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Power and Frequency Control of a Wind Energy Power System using Artificial Bee Colony Algorithm

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***Abstract*—The intermittent wind speed and load demand lead to fluctuation in system frequency (f) and power (P), which may cause serious problems for wind energy power system (WEPS). An energy storage device can be used to compensate for these disturbances. In addition, a damping controller can be employed to reduce oscillation associated with f and P. In the present work, superconducting magnetic energy storage (SMES) with power system stabilizer (PSS) is connected to the WEPS to control the fluctuation in f and P. A recently developed swarm intelligence technique, i.e., artificial bee colony (ABC) algorithm based proportional–integral–derivative (PID) controller is also used along with SMES and PSS to overcome the associated problem in WEPS. The control parameters of SMES, PSS and PID controller have been optimized by the ABC algorithm. Effectiveness of the WEPS model has been evaluated under various disturbances. The simulation results show minimum f and P deviations can be obtained by the proposed ABC based PID controller along with PSS and SMES.**

Keywords*—*wind energy power system, superconducting magnetic energy storage, power system stabilizer, artificial bee colony, proportional integral derivative controller

I. Introduction

In the last two decades, demand for renewable energy has been increased in electricity generation due to limited fossil fuel and environmental concern [1]. The contribution of wind energy is more among several renewable energy sources, because of wind availability and pollution free. However, its integration in utility grid may cause problems to the system's operation and control [2], [3]. In particular, frequency (f) and power (P) deviates as load demand and wind energy is variable in nature. Moreover, the insufficient system damping for frequency oscillations may lead to a serious problem in power flow [4]. In such cases, energy storage devices with power system stabilizer (PSS) may cause an essential task in enhancing system stability by controlling its f and P and so allowing an increased integration of wind energy in the power system. In this paper, to improve the quality of generated power and for uninterrupted power supply, wind turbine generator (WTG) system is coupled with diesel generator (DG) and an energy storage device such as superconducting magnetic energy storage (SMES) with PSS is introduced. This complete wind energy power system has been termed as "WEPS". The SMES provides adaptability and quick regulation, as it can accumulate the excess active power and deliver the same for varying load demand [5]. For damping the oscillation in f and P, the dynamic characteristics of PSS have been added [6] to the SMES device and has been termed as "SMPS". To enhance the contribution of wind energy in the WEPS, optimized control for power generation is also required.

Bio-inspired based swarm intelligence technique and evolutionary computation are recently evolved dominant optimization algorithms for optimum solution of complicated problems [7]. Artificial bee colony (ABC) algorithm developed by D. Karaboga is a new swarm intelligence algorithm, based on searching behavior of honey bees [8]. It has shown great performance and accuracy to solve many problems in power system such as optimal power flow, automatic generation control, economic load dispatch, unit commitment and many others [9]–[12]. The main benefits of this technique are its accuracy, simplicity, higher convergence rate, few control parameter requirements and independent of the initial conditions. In this paper, Artificial Bee Colony (ABC) algorithm based proportional integral derivative (PID) controller has been designed. It is also applied to optimize the control parameters of SMPS block in the WEPS model.

The content of the paper is coordinated as follows. Section II describes modeling of different energy sources in WEPS. In Section III, the mathematical problem of the present work is formulated. The ABC based optimization algorithm is presented in Section IV. Simulation results are presented and discussed in Section V. Finally, the conclusion is drawn in Section VI.

II. System Modeling

The WEPS model contains WTG and DG with their corresponding ABC based PID controllers for keeping the system in equilibrium state. In the present work, the WEPS considered is of 150 kW WTG and 150 kW DG [13]. To overcome the deviation in system f and P due to the fluctuation in load demand or/and wind speed, SMPS has been added to the WEPS. The block diagram of the considered model is shown in Fig.1 and its parameters are presented in

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Table 1. The total power output deviation (ΔP_T) of the system is evaluated by (1).

