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Application of Robust Super Twisting to Load Frequency Control of a Two-Area System Comprising Renewable Energy Resources

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Abstract: The main concern of the present article is to design a robust load frequency control for a two-area power system (TAPS) comprising renewable energy resources. Three different controllers are suggested. The first is based on a robust super twisting (ST) technique, which is an enhanced approach of the sliding mode control and is considered to be one of the most excellent control techniques. The second and the third are based on two recent metaheuristic techniques, namely the one-to-one based optimizer (OOBO) and hippopotamus optimizer (HO). The studied TAPS contains different energy resources, such as solar thermal, photovoltaic, wind energy, hydropower and energy storage in addition to other conventional sources. The OOBO and HO are used to determine the parameters of PI controllers, and the objective function is to minimize the integral square error of frequency and tie line power. The obtained results verify the high performance of the suggested three controllers with superiority to ST because of its intrinsic capability to cope with parameter changes.

Keywords: load frequency control; super twisting; hippopotamus optimizer; one-to-one based optimizer; solar energy; wind energy



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1. Introduction

Power systems (PS) are very complex networks that transfer huge amounts of power and comprise numerous generators of diverse kinds, transformers, transmission and distribution lines, and other electrical devices. In any electrical grid, generators are placed at specific locations to supply different loads that must work at a specified frequency and voltage. However, continuous load variations occur that result in deviations in voltage and frequency. Voltage and frequency deviations disturb the operation and efficiency of loads. Hence, it is vital to keep frequency and voltage constant at their nominal values. Control of voltage is the rule of the automatic voltage regulator and reactive power compensators, while control of frequency is the rule of speed governors and load frequency control (LFC) [1].

PS have a growing varying structure with high dimension, increasing use of renewable energy sources (RES) with different natures, and increasing need for storage schemes. A robust LFC is needed to accommodate the fluctuations in RES output power and load disturbances; therefore, the design of LFC becomes a challenge mission [2]. There are two main regulating loops to control frequency in power grids. The first is a local control loop called the primary frequency control, and the other is called the secondary control loop or the LFC [3]. During earlier days, LFC was implanted using traditional PID regulators, but recent control techniques include metaheuristic schemes, fuzzy regulators, sliding mode control (SMC), fractional order PID regulators, tilt integral derivative regulators, and artificial intelligence-based regulators. A comprehensive review regarding LFC types can be found in [4–6].

From the point of view of PS plant type, the LFC of a single-area PS (SAPS) comprising a thermal power plant is investigated in [7]; the same scheme but with a time delay has

been considered in [8]. The LFC of SAPS with a hydraulic power (HP) plant is analyzed in [9]. The LFC of an isolated micro grid is studied in [10]. RES, such as photovoltaic (PV) and wind energy (WE), are modeled and analyzed in [11,12]. The LFC of systems that have storage devices is analyzed in [13].

From the solution techniques point of view, there are many techniques to perform LFC, starting from the traditional PID controller to the application of artificial intelligence techniques. In [14], Fosha presented a scheme based on state variables to achieve optimum control. The optimal regulator approach was implemented in [15,16] for LFC to tune the PID regulator gains. Another approach was suggested by Sophia in [17], who designed LFC based on fuzzy logic (FL) to tune PI regulator gains. Another FL regulator is presented in [18] to adjust the PID parameters. Al-Majidi in [19] utilized an artificial neural network (ANN) to implement an optimal regulator. A more sophisticated approach is introduced by Mohseni in [20], which is based on an H₂-H_∞ regulator for LFC. Sondhi in [21] applied a fraction-order PID regulator for LFC, while Ahmed in [22] introduced an improved version of a tilted-integral-derivative regulator aimed at LFC.

Metaheuristic techniques are recent tools for optimization and are used by many researchers to tune the optimal gain constants of the regulator. Ogar in [23] used a particle swarm optimizer (PSO) to compute the optimum values of PID regulators of LFC, while a genetic algorithm (GA) is utilized by Daneshfar in [24] to tune a PID controller. Ballgobin in [25] merged a shuffled frog leaping and teaching learning optimizer to form a hybrid technique. Another hybrid optimization technique consists of PSO, and a grey wolf optimizer was used by Alahakoon in [26]. Najeeb in [27] used harmony search for the optimum design of the PID regulator. A mixed scheme consisting of GA and ANN is used by Dashtdar in [28]. El-Bahay in [29] used a coot optimizer to regulate the LFC regulator. A bacteria forage optimizer is used by Sarath in [30], while an ant lion optimizer is used by Satheeshkumar in [31]. Recently, SMC is used to design LFC by Mahmoud in [32], Kumar in [33], and Tran in [34].

In this article, super twisting (ST), which is a high-order technique of the SMC with supreme performance [35], is applied to design LFC of a two-area PS with a high contribution of RES. To verify the high performance of the proposed controller, its results are compared with those of two recent metaheuristic techniques utilized to compute the gains of the PI controllers. The two techniques are the hippopotamus optimizer (HO) and the one-to-one based optimizer (OOBO). The outcomes prove that the settling time and overshoot act better with an ST-based controller than heuristic-based controllers.

In view of the previous mentioned literature, the following are the main contributions of this work:

- A. The use of two new metaheuristic techniques, namely HO and OOBO, to specify the optimal parameters of the sliding surface used in ST.
- B. The application of the ST technique of the SMC to LFC, which is better suited for use in the case of nonlinear control and parameter change.
- C. The results are verified by comparing the ST performance with two recent metaheuristic methods, i.e., HO and OOBO, which are used to obtain the optimal PI controller gains.

