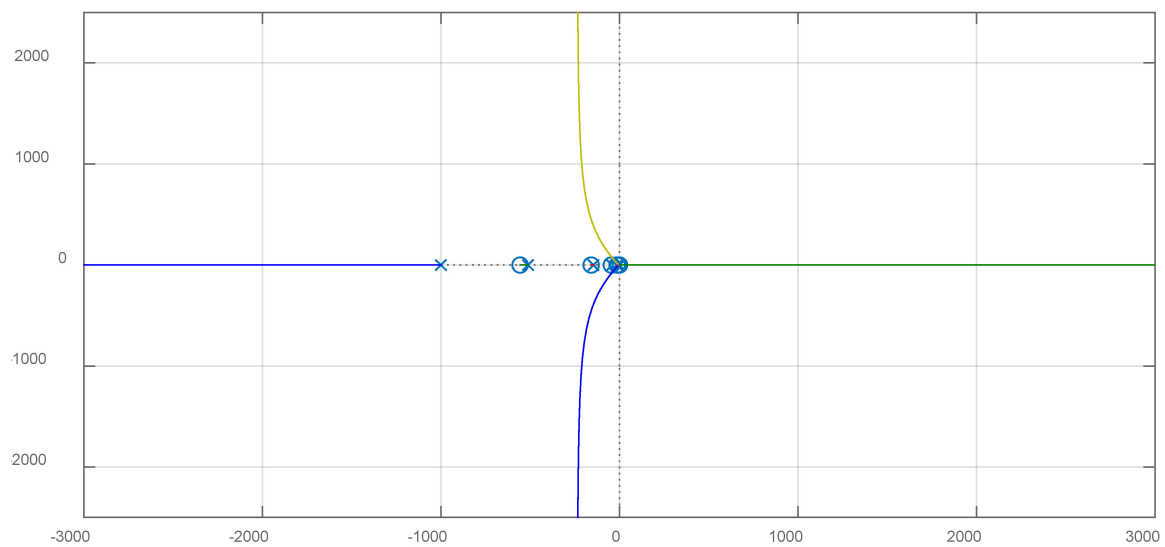
7.5.4. Case 4: Stability Test of the System in Time Domain and Frequency Domain

The stability test of the system can be achieved by analyzing the circuit in time domain as well as frequency domain. The time response and the frequency response are calculated by taking the bode plot and the root locus of the hybrid power system, as shown in Figure 8A,B. Even though the system is experiencing all the disturbances, Figure 8A,B demonstrate a stable system using the SCaAVOA-adjusted TID controller. As a result, the

model has been linearized, and the response has been obtained by inputting data at the controller's output and measuring the result at the power system's output. From the figure, it can be seen that the system is stable with the proposed TID controller.



(A) Bode plot



(B) Root locus

Figure 8. (A,B) Bode and root locus responses of the hybrid power system.

8. Conclusions

This study proposes a novel Sine Cosine-adopted African vulture optimization algorithm (SCaAVOA) for a tilt-integral-derivative (TID) regulator structure for frequency control of a hybrid five-region power system. The hybrid system considers different conventional and non-conventional sources along with some non-linearities, such as GRC and dead band. A comparison of the proposed calculation over the standard calculation in terms of simulation time and fitness function is examined initially. Furthermore, the SCaAVOA approach is then used to additionally investigate TID regulator limits for a five-area thermal system as well as a five-area, ten-unit hybrid power system for the frequency guideline. It can be seen from the comparison table that the rate of improvement in error (J) by the application of the SCA-AVOA-based TID controller in contrast to the

AVOA-based TID, the AVOA-based PID, and the AVOA-based PI are 3.79%, 28.38%, and 50%, respectively.

It can be seen from the correlation table that there is a high rate of decrease in the performance indices, i.e., in the J values. The simulation results show that the proposed SCaAVOA-based TID controller is useful for frequency regulation, when compared to the standard controller. In the present work, for each area, only thermal system modeling is included and some other system can be tested in the AGC, which can be considered in a future study of the proposed work. Future work will be focused on developing more precise control in the RES-dominated AGC. Furthermore, the authors will try to incorporate more detailed models of power system devices and different modes of operation.

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