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# Performance Analysis of Flower Pollination Algorithm Optimized PID Controller for Wind-PV-SMES-BESS-Diesel Autonomous Hybrid Power System

Israfil Hussain*‡, S. Ranjan*, D C Das*, N Sinha*

*Department of Electrical Engineering, National Institute of Technology, Silchar, India, 788010

(israfilhussain1@gmail.com, ranjan4c@gmail.com, dulal_nit@yahoo.co.in, nidulsinha@hotmail.com)

‡Corresponding Author; Israfil Hussain, Department of Electrical Engineering, National Institute of Technology, Silchar, India, 788010, Tel: +91 3842 242912, Fax: +91 3842 242912, israfilhussain1@gmail.com

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**Abstract**-Integration of the wind and solar power in an autonomous hybrid power system poses significant impacts on the system frequency affecting relay operation, consequence load disconnections, generation outage etc. leading to system collapse. An appropriate control strategy needs to be developed to maintain the system frequency within the permissible limit thus maintaining the stability of the power system. This paper presents a coordinated control strategy among the generating units in an autonomous hybrid power system comprising of wind turbine generator (WTG), the photo-voltaic system (PV), diesel engine generator (DEG), battery energy storage system (BESS) and superconducting magnetic energy storage (SMES). Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) are employed with DEG, BESS, and SMES so as to adjust the output power in response to the change in loading and or output power variation of renewable sources. The parameters of the controllers are optimized using Flower Pollination Algorithm (FPA). The system dynamic responses obtained the PI and PID controllers are compared. Simulation results revealed that FPA optimized PID controller outperform PI controller. Further, to check the robustness of the controllers, sensitivity analysis has been carried out.

**Keywords** Superconducting magnetic energy storage, Flower Pollination Algorithm, autonomous hybrid power system, photovoltaic system (PV), wind turbine generators, Frequency deviation.

## 1. Introduction

As per International Energy Agency, around 22% of the global population dwell without access to electricity, in 2008, this was equivalent to 1.5 billion people [1]. Most of them are living in the rural inaccessible terrain, where grid extension is extremely costly and also technically infeasible. Under these circumstances, autonomous hybrid power system in the presence of renewable resources is believed to be the most cost effective option to secure a decent living standard, preserving the environment at the same time. Nevertheless, renewable energy sources such as the wind, solar are intermittent and uncontrollable in nature [2]. Incorporation of these energy sources in the isolated hybrid system, which is the comparatively small size and has less inertia, causes an imbalance between generation and load demand leading to frequency fluctuation [3]. System frequency variation affects the relay operation, consequence load disconnections, generation outage etc. leading to system collapse. So an appropriate control strategy is important to keep the system frequency within the permissible limit.

In the past, many authors have carried out the investigation of an autonomous hybrid power system comprising of the wind, solar PV, and diesel generator. In such an autonomous hybrid system, diesel generator caters the load during non-availability of the wind or solar PV power, thus the system reliability increases [4, 5, 6]. Wang and Nehrir [7] presented active power management and control of a wind-PV-FC-electrolyzer-battery isolated hybrid energy system considering practical load profile. Simulation results reveal the suitable performance of the proposed active power management strategies. However, for better power management strategies, frequency control issue should have to be addressed. Proper management of renewable energy in an autonomous hybrid energy system consisting of the wind, solar PV, diesel, fuel cell, aqua electrolyzer flywheel, and battery has been presented by Lee and Wang [8]. Simulation results indicate the satisfactory performance. However, appropriate control strategy and effective coordination among different systems remain unexplored. Similar hybrid power system equipped with PI controllers for adjusting the power output from the subsystem in response to variation in the wind, solar, load etc. have been investigated in [9]. The responses are presented to show the satisfactory performance of the control strategy. Nevertheless, trial & error method were adopted for calculating the parameters of the PI controller, which cannot ensure the properly coordinated control among the subsystems against the uncertainties like variations in the wind, solar power and or change in the loading condition. Another fixed gains PI controller for frequency control of the wind, solar PV, fuel cell and double layer capacitor based hybrid power system as reported in [10], performed satisfactorily. Nonetheless, PI controllers with fixed parameters will work under limited operating point changes; under the variable wind, solar and or fluctuating loading conditions they may fail to maintain system stability. Therefore, to enhance the robustness and coordinated control among subsystems the parameters of the controllers need to be optimized simultaneously considering practically variable conditions.

