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Whale Optimization Algorithm Based Tilt Integral Derivative Control for Frequency Regulation in AC Microgrid with and without SMES

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Abstract: This paper presents the control scheme for frequency regulation against step load perturbations in an AC microgrid using tilt integral derivative (TID) controller, optimally tuned employing whale optimization algorithm (WOA)- a recently proposed evolutionary algorithm. The AC microgrid system considered for this study comprises the distributed generation (DG) systems-consisting primarily the renewable energy sources (RESs)-, energy storage systems (ESSs), and the diesel engine generator (DEG). The performance of the control scheme is assessed in respect of effective regulation of system frequency within nominal limits as judged in terms of peak overshoot/undershoot, settling time and the minimum value of the performance index-integral of time multiplied absolute error (ITAE). For comparative analysis, the performance of the proposed control scheme is judged against the conventional and adaptive network fuzzy inference system (ANFIS)-PID controllers also. Further, the effect of superconducting magnetic energy storage (SMES) on the frequency regulation is also analyzed besides testing the proposed control scheme for stability and robustness against parametric uncertainty & random step load variations. The use of WOA for optimal tuning of TID controller is the novel proposition in this paper which proves to be a very effective strategy in containing the frequency excursions in the AC microgrid under different operating conditions as against the other controllers implemented here. MATLAB/Simulink is used as the platform for system modeling and simulations.

Keywords: WOA, AC Microgrid, Frequency Regulation, RESs, TID, SMES

1. Introduction

Due to ever-increasing power demand and the adverse impact of conventional power generation sources on the environment, there is a paradigm shift towards the use of RESs for power generation across the globe. But, there are issues associated with RESs due to the unpredictability of weather conditions which need to be addressed. However, the concept of microgrid, comprising small power generation units of some Kilo-Watt (KW) as DG units along with ESSs, has emerged in the recent decade or so as a way forward to utilize the RESs for power generation [1]. The AC microgrid structure shown in Figure 1 [5], is a cluster of RESs, controllable loads, and the ESSs demonstrating the concept of microgrid [2-3]. For detailed explanation, one can refer to [5]. The microgrid gets connected with the main grid through point of common coupling (PCC) known as a static switch and responds to main grid control signals. The microgrid is usually operated in any of the two modes of operation namely, islanded mode and grid-connected mode [4].

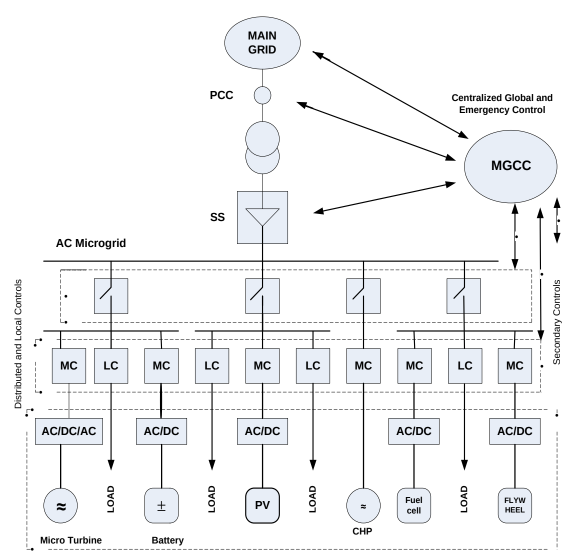

Figure 1. General Structure of AC Microgrid System [5].

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However, the focus of this study is the islanded mode of operation. In this mode, the microgrid is directly connected at the low or medium voltage at the distribution level. There are many control issues involved in the microgrid operation out of which frequency regulation is the most significant one and needs to be addressed by suitable control strategies [5] to ensure good quality of generated power. Therefore, the frequency regulation issue in AC Microgrid system with varying operating conditions has been taken up as is the focus of study in the present work.

Several control strategies have been reported in the literature for frequency regulation in microgrid when operating in islanded mode [6]. Synergetic use of battery energy storage system (BESS) with droop control is put forth in [7] for islanded microgrid which results in an improvement in transient frequency response. Demand response (DR) has also been demonstrated to provide reliable, low cost, and compatible alternative to conventional spinning reserve for supporting ancillary services [8]. A DR based algorithm, designed keeping into consideration the settling time, response of smart appliances, frequency peak overshoot time, is proposed in [9] for stabilizing system frequency. Advanced microgrid load management strategies are reported in [10] that enhance the operational capabilities of a microgrid in islanded mode. A new frequency regulation strategy, making use of the DR and the adaptive hill-climbing algorithm (AHC), is proposed in [11] to minimize the frequency deviations while at the same time regulating the voltage in a microgrid operating in islanding mode. A new droop algorithm based on voltage source inverter (VSI) output current is reported in [12] that facilitate sharing of reactive and active powers equally among all DG units aimed at regulating voltage/frequency. A control scheme is reported in [13] making use of a resistive load and permanent magnet AC machine in which wind energy is utilized for regulating frequency in a microgrid. A multistep load shedding scheme is presented in [14] for frequency regulation for inverter-based islanded microgrid system. Among many energy ESSs, SMES due to its fast dynamics and acting as an active power source, serves as an effective stabilizer for the frequency regulation in the event of sudden load changes [15-17].