The present work is ordered in the following form. The first section shows a literature survey for LFC. Section 2 introduces the details of the suggested system with a brief mathematical description of each source. The third section illustrates short notes about HO and OOBO optimizers. The fourth section briefly discusses the application of ST on LFC. The fifth part informs about the simulation of the proposed controllers. At the end, there is a short conclusion about the principal outcomes of the work.

2. System Modelling

In this paper, a hybrid TAPS that contains different energy resources is studied; these energy resources are explained as follows.

2.1. Solar Thermal Power Plant

The cost of electrical energy generated from the sun is decreasing [36]. Currently, solar thermal (STH) power plants are broadly used to provide either heat energy or electrical energy. The commonly used devices in STH system can be classified into two types: The first is a linear collector, like a parabolic trough and Fresnel's lenses, and the second is point-focused, like a parabolic dish and central tower. Solar radiation calculation is investigated by Abdelaal in [37,38]. The principle of operation of an STH plant depends on collecting the sun rays by the collectors and then reflecting the sun rays to the receiver, which contains a liquid (oil or molten salt). Therefore, the liquid temperature rises to an excessive value. The excessive temperature liquid interchanges the heat energy with water to provide superheated steam that drives a turbine and then generates electrical power. The first stage of collecting sun rays, reflecting them, heating the liquid, and exchanging energy with water of the STH plant can be modelled by the following equation [39]:

$$G_s(s) = \frac{K_{STH}}{\tau_{STH}s + 1} \quad (1)$$

where K_{STH} is the gain and τ_{STH} is the delay time of the first stage. The model of the speed governor (SG) and turbine is given by the following:

$$G_{GPT}(s) = \frac{K_{G_STH}}{T_{G_STH}s + 1} \quad (2)$$

$$G_{TPT}(s) = \frac{K_{T_STH}}{T_{T_STH}s + 1} \quad (3)$$

where T_{G_STH} and T_{T_STH} are the SG and turbine time delay, and K_{G_STH} and K_{T_STH} are the gain of the SG and turbine, respectively.

2.2. Photovoltaic Power Plant

When solar rays hit the solar cell (CS), photons hit electrons; as a result, electrons are freed, and electric current flows. The current is captured and transferred to wires; as a result, electrical energy is obtained. Electrical energy is supplied, provided that the light is incident on the CS. To work at the peak power of the CS, a maximum power point tracker should be used. Inverters are used to convert the energy to AC. The mathematical representation of the PV power plant is given by following equation [40]:

$$G_{PV} = \frac{K_{PV}}{\tau_{PV}s + 1} \quad (4)$$

where τ_{PV} and K_{PV} are the time delay and gain of the PV unit.

2.3. Wind Turbine Power Plant

The WT transforms energy contained in the wind to mechanical power, which is converted to electrical power. The output power is strongly affected by the wind speed. The WT can be modelled as follows [41]:

$$G_{WT} = \frac{\Delta P_{WT}}{\Delta P_{WT_inp}} = \frac{K_{WT}}{1 + \tau_{WT}s} \quad (5)$$

where ΔP_{WT} represents the change in the WT output power, ΔP_{WT_inp} represents the WT input power, and τ_{WT} and K_{WT} are the time delay and gain of the WT power plant.

2.4. Hydro-Power Plant

The mathematical representation of the hydro-turbine and penstock could be represented by the following [42]:

$$G_{H-T} = \frac{-T_{HT}s + 1}{0.5T_{HT}s + 1} \quad (6)$$

where T_{HT} represents the water delay time. The hydro-turbine SG is given by the following:

$$G_{H-T-G} = \frac{T_Rs + 1}{(T_{GHYS} + 1)(T_Rs + 1)} \quad (7)$$

where T_R is the reset in time and T_{GHYS} represents the governor delay time.

2.5. Battery Energy Storage System

The battery energy storage system (BESS) has an important impact in the case of high contribution of renewable energies, owing to weather variations. When there is a surplus in the generated power, the BESS absorbs energy and then releases it during a power decrease. The mathematical representation of the BESS is given by the following [43]:

$$G_B = \frac{K_B}{\tau_Bs + 1} \quad (8)$$

where K_B and τ_B are the BESS gain and time constants, respectively.

2.6. The Power System

The rotor dynamics of power system synchronous generators in both areas is represented by the following:

$$G_{PS} = \frac{1}{\tau_{PS}s + D} \quad (9)$$

where τ_{PS} is given by $2H$, H represents the inertia of the machine, and D represents the coefficient of damping.

The governing equation of the speed governor and turbine are given as follows:

$$\frac{\Delta Y}{\Delta P_{ref} - \frac{1}{R} \Delta f} = \frac{1}{\tau_{SG}s + 1} \quad (10)$$

$$G_{T-DG} = \frac{1}{\tau_Ts + 1} \quad (11)$$

where ΔP_{ref} is the reference input power, ΔY is the change in the governor controlling valve position, R is the speed regulation coefficient, Δf is the change in frequency, τ_{SG} is the SG delay time, and τ_T is the turbine delay time.

The constants of the suggested system are given in Table 1, where all data are found in [1–3].

Table 1. System parameters.