Different controllers and several optimization techniques for tuning the parameters of the controllers have been reported in the previous works [11-20]. GA optimized PI/PID [11, 12], Fuzzy based PI controller [13, 14], and neural network based PI controller [13], robust H-infinity controller [15, 16, 17, 18], PSO Fractional order controllers [19] has been employed with the renewable based hybrid power system for the control purpose. Firefly algorithm optimized PID controllers [20] were successfully employed for an interconnected power system for load frequency control. In [21] authors have used H-infinite loop shaping controller based on hybrid PSO and harmonic search for frequency regulation in hybrid distributed generation system. Authors in [22] have used quasi-oppositional harmony search algorithm for load frequency control of an autonomous hybrid power system.

Authors in [23] have carried out the operation of small hybrid autonomous power generation system in isolated, interconnected and grid connected modes.

In view of above, this work explores the performance and coordination control of PI and PID controllers of the proposed autonomous hybrid power system comprising of the wind, solar PV, SMES, BESS, and DEG. Inspired by the success of the recently developed Flower pollination algorithm (FPA) over another algorithm like, GA and PSO [24], the parameters of the PI/PID controllers are optimized using FPA. The proposed control strategy is expected to provide an effectively coordinated control among different subsystems by adjusting the output power during the uncertainties in the generation and or loading conditions so that frequency can be maintained within the acceptable limit. The scope of the work is summarized below:

i. The gains of PI and PID controllers are optimize using heuristic algorithms, FPA and investigate their dynamic performance in controlling the frequency fluctuation of the autonomous hybrid system.
ii. The proposed model compare the performance of FPA optimized PI and PID controllers for maintaining system frequency within the limit in the event of variations in any of the sub-components i.e., load, wind power, solar radiation or all.
iii. Sensitivity analysis by varying the load demand by ± 20% from its nominal value.
iv. Another sensitivity analysis was also carried out by incorporating the realistic features like randomly variable output from the wind and solar PV as well as load demand, so as to test the robustness of the proposed controllers.

The different sections of the paper are. Modeling of the proposed system is given Section 2. Details of Flower Pollination Algorithm are described in Section 3. Section 4 and 5 represent respectively, simulation results and conclusion.

## 2. Modeling of the System Components

The conceptual structure of autonomous hybrid power system along with its transfer function model are shown respectively, in Fig. 1(a) and Fig. 1(b). The capacity and parameters of the autonomous hybrid system areadopted from [5, 8, 12, 17] as follows: $K_{WTG}=1$, $K_{PV}=1.8$, $K_{DEG}=1/300$, $K_{BESS}=-1/300$, $K_{SMES}=-3/300$, $K_D=1$, $T_{WTG}=1.5$, $T_D=1$, $T_{BESS}=1$, $T_{SMES}=1$, $T_{PV}=T_{DEG}=1$

D=0.2, M=0.012, R=5, N=10, and Load= 230kW. Modeling of components of the proposed system has been presented in the following subsections.