The use of various evolutionary algorithms [18-21] for optimal tuning of controller gain parameters has been reported in respect of microgrid systems. For instance, Differential Evolution (DE) [18], Particle Swarm Optimization (PSO) [19], Hybrid Dragonfly (HDF), and Pattern Search (PS) [20] algorithms have been reported to have been used to optimize the gains of TID controller whereas Grey Wolf Optimizer (GWO) [21] to optimize the gains of fractional- order controller. Likewise, WOA, recently proposed by Mirjalili et.al [22], has found number of applications in many different areas such as Ladumor et al. [23] demonstrated the use of WOA in determining the solution of single area unit commitment problem, authors in [24] proposed optimal sizing and sitting of capacitors in the radial distribution network by the use WOA resulting in improvement of system stability, performance, and network reliability. A novel training algorithm based on WOA is proposed in [25] for optimizing the connection weights in neural networks and the results proved the effectiveness and competitiveness of the proposed algorithm as against other algorithms in respect of convergence speed and other performance measures. Authors in [26] demonstrated the use of WOA to see a liver position in the abdominal part of the body through liver segmentation in the MRI images. Authors in [27], effectively utilized WOA in optimal DG sizing and the effectiveness is demonstrated through its evaluation on typical IEEE 15, 33, and 85-bus radial distribution systems. WOA has found use in determining the emission constraint environment dispatch problem solution when the microgrid is operating in islanded mode [28]. Authors in [29] have tested WOA on IEEE 30-Bus System with six generating thermal units for the optimal solution of economic dispatch (ED) problem.

In the light of the above discussion, this paper presents the design and implementation of WOA optimized TID control scheme for frequency regulation in an AC microgrid under an islanded mode of operation subjected to load perturbations. For comparative analysis, some other evolutionary algorithms and the conventional controllers- integral, PI, PID-, optimized using WOA, have also been implemented. Also, the effect of SMES is analyzed besides assessing the stability with and without SMES and also the robustness under wide variations in system parameters and other random loading conditions.

This paper is organized as follows: After an introduction in Section 1, Section 2 explains the AC microgrid structure and describes the modeling of SMES. In Section 3, the control structure of TID controller and the WOA are explained. Simulation results are presented in Section 4 while Section 5 concludes the study.

2. System under Study

The AC Microgrid system structure as used in this work is as shown in Figure 2, which comprises DEG, wind turbine generator (WTG), solar photovoltaic (PV) system, fuel cell (FC), flywheel energy storage system (FESS), BESS, and SMES. The total generated power (P_s) in the AC Microgrid is the sum total of the powers from all sources and is given as in equation (1):-

$$P_s = P_{PV} + P_{WTG} + P_{FC} + P_{DEG} \mp P_{BESS} \mp P_{FESS} \mp P_{SMES} \quad (1)$$

Where,
P_{FC} is the power output of the DC-AC converter connected to FC
P_{PV} is the power output of the DC-AC converter connected to PV
P_{WTG} is the power output of WTG
P_{FESS} is the exchanged power of FESS
P_{BESS} is the exchanged power of BESS
P_{SMES} is the exchanged power of SMES and
P_{DEG} is the output power of DEG

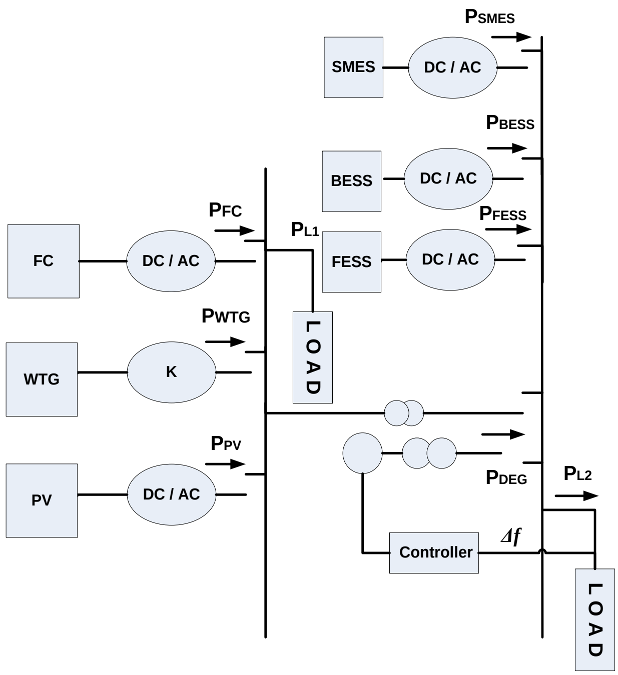

Figure 2. AC Microgrid System Configuration.

The ratings of the loads and DG units in (KW), as presented in Table 1, are adapted from [30]. DEG acts as a spinning reserve to supply power as per the need to regulate frequency. The transfer function representation of the microgrid model has been presented in Figure 3 with the parameter values given in Table 2 [5], [30].