Plant Type	Parameters	Plant Type	Parameters
Solar Thermal	$\tau_{S-TH} = 1.8 \text{ s}$	Power system	$H_1 = H_2 = 3 \text{ s}$
	$K_{S-TH} = 1.8$		$D_1 = D_2 = 1$
PV	$K_{G-STH} = K_{T-STH} = 1$	BESS	$R_1 = R_2 = 0.05 \text{ pu}$
	$\tau_{T-STH} = 0.3 \text{ s}$		$K_B = -0.003$
	$K_{PV} = 1$		$T_B = 0.1 \text{ s}$
	$T_{PV} = 1.8 \text{ s}$		$K_{WT} = 1$
		Wind Turbine	$T_{WT} = 1.5 \text{ s}$

3. Hippopotamus and One-to-One Based Optimizers

As mentioned in the introduction of this paper, metaheuristic techniques are used to LFC. For example, GA is used to tune fractional order PID controller in [44], while it is used to tune the gains of PID in [45]. HO and OOBO techniques have been realized for optimal estimation of the PI regulator for LFC of the TAPS. According to Amiri [46], HO has superior performance compared with other challenging heuristic optimizers, whereas, as stated by Dehghani [47], OOBO has an excellent convergence rate. Both techniques have been tested on numerous systems, and they have accurate results. More information about both optimizers can be found in [46,47].

Four performance indices can be utilized to measure the frequency error in PS. The first is the integral time weighted squared error (ITSE), the second is the integral time weighted absolute error (ITAE), the third is named the integral of square error (ISE), and the last one is the integral of absolute error (IAE). These four indices can be utilized as objective function (OF) for the heuristic optimizers; the most popular and commonly used is the ISE because of its high performance [48]. In the TAPS, this index is defined by the following:

$$OF = \int_0^{t_f} [\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2] dt \quad (12)$$

where Δf_1 and Δf_2 are the frequency deviations in areas 1 and 2, respectively. ΔP_{tie} is the tie line deviation.

4. Sliding Mode Control and Super Twisting

SMC was suggested and implemented in 1950 in the Soviet Union by Utkins and Itkis [49]. During the last years, there is a noteworthy attention on SMC. SMC is a robust procedure since it is not sensitive to system parameter variation [50]. Due to its implementation simplicity, it has gained widespread use in many applications [51]. SMC can benefit to achieve specific favorite control performance [52]. There are two phases for implementing SMC, the reaching phase, in which the trajectory moves in the direction of the switching surface and arrives there in a finite amount of time, and the sliding phase, in which the state trajectories slide and stay on this surface, which is referred to as the sliding surface [34].

There are many versions of SMC. ST has a high-performance control and is easy to implement. There is a common problem that exists in all versions of SMC, which is the chattering problem due to the high switching speed of SMC [53]. All SMC techniques intend to direct the controlled system to a specified surface called the sliding surface. An important requirement for the sliding surface is that it must be constructed to achieve the desired control objectives [51].

4.1. Super Twisting Control Law

The control input could be written as follows:

$$u = c |S|^{\frac{1}{2}} \operatorname{sgn}(S) + b \int \operatorname{sgn}(S) dt \quad (13)$$

If the area control error for area 1 is e_1 , then the sliding surface S is given as follows:

$$S = \dot{e}_1 + ce_1 \quad (14)$$

The proper values of c_1 and b_1 are vital for the selection of the sliding surface. In this paper, the values of c_1 and b_1 are obtained by using the HO. The HO will tune the sliding surface to obtain the optimal values of c_1 and b_1 .

4.2. Validation of the Proposed Scheme

In order to prove the high performance of the suggested technique, a simple TAPS model will be used. The block diagram of this system is shown in Figure 1, and the data are

found in [54]. The three techniques (ST, HO, and OBOO) are tested using the test system, and the values of the ST, OBOO PI controller, and HO controller are given in Table 2. The search space of the parameters of the PI controller ranges from 0 to 100; this range is decided after many trials to determine the stable region of the system. As noticed in Table 2, both OBOO and HO controller parameters have close values, which prove the accuracy of both methods. The frequency deviation in area 1 is shown in Figure 2, due to a step load change of 0.2 pu. As shown in Figure 2, the maximum overshoot (OS) in the case of ST is 1.4×10^{-3} pu, which is less than that obtained with the other methods, i.e., HO and OBOO controllers result in equal OS, which is 0.009 pu. The settling time is 7 s with ST, while it is 60 s with both HO and OBOO controllers. The drawback of the ST controller is the known chattering problem of the SMC.