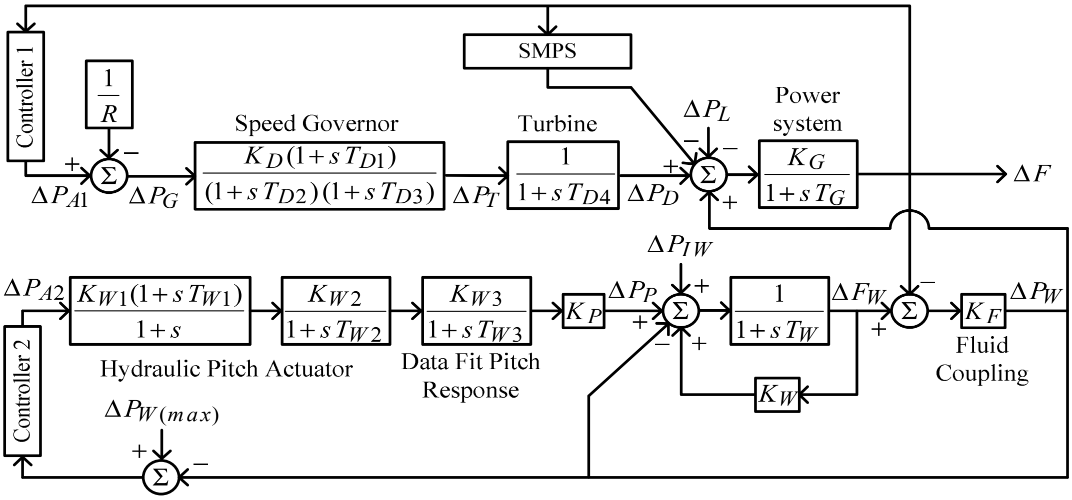

Fig 1. Block diagram of the WEPS model

$$\Delta P_T = \Delta P_W + \Delta P_D - \Delta P_S - \Delta P_L \tag{1}$$

Where, ΔP_W , ΔP_D and ΔP_S is the output power deviation in WTG, DG and SMPS and ΔP_L is the deviation in load demand.

TABLE I. PARAMETERS OF WEPS MODEL

Model	Parameter
WTG	$K_{W1}=1.25,\ K_{W2}=1,\ K_{W3}=1.4,$ $K_P=0.08,\ K_W=0.0033,\ K_F=1.494,$ $T_{W1}=0.6$ s, $T_{W2}=0.041$ s, $T_{W3}=1$ s, $T_W=4$ s
DG	$K_D=0.333,\ T_{D1}=1$ s, $T_{D2}=2$ s, $T_{D3}=0.025$ s, $T_{D4}=3$ s
SMPS	$K_S=80,\ T_S=10$ s, $I_{S0}=2$
Power system	$K_G=72,\ T_G=14.4$ s, $R=5$

A. Modeling of WTG

From Fig. 1, the WTG model consist of hydraulic pitch actuator, data fit pitch response, turbine and fluid coupling coupled with generator. The modeling equations of WTG in s-domain are expressed by (2)-(5).

$$\Delta P_P = K_P \frac{K_{W1}K_{W2}K_{W3}(1+sT_{W1})}{(1+s)(1+sT_{W2})(1+sT_{W3})}\Delta P_{A2} \tag{2}$$

$$\Delta F_W = \frac{1}{1+sT_W}(K_W \Delta F_W - \Delta P_W + \Delta P_P + \Delta P_{IW}) \tag{3}$$

$$\Delta P_W = K_F(\Delta F_W - \Delta F) \tag{4}$$

$$\Delta F = \frac{K_G}{1+sT_G}(\Delta P_W + \Delta P_D - \Delta P_S - \Delta P_L) \tag{5}$$

B. Modeling of DG

When the power generated by WTG is not adequate to fulfill the load demand, DG system works to supply the shortage power in WEPS. From Fig. 1, the modeling equations of DG in s-domain are given by (2)-(5).

$$\Delta P_G = \Delta P_{A1} - (1/R)\Delta F \tag{6}$$

$$\Delta P_T = \frac{K_{D1}(1+sT_{D1})}{(1+sT_{D2})(1+sT_{D3})}\Delta P_G \tag{7}$$

$$\Delta P_D = \frac{1}{1+sT_{D4}}\Delta P_T \tag{8}$$

C. Modeling of SMPS

When there is an abrupt variation in load demand or wind energy, the accumulated energy in SMPS is released immediately to the system, as the governor and other control device initiate to establish the WEPS to a new stable state. The input control signal to the SMPS block is the frequency deviation (ΔF) signal as shown in Fig. 2. The equations of deviation in voltage, inductor current and active power output are given in (9)-(11).