TABLE 1. LOAD AND DG UNITS' RATING

DG Source	Rated Power (KW)	Load in (KW)	
PV	25	P_{L1}	220
WTG	125		
FC	70		
DEG	150	P_{L2}	200
BESS	40		
FESS	40		

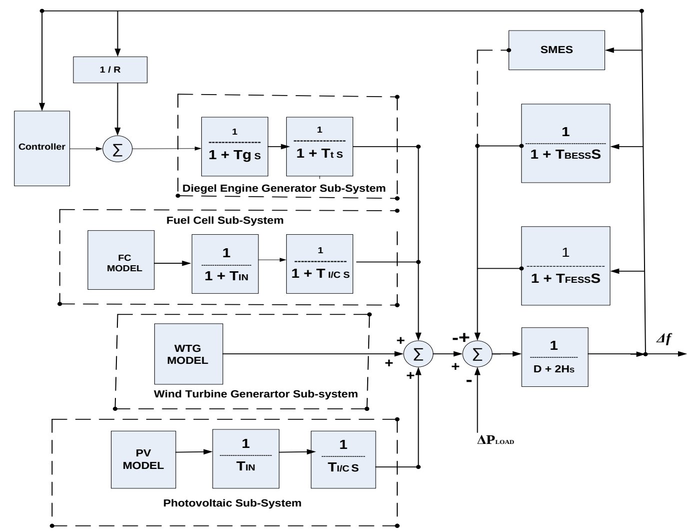

Figure 3. AC Microgrid Transfer Function Model.

TABLE 2. MICROGRID PARAMETER VALUES

Parameter	Values
D (pu/Hz)	0.015
H (pu s)	0.1667
T_{FESS} (s)	0.1
T_{BESS} (s)	0.1
R (Hz/pu)	3
Tg (s)	0.08
T_t (s)	0.4
$T_{I/c}$ (s)	0.004
T_{IN} (s)	0.04

The model of the microgrid is built and simulated in MATLAB/Simulink with the controllers and evolutionary optimization algorithms employed for frequency regulation study under the step load change disturbance.

2.1 SMES Modeling

The SMES is an active power source whose transfer function model is shown in Figure 4. Because of its fast dynamics, SMES can play an important role for frequency stabilization in power systems and for that matter in AC microgrid. The only drawback it suffers from is the requirement of very low temperature which is difficult to implement in practice. The detailed explanation on the working principle and mathematical equivalent can be referred from [15-16] whereas, a brief explanation is in order here.

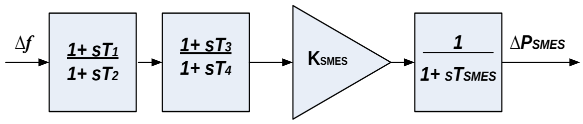

Figure 4. SMES Transfer Function Model.

Power expression is presented below where ΔP_{SMES}, the exchange power of SMES is described as

$$\Delta P_{SMES} = \left[\frac{1+sT_1}{1+sT_2}\right]\left[\frac{1+sT_3}{1+sT_4}\right]\left[\frac{K_{SMES}}{1+S^{T}SMES}\right]\Delta f \tag{5}$$

Where,
T_{SMES} is the SMES Time Constant
K_{SMES} is the Stabilization Gain
T_1, T_2, T_3, T_4, are the Time Constants
Δf is the SMES input signal

TABLE 3 SMES PARAMETER VALUES [17]

Parameter	Values
T_1	0.2333s
T_2	0.016s
T_3	0.7087s
T_4	0.2481s
T_{SMES}	0.03s
K_{SMES}	0.2618

For smooth working of SMES, the values of T_1, T_2, T_3, T_4, and T_{SMES}, as presented in Table 3 [17], are implemented, and the value of K_{SMES} used is the optimal value as obtained using WOA.

3. Control Structiures and Algorithm

The control structures and the evolutionary algorithms implemented here are explained in the following subsections:

3.1. Control Structure

The main control structure used in this work is TID, whereas, for comparative analysis, the conventional three-term controller- PID- and its variants are also implemented. These controllers are optimally tuned using WOA. TID controller essentially can be considered as a tuneable compensator with three control parameters i.e. K_P, K_I and K_D and one tuning parameter (n). TID resembles the PID controller structure with the proportional behavior, in this case, being represented by the transfer function: $s^{-1/n}$ or $1/S^{1/n}$. And this transfer function block, as shown in Figure 5, is known as 'Tilt' compensator, which along with other blocks put together establishes the TID compensator. It is known to have excellent characteristics in so far as maintaining the stability of system response under parametric variations and disturbance is concerned, besides being amenable to tuning easily [20], [31-32]. Tilted behaviour results in providing feedback gain in terms of frequency component which is tilted regarding the pick gain/frequency of the normal compensator. The TID can be mathematically described as in Eqn. (6) and (7).

$$U_{TID} = G_{TID}(s,\theta)\, E_{TID}(s) \tag{6}$$

$$E_{TID} = R_{TID}(s,\theta) - Y_{TID}(s) \tag{7}$$

Where, $G_{TID}(s,\theta)$ is the transfer function of the TID controller in s domain with $s \in \mathbb{C}$ and parameterized by $\theta \in R^4$.