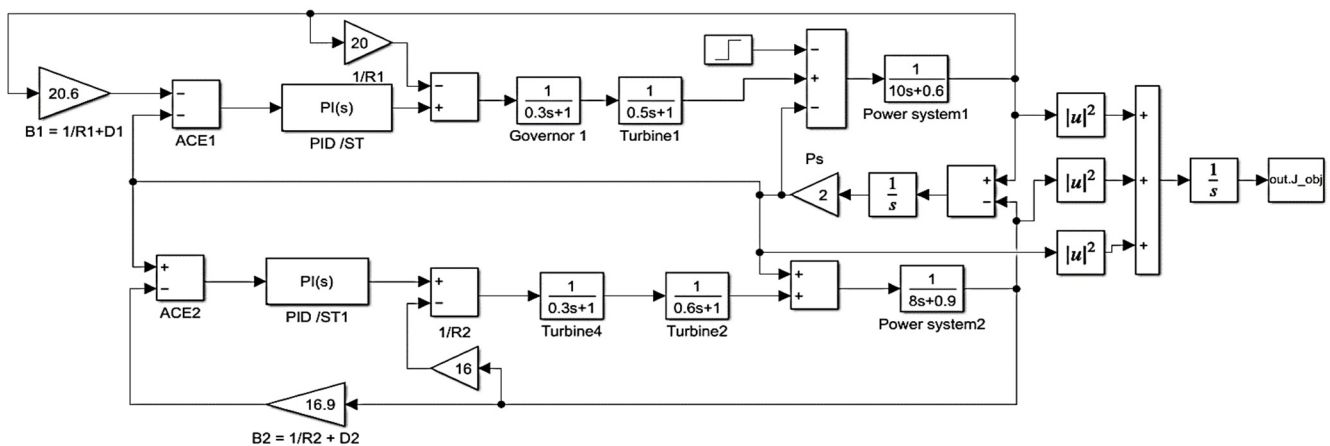


Figure 1. Test two-area system.

Table 2. Controller parameters.

Controller	Area 1		Area 2	
	K_{P1} (or c_1)	K_{I1} (or b_1)	K_{P2} (or c_2)	K_{I2} (or b_2)
OBOO	0.4658	0.6468	1.2780	0
HO	0.4365	0.6465	1.0949	0.0820
ST	3.8341	31.1777	1.8890	0.3802

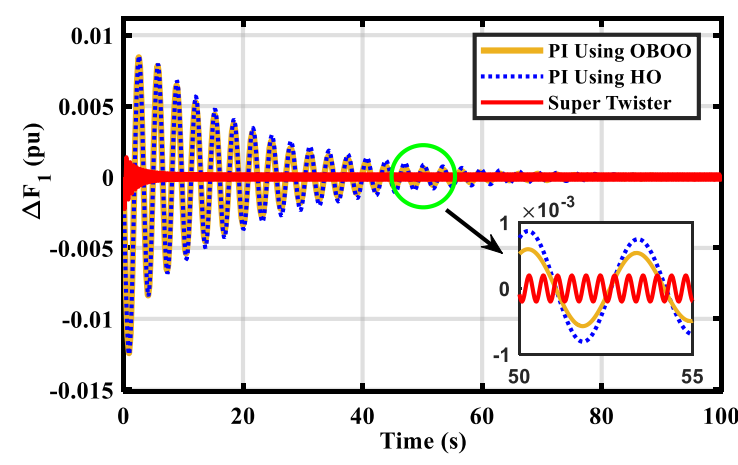


Figure 2. Frequency deviation in area 1 with the three controllers.

Figure 3 shows the frequency deviation in area 2, which has similar explanations as in the case of area 1, to confirm that the ST has the lowest OS and the least settling time as

compared to the other controllers. The tie line power in pu is shown in Figure 4. All the previous figures prove the high performance of the ST controller.

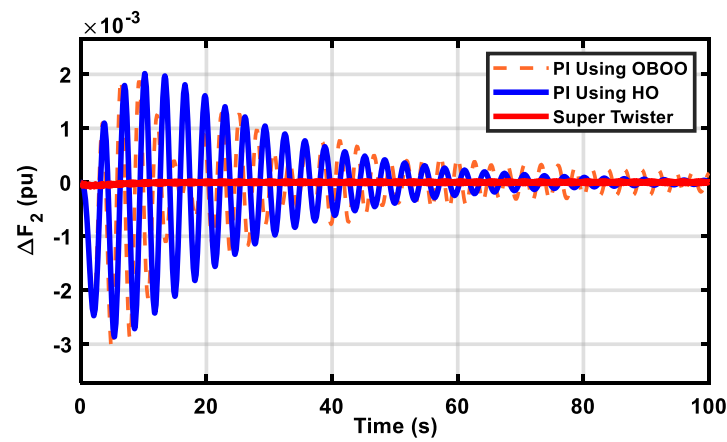


Figure 3. Frequency deviation in area 2 for the test system.

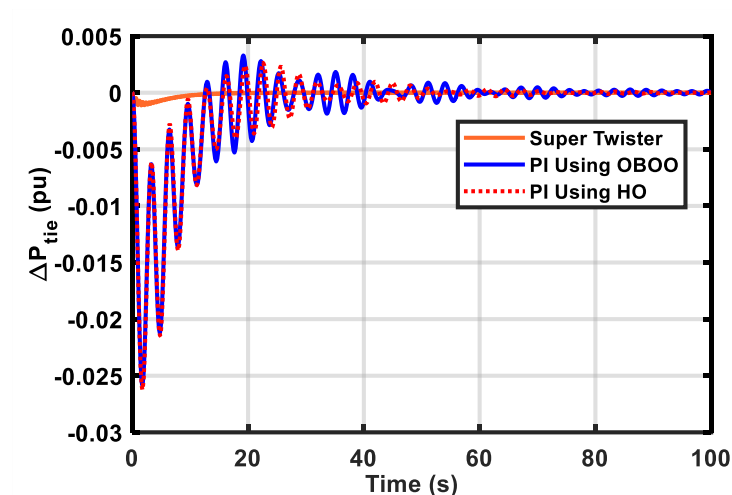


Figure 4. Tie line variation in pu for the test system.

5. Simulation Results

The suggested system is simulated employing SIMULINK, and it is shown in Figure 5, where all parameters are given in the figure. The analysis is performed by applying a sudden change in the load of 0.20 pu in the first area at time $t = 5$ s, followed by another load change at $t = 20$ s.