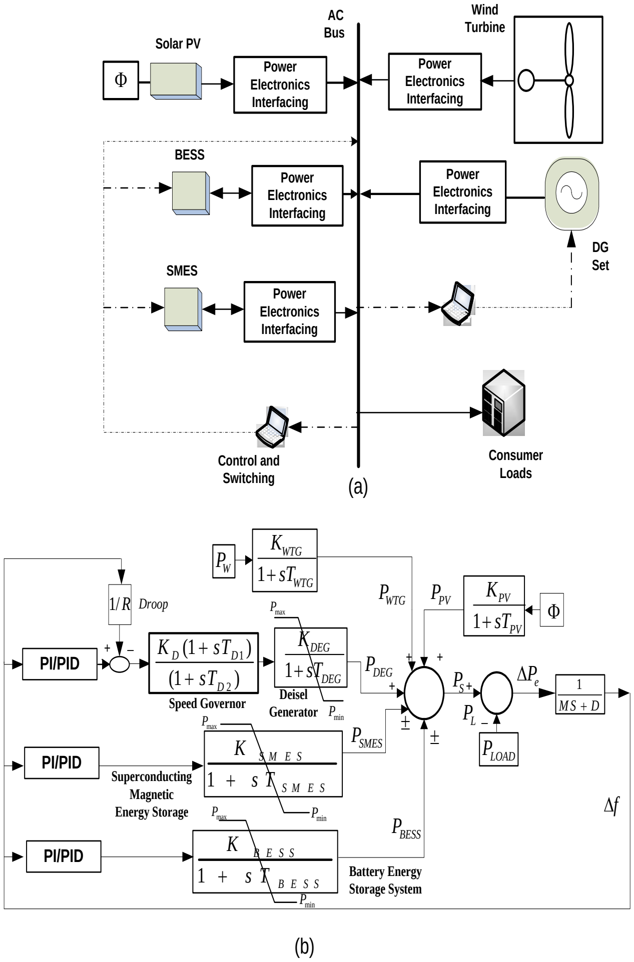


**Fig. 1** (a) Conceptual structure of solar PV-diesel autonomous hybrid energy system, (b) Transfer function model power.

### 2.1 Wind turbine generator

Wind turbine power is the result of the kinetic energy from the wind. The output mechanical power Pmech, from the wind turbine, is given [25]

$$P_{mech} = C_p(\lambda,\beta)P_{wind} = \frac{1}{2}C_p(\lambda,\beta)\rho A v^3 \qquad (1)$$

where $P_{wind}$, the air streams kinetic power, v is the wind velocity, $\rho$ and R corresponds to air density and radius of the turbine propeller, respectively. $C_p$ represents power coefficient or the wind turbine rotor efficiency. The transfer function model depicting first order [14] of WTG is given by

$$G_{WTG}(s) = \frac{K_{WTG}}{T_{WTG}s+1} \qquad (2)$$

Where $K_{WTG}$ and $T_{WTG}$ are gain and time constant of WTG.

### 2.2 Solar PV system

Photovoltaic (PV) is the equipment for exchanging the solar energy to the electrical energy. PV arrays are built up with the combined series/parallel of PV solar cells. Its power is dependent on the irradiation and temperature. Hence, the output power from PV system is intermittent in nature. The transfer function of the PV system is represented [8] as

$$G_{pv}(s) = \frac{K_{pv}}{T_{pv}s+1} \qquad (3)$$

Where $K_{pv}$ and $T_{pv}$ are the gain and time constant of PV system.

### 2.3 Diesel engine generator (DEG)

The diesel engine is coupled with the synchronous generator to produce the electrical power output. Diesel generator acts as a backup generating unit to cater load demand during non-availability of the wind, solar power. Diesel prime mover adjusts the fuel injected in response to load demand. For detailed study authors may refer to [12]. The first order transfer function for the DEG as proposed in [8] is given by

$$G_{DEG}(s) = \frac{K_{DEG}}{T_{DEG}s+1} \qquad (4)$$

Where $K_{DEG}$ and $T_{DEG}$ are the gain and time constant of DEG.