The transfer function, $G_{TID}(s,\theta)$, can be expressed as in Eqn. (8)

$$G_{TID}(s,\theta) = \frac{K_T}{s^{\frac{1}{n}}} + \frac{K_I}{s} + K_S \tag{8}$$

$$\text{Where, } \theta^T = [K_T\ K_I\ K_D\ n] \tag{9}$$

Here, θ represents the vector comprising four control parameters- K_P, K_I, K_D, and n- where $n \in R$ and $n \neq 0$. TID controller has built-in flexibilities in respect of controller parameters with significant properties such as higher rejection ratio, simpler tuning, and less sensitive to deviations in plant parameters and hence less effect on closed-loop response. In this study, the TID controller parameters are tuned with an evolutionary optimization algorithm called WOA. Peak overshoot/undershoot, and settling time values usually are used as the performance measures of any system in the time domain. Further, usually, four different performance criteria: integral of squared error (ISE), integral of absolute error (IAE), integral of time multiplied squared error (ITSE) and ITAE are used for controller design [33]. Among all of these criteria, ITAE criterion integrates the absolute error with time multiplication, therefore, presents the actual error as is required for controller design. For this reason, ITAE finds merit in being selected as the objective function in this work. Limit on controller parameters restricts the controller gains and as such serves as the constraints for the optimization process. So, the optimization problem formulation is as under:

Minimize *J*
Subject to
$K_{P\,min} \le K_P \le K_{P\,max}$
$K_{I\,min} \le K_I \le K_{I\,max}$
$K_{D\,min} \le K_D \le K_{D\,max}$
$n_{min} \le n \le n_{max}$

Where, J represents fitness function, while $K_{X\,min}$ and $K_{X\,max}$ represent the minimum and maximum values of controller gain parameters.

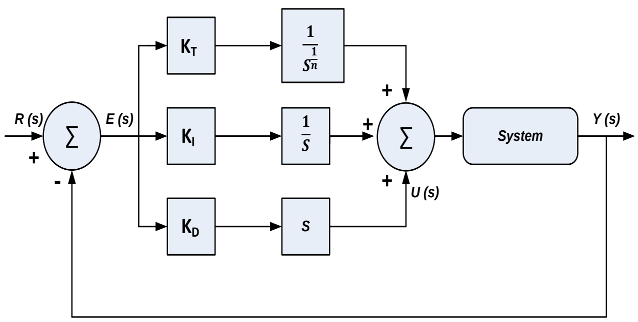

Figure 5. TID Controller Structure.

3.2. Whale Optimization Algorithm (WOA)

WOA is the recently introduced new search heuristic algorithm [22] which is centered around the idea of simulated hunting behavior of humpback whales. The WOA mutation process is governed by the difference between the sampled pairs of solutions in the population.

The optimization process involves a number of variables D, formulated as dimensional vector D, and population of X solution vectors generated randomly that remains restricted between parameter bounds. The algorithm runs in an iterative process in order to further improve the solution. With this brief background, the working of WOA is explained with the help of a flowchart as presented in Figure 6. For details of WOA, readers are referred to [22]. While implementing the algorithm in this work, the maximum number of iterations of search agents is taken as 30 each.

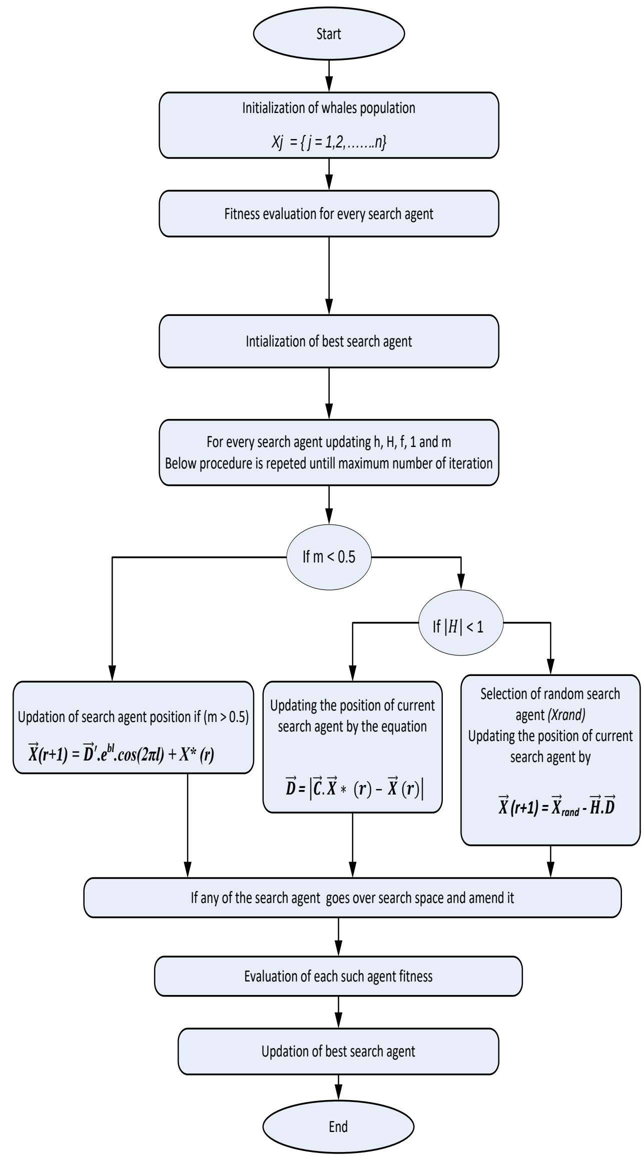

Figure 6. WOA Flow Chart.