To implement both the HO and OBOO, the number of iterations for both optimizers is taken as 25, whereas the population size is 50. Table 3 shows the PI controllers' gains of both optimizers.

Table 3. Gains of the PI regulator.

Optimizer	Area One	Area Two	OF Value
HO	$K_P = 3.2998$ $K_I = 6.2767$	$K_P = 0.2770$ $K_I = 0$	3.8260×10^{-5}
OBOO	$K_P = 3.6424$ $K_I = 5.7919$	$K_P = 0.0240$ $K_I = 3.467 \times 10^{-4}$	1.05×10^{-5}

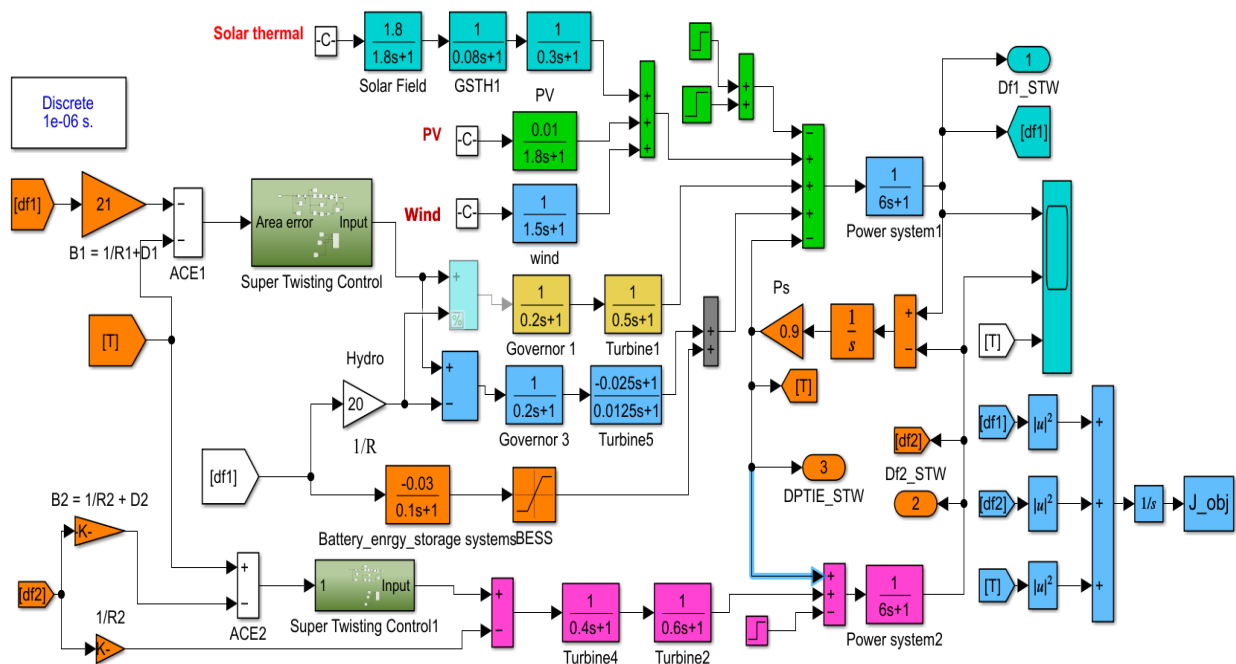


Figure 5. The studied two-area system.

In the next section, different cases will be implemented to test the performance of ST, HO, and OBO.

5.1. Case 1

In this event, the load in area 1 is suddenly raised by 0.2 pu at $t = 5$ s, and another load increase of 0.2 pu is applied at $t = 20$ s for a total 0.4 pu change in load power. As illustrated in Figure 6, the ST controller is capable of decaying any variation in frequency with almost zero state error. The maximum overshoot in frequency deviation in area 1 is less than 2×10^{-3} pu. Figure 7 demonstrates the deviation in frequency in area 2, which is very small and is less than 3×10^{-5} pu. Figure 8 shows the power variation in the tie line, which is also very small and is less than 6×10^{-4} pu. The previous figures verify the good performance of the ST regulator and its powerfulness for frequency and tie line power tuning.

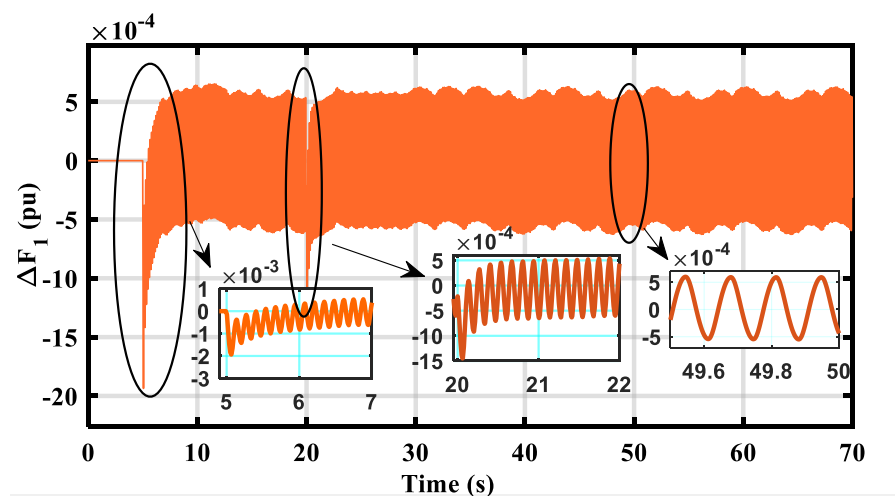


Figure 6. Frequency variation in area 1 caused by sudden change in its demand.