$$\Delta E_S = \frac{1}{1+sT_S}\left(K_S \frac{(1+sT_1)(1+sT_3)}{(1+sT_2)(1+sT_4)}\Delta F - K_I \Delta I_S\right) \tag{9}$$

$$\Delta I_S = \frac{1}{sL}\Delta E_S \tag{10}$$

$$\Delta P_S = \Delta E_S(\Delta I_S + I_{S0}) \tag{11}$$

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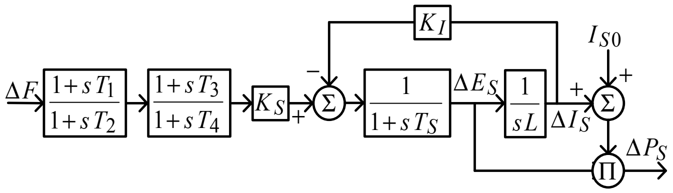

Figure 2. Block diagram of the SMPS model

III. MATHEMATICAL PROBLEM FORMULATION

The main objective in this paper is to bring the deviation of f and P close to zero as soon as possible, whenever the system goes through wind speed change or/ and disturbances in load demand. In order to acquire this, the objective function is formulated for modeling of the ABC based PID controller and for finding the optimized control parameters of SMPS unit. The most frequently applied performance metrics are integral absolute error (IAE), integral square error (ISE) and integral of time weighted squared error (ISTE) [14]. Among these, ISTE is selected as the objective function due to having some advantages over other two metrics [20]. The constrained optimization problem for the tuning of parameters of the WEPS is subjected to their limits. Expression for the IAE, ISE and ISTE is given below in (12).

$$\left.\begin{aligned} IAE &= \int_0^\infty |\Delta F|\,dt \\ ISE &= \int_0^\infty |\Delta F|^2\,dt \\ ISTE &= \int_0^\infty t|\Delta F|^2\,dt \end{aligned}\right\} \tag{12}$$

IV. ABC ALGORITHM

The ABC algorithm begins by defining some variables such as population of bees (SN), maximum cycle number (MCN), objective function and function variables. Functions for testing the probability, fitness and optimization of the objective function are also included. Each honey bees are divided into three types: Employed, Onlooker and Scout bees, which are assigned for different task according to their behavior. The whole searching procedure of this algorithm in each cycle is grouped into four steps: initialization, employed, onlooker and scout step [15]. In the initialization state, the ABC algorithm generates SN initial solutions of randomly chosen population. Each i[th] solution is obtained, within its upper (x_j^{max}) and lower (x_j^{min}) range of the selected j[th] decision variable, using (13).

$$x_{ij} = x_j^{min} + rand[0,1](x_j^{max} - x_j^{min}) \tag{13}$$

$$i = 1,2,3,\ldots,SN \text{ and } j = 1,2,3,\ldots,D$$

Where, D is the number of decision variables in the corresponding objective function.

After initialization step, all SN solutions proceed through consecutive cycles of other three steps until MCN is reached. In each cycle, every employed and onlooker bees generates a new food source v_{ij} by updating the associated food source x_{ij} by (14).

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}), \text{ while } i \neq k \tag{14}$$

Where ϕ_{ij} is a random number between [−1, 1] and $k = 1,2,3,\ldots,SN$. ϕ_{ij} is used to vary the positions of food sources around x_{ij}. The difference between x_{ij} and x_{kj} in (14) close to zero, leads the solution to its optimized value.

A specific food source is chosen by onlooker bees based on its probability (P_i) for selecting better nectar, which is analyzed by the expression in (15).

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \tag{15}$$

Where fit_i is its fitness value of the food source i. The fitness value is tested for updated candidate solution v_{ij} in (14) and its value is compared with old one. The solution having better fitness is memorized. If the fitness value of a specific food source is not improved till predefined limit, it is abandoned and replaced by new source found by scout bees according to (13). After this, the whole procedure is repeated and memorizes the best solution searched so far.