### 2.4 BESS and SMES

SMES is a suitable option to smooth out fluctuations in the wind and solar PV based isolated hybrid power system because of its several advantages like quick response time (millisecond), high cycle life, high efficiency (>95%) and high power density [26]. Nevertheless, maintaining cryogenic temperature is an expensive and difficult process [27]. While BESS is a cost-effective option for this condition as it has high energy density and ability to supply energy for a long time. However, it has some limitations such as slower rate of charging/discharging due to its chemical reaction process, limited cycle life [26]. In this work, to exploit the benefits of both the energy storage devices, i.e., instantaneous power as well as long-time energy supplies in a renewable based hybrid power system, combined application of SMES and BESS device has been considered. SMES and battery complement to each other. BESS stores energy in the electrochemical process whereas; SMES stores the energy in the magnetic field. Overview, a recent development, and application of BESS and SMES are covered in [28, 29]. The first order transfer function model of BESS [8] and SMES [17] are expressed by:

$$G_{BESS}(s) = \frac{K_{BESS}}{1 + sT_{BESS}} \tag{5}$$

$$G_{SMES}(s) = \frac{K_{SMES}}{1 + sT_{SMES}} \tag{6}$$

Where $K_{BESS}$ and $T_{BESS}$ represents the gain and time constant of BESS whereas $K_{SMES}$ and $T_{SMES}$ are the gain and time constant of SMES.

2.5 *Power and frequency deviations*

Any mismatch in active power primarily affects the frequency and similarly, hence the present work as mentioned earlier; investigate the frequency control strategy of renewable based hybrid power system.

The active power balance expression for the hybrid energy system is given as

$$P_S = P_{WTG} + P_{PV} + P_{DEG} \pm P_{SMES} \pm P_{BESS} \tag{7}$$

Where $P_{WTG}$, $P_{PV}$, $P_{DEG}$, $P_{SMES}$ and $P_{BESS}$ are the power output from WTG, PV, DEG, SMES, and BESS respectively. The mismatch between the load demand $P_L$ and total power supply $P_S$ is given by

$$\Delta P_e = P_S - P_L \tag{8}$$

Controllers employed with DEG, BESS and SMES adjust the output power to eliminate. The relation between system frequency deviation ($\Delta f$) and $\Delta P_e$ is given by [8]

$$\Delta f = \frac{\Delta P_e}{K_{sys}} \tag{9}$$

The expression for first order transfer function of system frequency can be expressed by first order as [8]

$$G_{sys}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{sys}(1 + sT_{sys})} = \frac{1}{Ms + D} \tag{10}$$

M and D represent inertia and damping constant respectively while $G_{sys}(s)$, $K_{sys}$ and $T_{sys}$ are the transfer function, system frequency and time constant of hybrid power system respectively.

2.6 *Performance Index*

For, the present system, integral square error (ISE) has been considered as the performance index, we have

$$J = \int_0^t (\Delta f)^2 dt \tag{11}$$

The objective is to Minimize J, subject to the constraints given below

$$K_p^{\min} \le K_p \le K_p^{\max} \tag{12}$$

$$K_i^{\min} \le K_i \le K_i^{\max} \tag{13}$$

$$K_d^{\min} \le K_d \le K_d^{\max} \tag{14}$$

The present system has been modeled in Matlab/Simulation, where three controllers were employed with DEG, SMES, and BESS, respectively. In the case of PID controller based model, the objective function, J is minimized by optimizing $K_p$, $K_i$ and $K_d$ parameters for each of these three controllers simultaneously. When the model is employed with PI controllers, the similar process is followed while optimizing the $K_p$ and $K_i$ parameters of each of the PI controllers. The ranges of the variables are given in Table 1.

**Table 1** Ranges of variables

| Variables | Minimum | Maximum |
|---|---|---|
| $K_P$ | 1 | 33000 |
| $K_i$ | 0 | 31000 |
| $K_d$ | 0 | 1500 |

## 3. Flower Pollination Algorithm

Xin-She Yang has proposed flower pollination algorithm in the year 2012 [21], which is based on the idea of flower pollination process. The pollination process carries the pollen from the male parts of a flower to the female part called stigma of a flower. Pollinators can be very diverse. It is estimated that there are at least two hundred thousand varieties of pollinator exist in nature like insects, bats, and birds [21]. In nature, two types of pollinations are found, one called biotic pollination and second called abiotic pollination process.