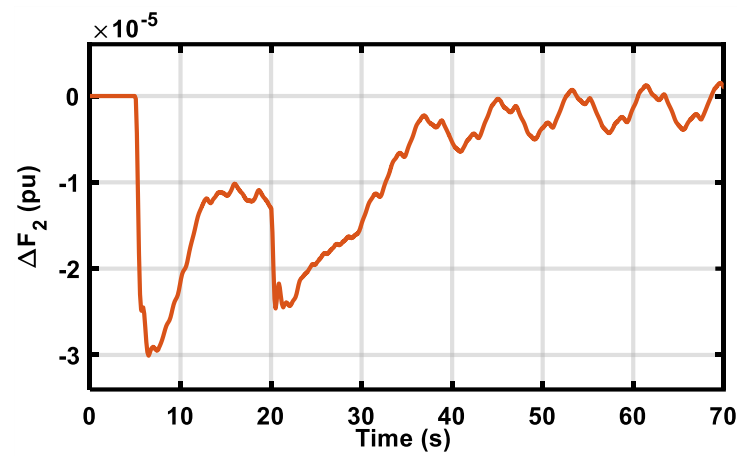


Figure 7. Frequency variation in area 2 caused by abrupt change in demand in area 1.

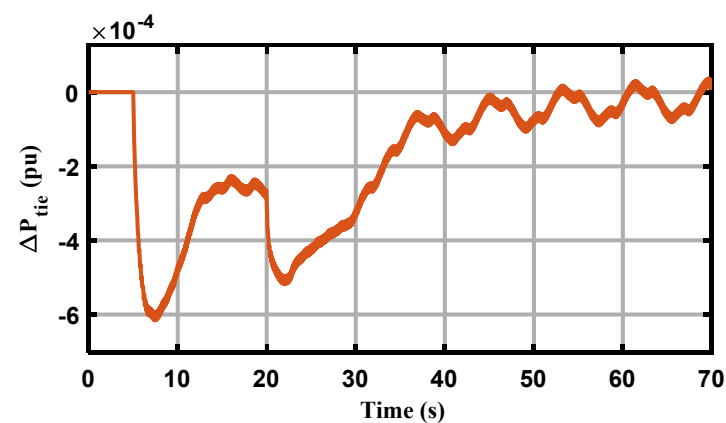


Figure 8. Tie line power variation caused by abrupt change in demand in area 1.

For the sake of comparison with the ST controller, both OBO and HO algorithms are used. The performance characteristics of the three controllers are given in Figures 9–11. Figure 9 displays the frequency variations in area 1; the advantage of the ST regulator over both the HO and OBO regulators is obvious in terms of overshoot, settling time, and steady-state error. Moreover, HO and OBO have close response characteristics.

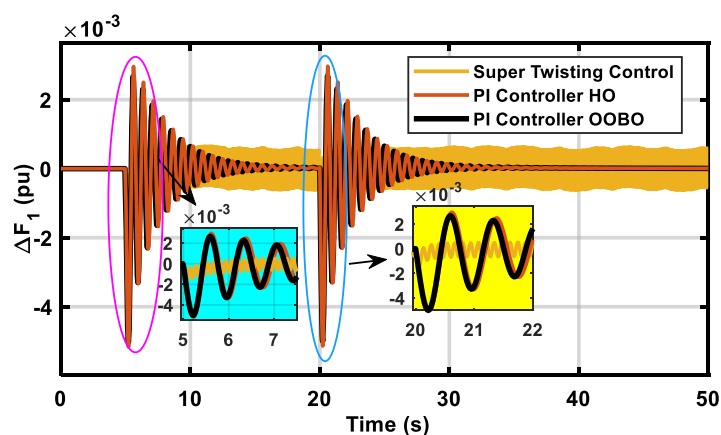


Figure 9. Frequency variation in area 1 with the three controllers.

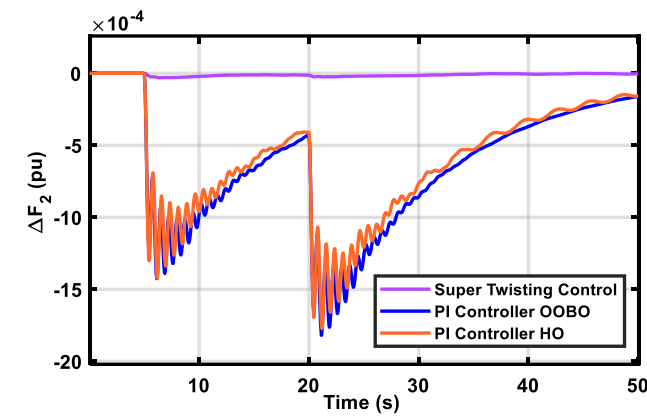


Figure 10. Frequency variation in area 1 with the three regulators.