The processes of ABC algorithm in stepwise are given below.

a) Initialize the population with random solutions x_{ij} using (13)

b) Find the fitness of the population

c) Cycle = 1

d) Repeat

e) Calculate new solutions for the employed bees using (14) and evaluate fit_i

f) Apply the greedy selection process

g) Find the probability values P_i for the solutions x_{ij} using (15)

h) Update new solutions v_{ij} from the selected solutions x_{ij} for the onlooker bees depending on P_i and evaluate fit_i

i) Apply the greedy selection process

j) Search abandoned solution for scout bees, if exists, and replace it with a new randomly produced solution x_{ij} by (13)

k) Memorize the best solution achieved so far

l) Cycle = cycle + 1

m) Until cycle = MCN

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V. Simulation Results and Discussion

In this work, the procedure of ABC optimization method is directly executed for finding the optimized parameter value of SMPS block shown in Fig. 2 by assigning each candidate solution as the optimum value. It has been also utilized to tune the gain of both PID controller of WTG and DG system in WEPS model. The effectual impact of the proposed ABC based PID controller to control the system f and P fluctuations of the WEPS model shown in Fig. 1 is analyzed by MATLAB Simulink The parameters of WEPS model for its simulation is given in Table 1. The simulation has been carried out for three types of configuration. The model in Fig. 1 with only PID controller is referred to as “Only PID” configuration, model with SMPS block and PID controller is assigned as “PID + SMPS” configuration and the proposed ABC based PID controller with optimized parameter value of SMPS is referred as “ABC PID + SMPS” configuration. In this paper, the configuration of “Only PID”, “PID + SMPS” and “ABC PID + SMPS” model are simulated individually and their performance is compared mutually. In addition, the proposed “ABC PID +SMPS” based WEPS effectiveness is validated by simulation studies under two disturbance conditions such as (a) 1 % step surge in load demand and (b) 1 % step surge in both load demand and in wind speed.

The response of ΔF and ΔP_T with 1% step sudden increment in load demand for the various configurations of the studied power system model (namely ‘Only PID’, ‘PID + SMES’ and ‘ABC PID + SMES’) are shown in Fig. 3 (a) and Fig. 3 (b), respectively. From Fig. 3, it can be observed that the proposed ‘ABC PID + SMES’ model configuration performs better than the other two configurations (i.e. ‘Only PID’ and ‘PID + SMES’) for reducing the deviation in both f and P. Thus, ‘ABC PID + SMES’ configuration in the WEPS model works more efficiently than other two model configurations.

Another simulation has been performed by considering simultaneous step disturbance of 1 % step increase in both load demand and wind speed. The simulation results of ΔF and ΔP_T with this sudden simultaneous perturbation for the three distinct configurations of the WEPS model are displayed in Figs. 4 (a) and 4 (b) respectively. From these figures, it can be seen that the power and frequency transient response of proposed ‘ABC PID + SMES’ model configuration decays in a better way as compared with the other two model configurations. Three performance metrics (IAE, ISE and ISTE) values for the three discussed configurations with two distinct disturbance levels are presented in Table 2. These three performance metrics value for the ‘ABC PID + SMPS’ configuration is lower as compared with either ‘PID + SMPS’ or ‘Only PID’ configuration. The above analyses affirm that the optimal transient response acquired by proposed model is best for controlling system f and P fluctuations in WEPS.