Xin-She Yang has considered following four rules to simply the algorithm [21]:

a. Global pollination process consists of biotic and cross-pollination, and movement of the pollinators which carries the pollen obeys Levy flights.

b. For the action of local pollination, it considers both abiotic and self-pollination.

c. Flower constancy of the pollinator's is equivalent to the reproduction probability, which is proportional to the similarity of two flowers involved.

d. For the controlling action of local and global pollination, a switch probability $p \in [0, 1]$ is considered.

Because of Levy flights FPA algorithm possesses more explorative power and lesser probability of getting trapped in local optima resulting into its better performance in highly non-linear optimization problems. Hence, this algorithm is considered for optimizing the controller gains in this proposed work. For detailed study including pseudo- code readers may refer to [21].

## 4. Result Analysis

This section presents the dynamic performances and analysis of the system under consideration using time-domain simulation. As the hybrid system contains solar and wind power which are intermittent in nature, there is a mismatch in active power generation and load demand. These leads to the system frequency deviation. Thus, the system is employed with the controllers, which automatically regulate the power output from the DEG, BESS, and SMES. This, in turn, eliminates the frequency deviation. The simulation time of the present system is considered as 120s.Flow chart as shown in the Fig. 2 explains the models and steps of the Matlab simulation.

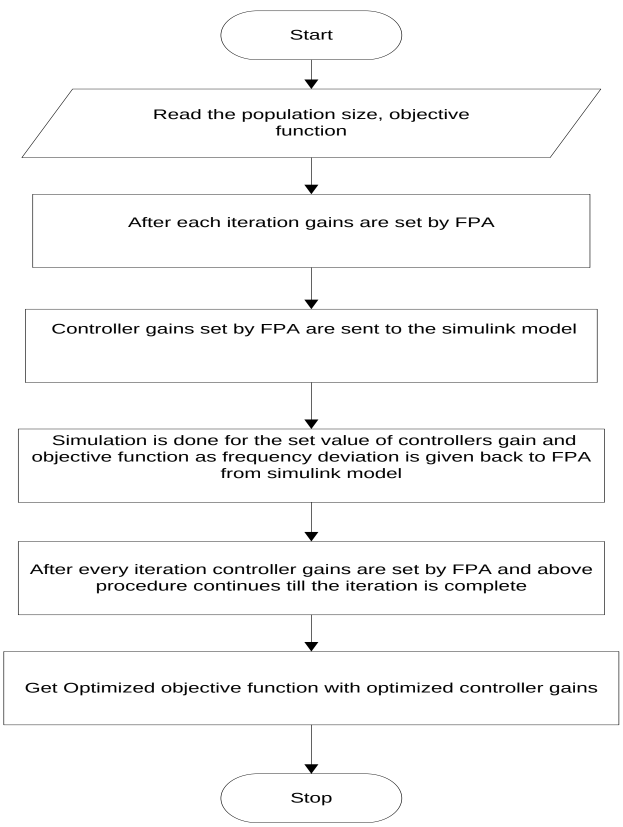


**Fig. 2** Flow chart explaining the models and steps of the Matlab simulation.

### *4.1 Base loading: Case 1*

Here, the dynamic performance of the proposed system is investigated when subjected to a disturbance in $P_{PV}$ and$P_{WTG}$. Fig. 3 presents the $P_{PV}$, $P_{WTG}$ and load demand ($P_{Load}$). As it can be seen that during 0<t<40 s, the demand and the supply do not match, hence the deficit in power is provided throughDEG, BESS, and SMES, through the action of the controllers. The output power from the DEG, BESS and SMES is shown in Fig. 4. The amount of output power from each of the generating unit i.e., DEG, BESS and SMSES is dependent on the feedback signal to the concerned controllers, hence the output power from the generating unit is different for PI and PID controllers. During the time period from 40<t<80 s, the total generated power is matched with the demand, hence there is no power generation by the DEG, BESS or SMES. Again, during 80 < t < 120 s, there is a surplus power, which is fed to the BESS and SMES for storage purpose which can be utilized at the time of peak hours.