4. Results and Discussion

The system of Figure 3 is investigated under the following scenarios:

4.1) Comparative analysis of WOA performance
4.2)TID controller implementation and its comparative performance analysis
4.3) Effect of SMES
4.4) Stability Assessment
4.5)Sensitivity Assessment concerning Parametric Variations and
4.6) Performance under random load change

For the implementation of optimization algorithms, MATLAB programs (.m files) are developed and executed with ITAE, as per Eqn. (10), being used as the cost function known to be giving the minimum values of the peak undershoot/overshoot and the settling time [33].

$$\text{ITAE} = \int_0^T |\Delta f| . t . dt \qquad (10)$$

Where T is the simulation time, Δf is the change in frequency

The values of 'n' are taken as bounded in the range [2 to 3] [32] whereas, the values of controller parameters: K_P, K_I, K_D are considered in the range of [-2 to 2]. But, in case of ANFIS-PID controller, the input scaling factors: K_1 and K_2 are considered in the range of [0 to 1]. The step load change is considered as 10%. TID controller optimally tuned using WOA constitutes the novel control strategy put forth in this work.

4.1) Comparative Analysis of WOA Performance

To assess the supremacy of the WOA, the system of Figure 3 without SMES is simulated for frequency regulation under 10% step load perturbation with the TID controller, optimally tuned with WOA, that gives the optimal values as: n = 2.1156, K_P = 0.9967, K_I = -0.1962, and K_D = 0.0521. Besides WOA, the system is also studied by employing other evolutionary algorithms: DE, PSO, and GWO, independently, for tuning the TID controller parameters. The performance of the system is assessed in terms of peak undershoot, settling time, and the minimum values of the performance index, ITAE.

Figure 7 shows the response of all the algorithms qualitatively, whereas in Table 4 is given the quantitative comparison of different optimization algorithms. From Figure 7 and Table 4 and the effectiveness of WOA over other algorithms is established. As can be seen in figure 7, the response with WOA is less oscillatory and settles relatively faster as compared to others. Also, Table 4 makes it clear that the values of settling times, peak undershoots, and the ITAE are the minimum in case of WOA. Therefore, the WOA has proved to be very competitive and turns out to be the outperforming other algorithms.

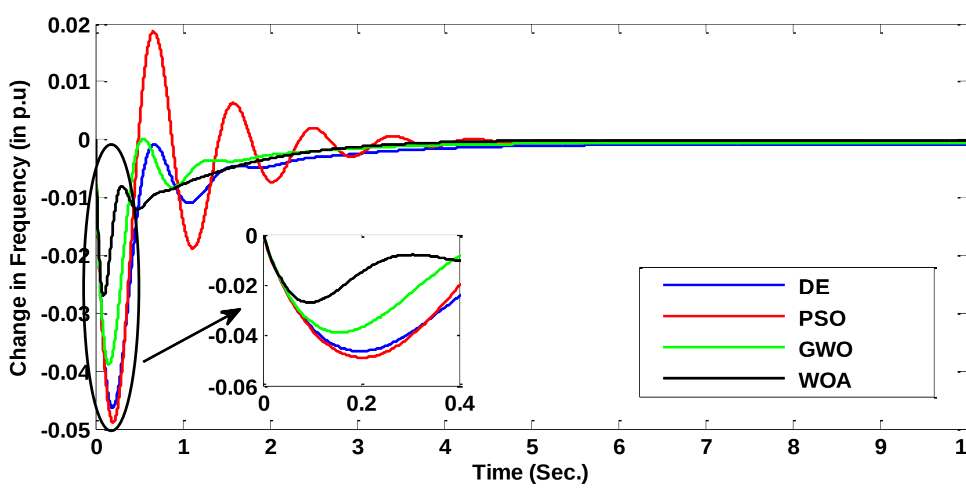

Figure 7. Frequency Deviation Responses.

TABLE 4. COMPARISON OF DIFFERENT OPTIMIZATION ALGORITHMS

Controllers	DE-TID	PSO-TID	GWO-TID	WOA-TID
ITAE	0.0705	0.0420	0.0333	0.0233
Settling Time	3.5844	3.3629	3.5348	3.0743
Peak Undershoot	0.0463	0.0429	0.0366	0.0287
Controller Parameters				
K_P	0.1934	1.7644	0.7921	0.9967
K_I	-0.1146	-0.0928	-0.0835	-0.1962
K_D	-0.3580	-0.2821	-0.0345	0.0521
n	2.8557	2.5698	2.9380	2.1156