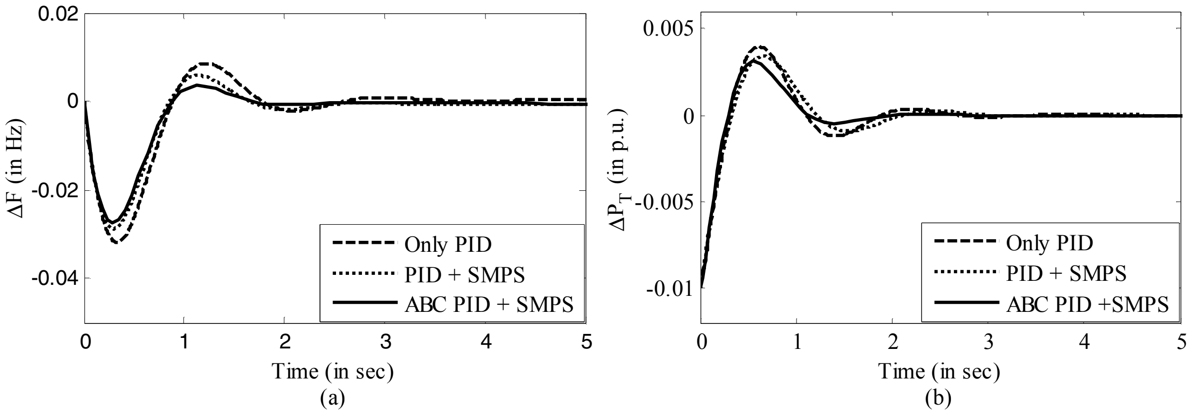

Figure 3. Comparison of different system configuration of (a) ΔF (in Hz) and ΔP_T (in p.u.) for 1% step increment in load demand

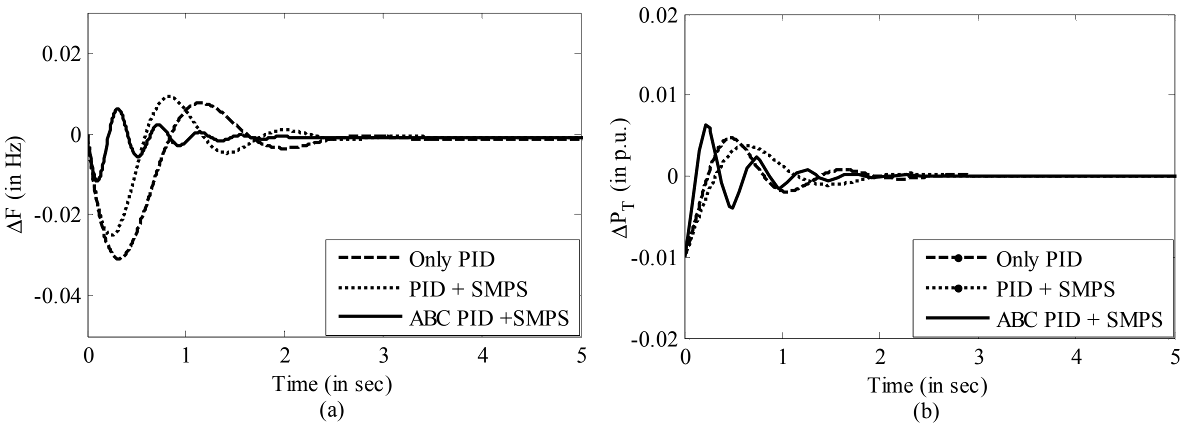

Figure 4. Comparison of different system configuration of (a) ΔF (in Hz) and ΔP_T (in p.u.) for 1% step increment in load demand and wind speed

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TABLE II. PERFORMANCE METRICS FOR DIFFERENT SYSTEM CONFIGURATIONS WITH DIFFERENT DISTURBANCES

Model	1% change in load demand		
	IAE	*ISE*	*ISTE*
Only PID	0.0530	0.0194	0.0041
PID + SMPS	0.0295	0.0108	0.0007
ABC PID + SMPS	0.0160	0.0047	0.0001
Model	**1% change in load demand and wind speed**		
	IAE	*ISE*	*ISTE*
Only PID	0.0721	0.0434	0.0116
PID + SMPS	0.0419	0.0247	0.0014
ABC PID + SMPS	0.0293	0.0081	0.0003

VI. CONCLUSION

In the presented paper, frequency and power deviation due to change in load demand and wind speed in a WEPS model has been controlled. This model is consist of a DG, WTG and SMES coupled with PSS device. The controller considered is an artificial bee colony based PID controller. In addition, the tunable parameters of WEPS model have been optimized by employing the ABC algorithm. In order to get the quality power supply requirement with variable load demand and wind speed, a detailed analysis of the model having three different system configurations has been investigated. From the simulation results, it may be observed that 'Only PID' and 'PID + SMES' configuration perform well under normal situation. However, it may not operate satisfactorily during the load variation and intermittent wind speed condition. Whereas, utilization of 'ABC PID + SMPS' configuration is really favorable in achieving the global optimal solution for controlling the system frequency and power under various disturbances.

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