Thus, the discrepancy between power generation and consumption is automatically alleviated by the action of the controllers, which automatically regulate the power variation from the DEG, BESS, and SMES. This, in turn, eliminates the frequency deviation. Fig. 5 illustrates the comparative performance of transient response of frequency deviation for the present system obtained using FPA optimized PI and PID controllers. The responses as shown in Fig. 5, clearly reveal that FPA optimized PID

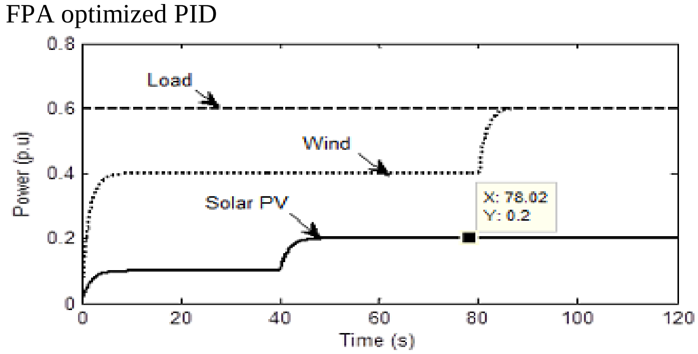


**Fig. 3** Load demand,$P_{WTG}$ and $P_{PV}$ system, case 1.

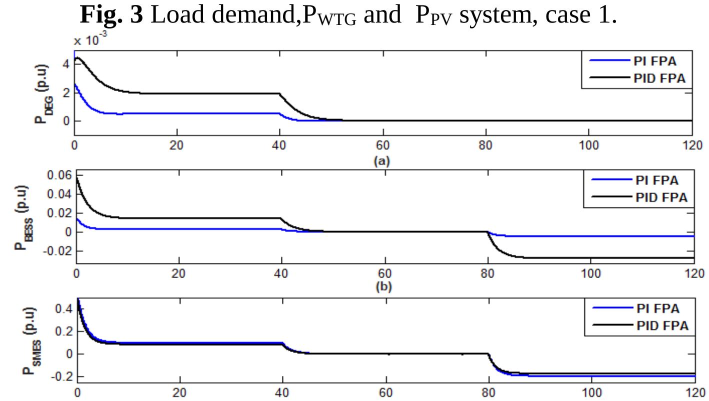

**Fig. 4** Output power of DEG, BESS, and SMES, case1

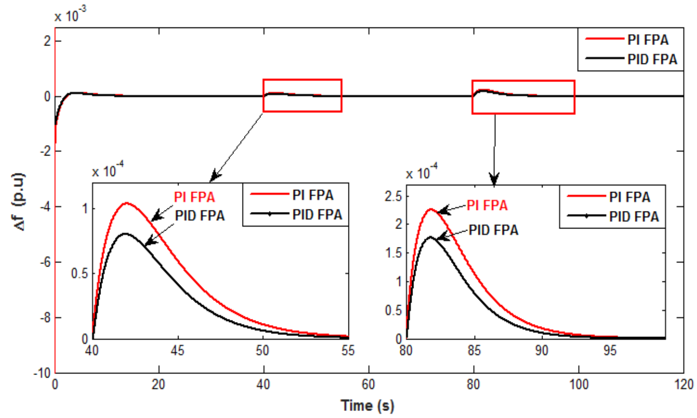


**Fig. 5** Transient response of $\Delta f$ observed with FPA optimized PI and PID controllers, case1

Controller outperform the PI controller in terms of peak transient deviation and settling time. Table 2 presents the tuned parameters of FPA technique, while the gain values of the PI and PID controllers obtained through FPA are presented in Table 3 and Table 4respectively. The frequency deviations (Δf in Hz) for various conditions are presented in Table 5, which also confirms the superiority of the PID controllers.