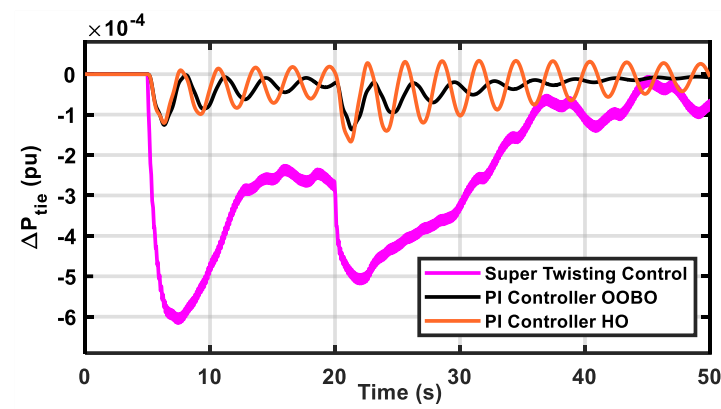


Figure 11. Tie line power variations with the three controllers.

Figure 10 shows the frequency fluctuations in area 2 for the three regulators. The frequency deviation is almost zero in the case of ST, whereas there are some oscillations in the case of the OOBO and HO regulators. Figure 11 shows the deviation in tie line power in pu, which is very small.

Table 4 summarizes the dynamic performance in case 1 for a load disturbance of 0.2. The maximum overshoot (OS) in frequency deviation in area 1 is less than 3×10^{-5} pu. The 2% settling time (T_s) with the ST proposed method is 6.6 s, while it is 19.5 s with HO and OOBO.

Table 4. Case 1 system dynamic performance.

Optimizer	Area One (ΔF_1 pu)	Area Two (ΔF_2 pu)
HO	OS = -2.96×10^{-3} T_s = 19.5 s	OS = -1.422×10^{-3} T_s = 19.5 s
OOBO	OS = -2.6×10^{-3} T_s = 19.95 s	OS = -1.425×10^{-3} T_s = 19.95 s
ST	OS = -1.88×10^{-3} T_s = 6.6 s	OS = -2.48×10^{-5} T_s = 6.6 s

5.2. Case 2

In this case, the load in area 1 is abruptly decreased by 0.2 pu at $t = 5$ s, and another load decrease of 0.2 pu occurs at $t = 20$ s for a total 0.4 pu change in load power. The response is nearly comparable to the preceding case, and the responses of frequencies and tie line power with the TA are demonstrated in Figures 12–14.

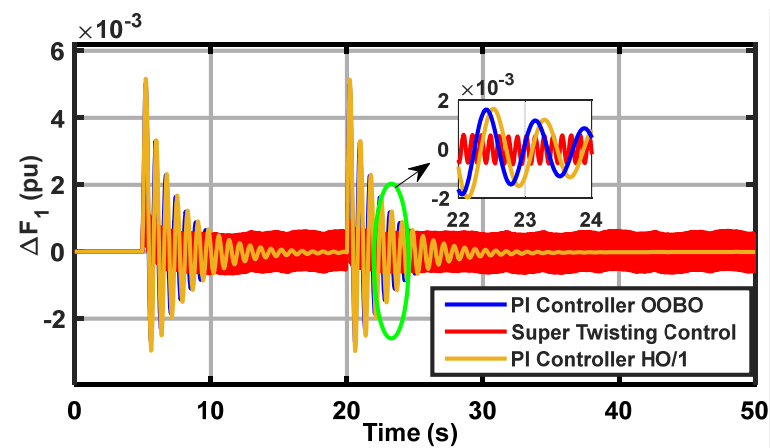


Figure 12. Frequency response in area 1 with the three regulators.

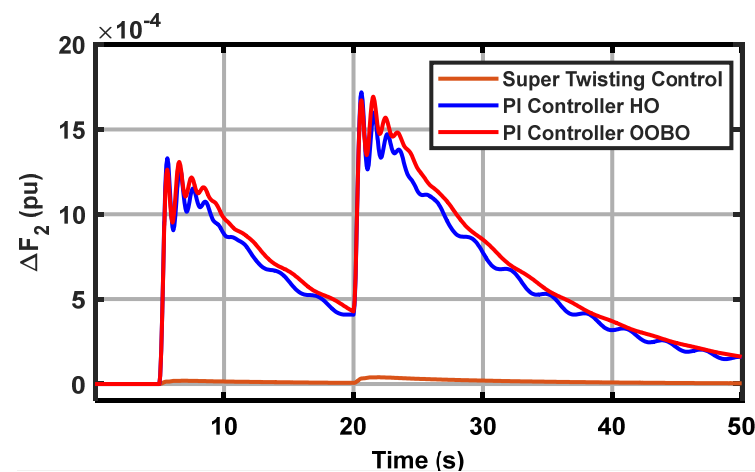


Figure 13. Frequency variation in area 2 with the three regulators.

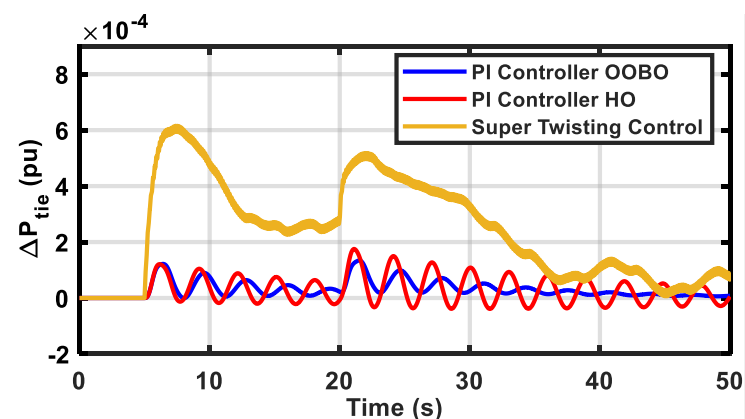


Figure 14. Tie line power variations for case 2.