4.2) TID controller implementation and its comparative performance analysis

The TID controller and for its comparative performance analysis, the conventional Integral, PI, PID, and ANFIS-PID controllers, all optimally tuned using WOA, are implemented on the system model shown in Figure 3 but without SMES and the performance in respect of frequency regulation is studied with step load change of 10%. Figure 8 depicts the comparative performances of these controllers in terms of frequency deviations qualitatively, whereas in Table 5 gives the quantitative comparison of performances of different co-

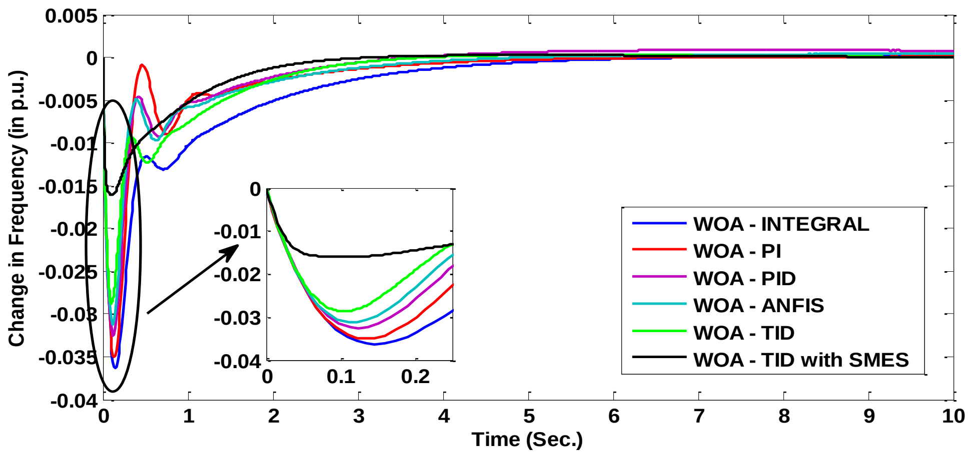

Figure 8. Frequency Deviation Responses.

TABLE 5. COMPARATIVE ANALYSIS OF DIFFERENT CONTROLLERS

Controllers	WOA-Integral	WOA-PI	WOA-PID	WOA-ANFIS	WOA-TID (without SMES)	WOA-TID with SMES
ITAE	0.0415	0.0405	0.0358	0.0304	0.0233	0.0160
Settling Time	4.9127	4.0555	3.8300	4.3179	3.0743	2.6904
Peak Undershoot	0.0363	0.0326	0.0326	0.0312	0.0287	0.0161
Controller Parameters						
K_P	--	1.5221	1.2221	1.3109	0.9967	0.8196
K_I	0.0122	0.0201	0.2231	0.2607	-0.1962	-0.1662
K_D	--	--	0.1667	0.0909	0.0521	0.0503
n	--	--	--	(K_1) 0.2551	2.1156	2.2488
	--	--	--	(K_2) 0.3156	--	--

trollers in terms of standard performance measures viz. peak undershoots, settling time and the minimum values of the cost function-ITAE.

In frequency regulation studies, peak undershoot carries a significant role vis-à-vis the settling time. From the comparative analysis of results, as presented qualitatively and quantitatively in Figure 8 and Table 5, respectively, it is clearly evident that the proposed WOA optimized TID controller proves very effective in improving the frequency regulation performance as compared to the other controllers implemented here and the system dynamics get improved in respect of less oscillatory response. The settling times and the ITAE values are the least in the case of WOA-TID, as can be seen in Table 5.

4.3) Effect of SMES

SMES basic configuration in respect of the transfer function model is shown in Figure 4. To study the effect of SMES on the frequency regulation, SMES is integrated as constituent in the system model as presented in Figure 3 with TID controller being the control strategy. The stabilization gain (K_{SMES}) of the SMES is optimized using WOA and implemented in simulations. The comparative transient behavior with and without SMES is shown in Figure 8 and Table 5. From the response, it can be observed that with SMES the transients of system frequency get suppressed faster which in a way means the

SMES has a positive effect on the system response reflected in terms of minimum frequency undershoots and mitigation of oscillations sooner than the case without SMES.

4.4) Stability Assessment

The stability of the closed-loop system model is investigated in terms of eigenvalues which for this study are as presented in Table 6. As can be seen, all the eigenvalues lie in the left half of's' plane meaning thereby the closed-loop system is stable. Further, most of the closed-loop eigenvalues have a sufficiently negative real part, which means the closed-loop system has reasonable stability margin. Another observation is that the imaginary part being very small results in the smooth and fast decay of system dynamic responses.