It is expected that the controllers (PI/PID) gains obtained in case 1 will work well under other different operating conditions as well. Same has been examined in the following sections through sensitivity analysis considering different operating conditions.

**Table 2** FPA parameters

| Generations | Population | Switch Probability | Step size |
|---|---|---|---|
| 200 | 50 | 0.8 | 1.5 |

**Table 3** Gain values of FPA optimized PI controller

| Case | Case1 | Case2 | Case3 | Case4 |
|---|---|---|---|---|
| $K_p DEG$ | 1094.25 | 524.25 | 619.38 | 494.21 |
| $K_i DEG$ | 257.89 | 141.28 | 211.41 | 134.81 |
| $K_p SMES$ | 3255.48 | 82.04 | 114.01 | 102.04 |
| $K_i SMES$ | 1387.61 | 804.28 | 599.87 | 1001.28 |
| $K_p BESS$ | 3210.64 | 112.89 | 99.74 | 119.89 |
| $K_i BESS$ | 1201.29 | 541.25 | 739.65 | 491.25 |

| Case | Case1 | Case2 | Case3 | Case4 |
|---|---|---|---|---|
| $K_p DEG$ | 2101.24 | 1912.74 | 2700.34 | 2299.02 |
| $K_i DEG$ | 1374.28 | 1411.19 | 1797 | 987.078 |
| $K_d DEG$ | 31.01 | 32.89 | 34.74 | 42.17 |
| $K_p SMES$ | 3698.89 | 4521.43 | 5001.24 | 189.42 |
| $K_i SMES$ | 1697.46 | 2013.35 | 2498.21 | 1104.06 |
| $K_d SMES$ | 210.97 | 385.67 | 234.45 | 179.12 |
| $K_p BESS$ | 15987.24 | 14170.56 | 17021 | 12200.71 |
| $K_i BESS$ | 9997.04 | 9982.23 | 12956 | 7979.13 |
| $K_d BESS$ | 1398.74 | 1235.47 | 1010 | 897.41 |

**Table 4** Gain values of FPA optimized PID controller

**Table 5** Maximum frequency deviations (Δf in Hz)

| Case | Case1 | | Case2 | |
|---|---|---|---|---|
| Time(s) | t=40s | t=80s | t=40s | t=80s |
| $\Delta f$ | Over shoot | Over shoot | Undershoot | Overshoot |
| PI FPA | 0.0001030 | 0.0002254 | -0.0536500 | 0.114600 |
| PID FPA | 0.0000801 | 0.0001762 | -0.0004389 | 0.000955 |
| Case | Case3 | | Case 4 | |
| Time(s) | t=40s | t=80s | Random | |
| $\Delta f$ | Undershoot | Overshoot | Overshoot | |
| PI FPA | -0.1181 | 0.2455 | 0.0002748 | |
| PID FPA | -0.0004493 | 0.0009824 | 0.0001512 | |

*4.2 Sensitivity analysis for change in loading condition by ±20%: Case 2*

Fig. 6 presents the variations in $P_{Load}$, $P_{WTG}$, and $P_{PV}$. In this case, sensitivity analysis of the controllers (PI/PID) is performed to check their robustness. The parameters of the (PI/PID) controllers are obtained using FPA under step disturbance of the nominal load (i.e., ±20% of the 0.6 p. u) with wind and solar power remains same. In order to evaluate the performance of the controllers with their optimum parameters as obtained in case 1, their performance in terms of frequency deviation has been compared with that of their counterparts as obtained under changed condition. Fig. 7 presents the comparative performance in terms of frequency response. From this figure, it is observed that even though the load is changed by ±20%, the frequency deviation is almost similar in both the cases i.e., using controllers with their optimum parameters in case 1 as well as in case 2. Therefore, one can infer that the parameters that were obtained in case 1 work well with ±20% change in the loading condition, hence they are quite robustness. The gain values of PI and PID controllers that were optimized with FPA technique are given in Table 3 and Table 4 respectively. Fig. 7 shows sensitivity analysis of frequency deviation when employed with FPA optimized conventional PI and PID controllers.