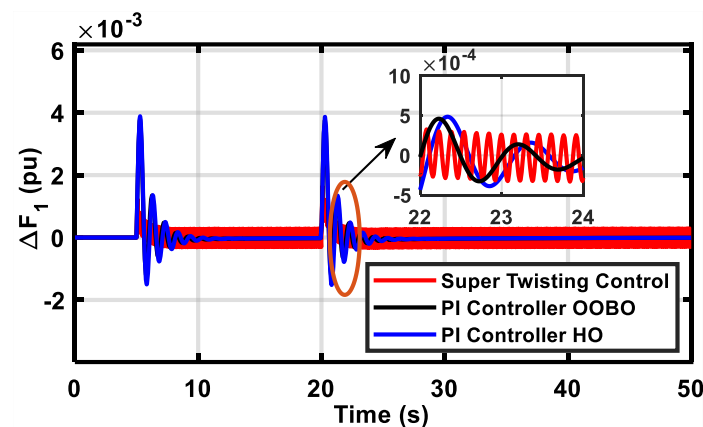
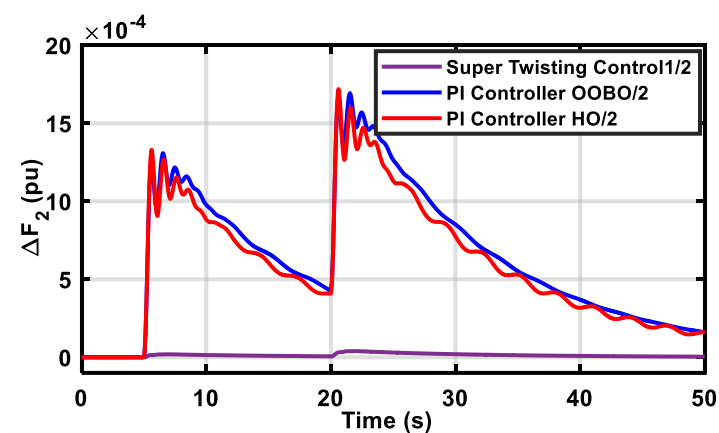
As illustrated by the previous figures, all the controllers can diminish any oscillations in frequency with almost zero state error. The OS in frequency deviation in area 1 is less than 3×10^{-5} pu. The Ts with the ST proposed method is 6.6 s in area 1 and 5.1 s in area 2, which is lower than that with HO and OOBO. Table 5 summarizes the dynamic performance in case 2 regarding the OS and TS.

Table 5. Case 2 system dynamic performance.

Optimizer	Area One (ΔF_1 pu)	Area Two (ΔF_2 pu)
HO	OS = -2.96×10^{-3} Ts = 19.5 s	OS = 1.33×10^{-3} Ts = 19.2 s
OOBO	OS = -2.6×10^{-3} Ts = 19.95 s	OS = 1.2635×10^{-3} Ts = 20 s
ST	OS = -1.88×10^{-3} Ts = 6.6 s	OS = 1.8×10^{-5} Ts = 5.1 s

5.3. Case 3

The ST controller is robust for any change in parameters; therefore, in this case, the power system time constant will be changed from 3 to 5 s for an approximately 67% change in the time constant in the presence of the disturbance as in case 2. The responses are exhibited in Figures 15 and 16. Figure 15 demonstrates the frequency response in area 1, and Figure 16 displays the frequency response in area 2. As observed in Figures 15 and 16, the ST has a very small effect by the parameter variation, which is the main feature of SMC, where other controllers are strongly affected by the parameter change, especially during transient. The maximum overshoot is 0.9×10^{-3} in the case of ST, while it is approximately 4×10^{-3} in the case of the other controllers, which prove the fact that ST is not affected to any parameter change.

**Figure 15.** Frequency deviation in area 1 with the three controllers.**Figure 16.** Frequency fluctuations in area 2 with the three controllers.

The proposed ST controller has a better performance regarding both OS and Ts as reported in Table 6.

Table 6. Case 3 system dynamic performance.

Optimizer	Area One (ΔF_1 pu)	Area Two (ΔF_2 pu)
HO	OS = 3.9×10^{-3} Ts = 11.4 s	OS = 1.332×10^{-3} Ts = 19.2 s
OOBO	OS = 3.77×10^{-3} Ts = 11.8 s	OS = 1.31×10^{-3} Ts = 20 s
ST	OS = 1.23×10^{-3} Ts = 6.2 s	OS = 5.5×10^{-5} Ts = 5.5 s

6. Conclusions

The goal of the present work is to use ST to control frequency in a TAPS with different energy sources with different dynamic characteristics. For the sake of comparison with the ST controller, two different controllers are used, OOBO and HO, to compute the optimal gains of the PI regulators. The optimal sliding surface for ST is obtained by both OOBO and HO, and the control law for ST is specified. The integral of square errors has been utilized as the OF to obtain the gains for both area controllers. Three cases are considered to test the performance of the three controllers. The first case is by increasing the demand in area 1 by 0.2 pu and another 0.2 pu at different times. The simulation results for this particular case show that the ST has a superior performance over the other controllers. Case 2 is by decreasing the load in area 1 by the same manner as in case 1, which has the same conclusion as the first case. Case 3 is by changing the time constant of the network. Case 3 proves that ST is not affected by parameter change, whereas other techniques are strongly affected by parameter change. Since only simple energy sources are considered in this paper, it is recommended that, for any future study, the exact models for each energy source should be considered.

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