TABLE 6. CLOSED-LOOP SYSTEM EIGEN-VALUES

Without SMES	With SMES	
-0.0374 + 0.0989i	-0.4676 + 0.3793i	-0.4676 - 0.3793i
-0.0374 - 0.0989i	-0.0479 + 0.0634i	
-0.1302 + 0.0000i	-0.0479 - 0.0634i	
-0.0453 + 0.0000i	-0.1288 + 0.0000i	
-0.0006 + 0.0000i	-0.0006 + 0.0000i	
-0.1000 + 0.0000i	-0.0479 + 0.0000i	
0.0000 + 0.0000i	-0.0413 + 0.0000i	
-0.0067 + 0.0000i	-0.1000 + 0.0000i	
-2.5000 + 0.0000i	0.0000 + 0.0000i	
-0.2500 + 0.0000i	-0.0067 + 0.0000i	
	-2.5000 + 0.0000i	
	-0.2500 + 0.0000i	

4.5) Sensitivity Assessment with regard to Parametric Variations

The sensitivity of the system (Figure 3) to parametric variations is also investigated while the control strategy used is TID controller, optimally tuned using WOA, and the perturbation is in terms of step load change of 10%. The frequency deviation responses with ± 25, and ± 50 variations in parameters without and with SMES, respectively are presented in Figures 9 and 10 whereas; the normal values of system parameters are as given in Table 2. The TID controller parameters are kept constant as at normal values of system parameters. As can be inferred from Figures 9 and 10, the control scheme is very robust against the parametric variations meaning thereby less sensitive to the parametric variations. The controller is able to maintain frequency stability.

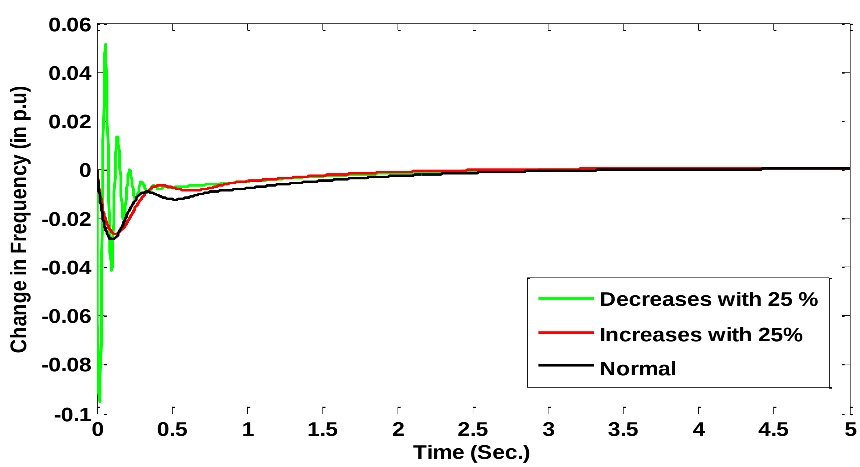

Figure 9. Frequency response using TID Controller without SMES.

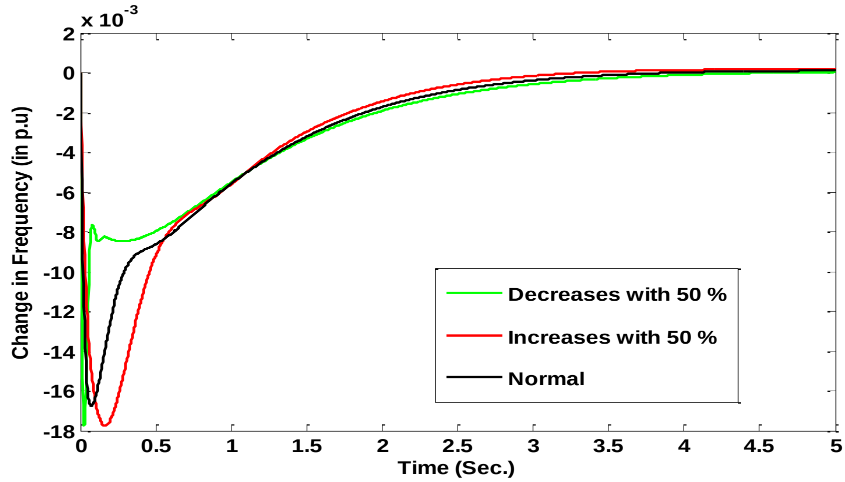

Figure 10. Frequency response using TID Controller with SMES.

Further, to assess the sensitivity against any random parametric variation, the system parameters are significantly changed as per Table 7. Figure 11 gives the closed-loop frequency response of the system under these random changes in system parameters whereby it is clear that the conventional PID controller gives a degraded response with these parametric changes whereas, the TID controller is effectively able to handle these variations.

TABLE 7 UNCERTAIN PARAMETERS AND THEIR VARIATION RANGE

Parameter	Actual Value	Variation Range	New Value
R	3	+25%	3.75
D	0.015	-50%	0.0075
H	0.08335	-45%	0.04584
T_t	0.4	-45%	0.22
T_g	0.08	+55%	0.124
T_{FESS}	0.1	+40%	0.14
T_{BESS}	0.1	+50%	0.15

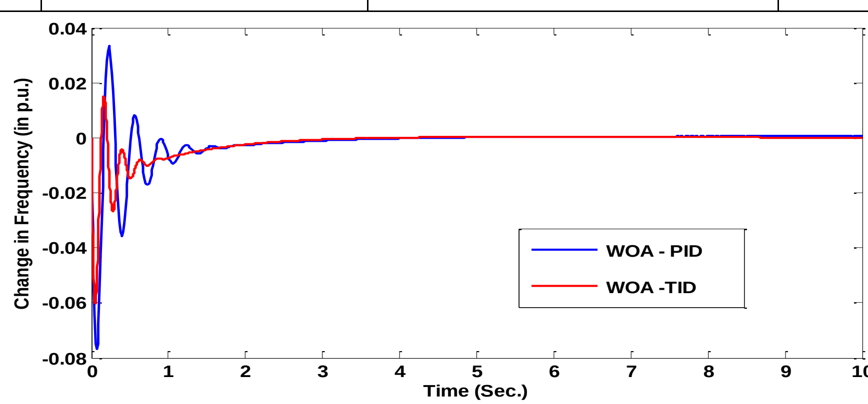

Figure 11. Frequency Response under the parametric changes as per Table 7.

4.6) Performance under random load change

The frequency regulation is also studied under the random load changes as per the pattern shown in Figure 12, which is variable both in duration and magnitude. For the comparative analysis, the performance of the WOA optimized TID controller is compared with that of the WOA optimized PID controller. As can be seen in Figure 13, the TID controller gives reasonably good results as compared to the conventional PID against the random load conditions. Also, the effect of SMES is visible here in this Figure.

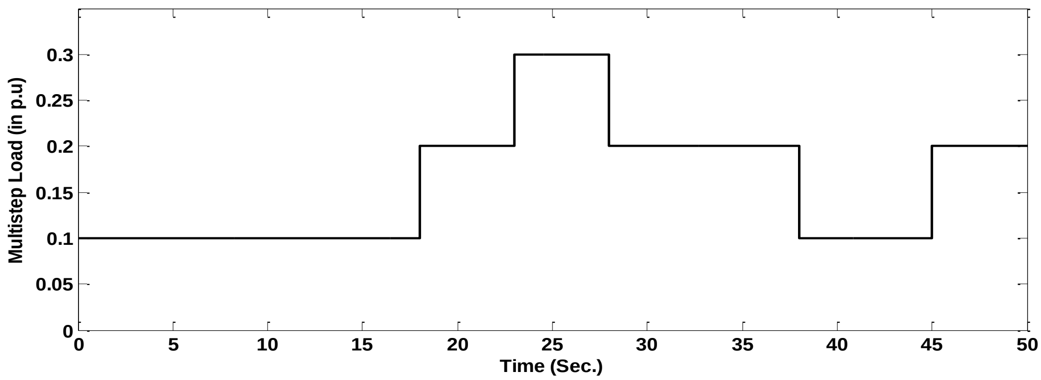

Figure 12. Random Loading Pattern.

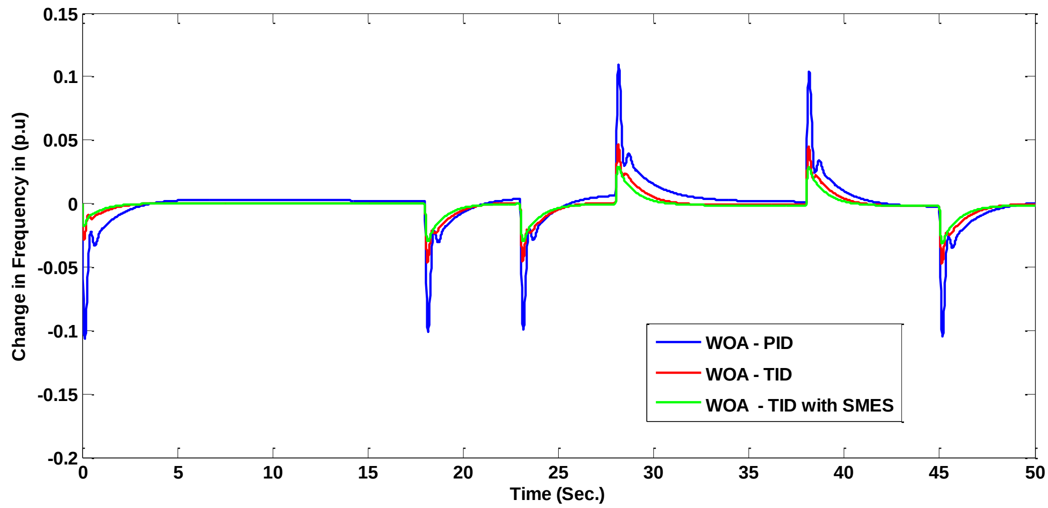

Figure 13. Frequency Response under random load variations.

5. CONCLUSIONS

This paper first establishes the supremacy of WOA as against some other evolutionary algorithms and then the WOA is put to use to optimally tune the TID controller which is employed as the novel control strategy for frequency regulation in the AC microgrid under varied operating conditions in terms of load variations. Comparative performance analysis of the proposed control strategy is also carried out against the conventional and ANFIS-PID controllers. Further, the effect of SMES on frequency regulation is also investigated besides testing the proposed control strategy against random load and the system parametric variations. It is observed that when the SMES is used in coordination with BESS and FESS, the system performance gets improved and the frequency transients are suppressed to a large extent. The sensitivity analysis carried out against the system parametric variations and the random load changes proves the robustness of the proposed scheme. As per the simulation results, the WOA optimized TID control scheme holds good potential in frequency regulation applications in AC microgrid systems.

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