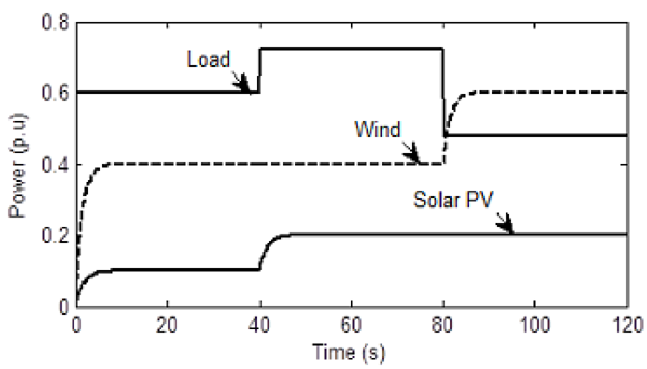


**Fig. 6** Load demand; output powerof $P_{WTG}$ and $P_{PV}$ system, case 2.

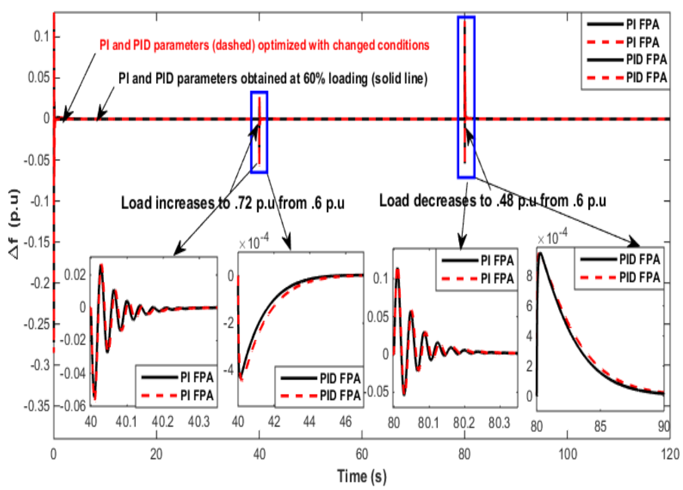


**Fig. 7** Frequency deviation for FPA optimized PI and PID controller, case 2.

*4.3 Sensitivity analysis for change in loading condition by ±50%: Case 3*

This is similar to case 2, with the only difference that the loading condition has beenchanged by ±50% from its base loading of 60%. Figure 8 shows the load demand; output power of $P_{WTG}$ and $P_{PV}$ system. The deviation of frequency responses is compared with that obtained with 60% loading and the results show thatboth the responses are somewhat similar. Hence, this also implies the robustness of the controllers. The gain values of PI and PID controllers that were optimized under this changed condition with FPA technique are given in Table 3 and Table 4 respectively. Fig. 9 shows the sensitivity analysis of frequency deviation when employed with FPA optimized PI and PID controllers.

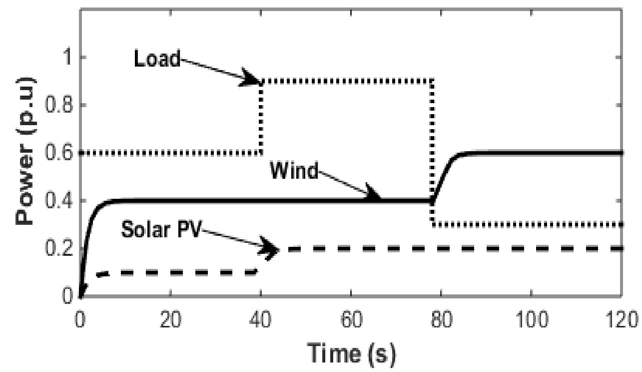


**Fig. 8** Load demand; output power of $P_{WTG}$ and $P_{PV}$ system, case 3.

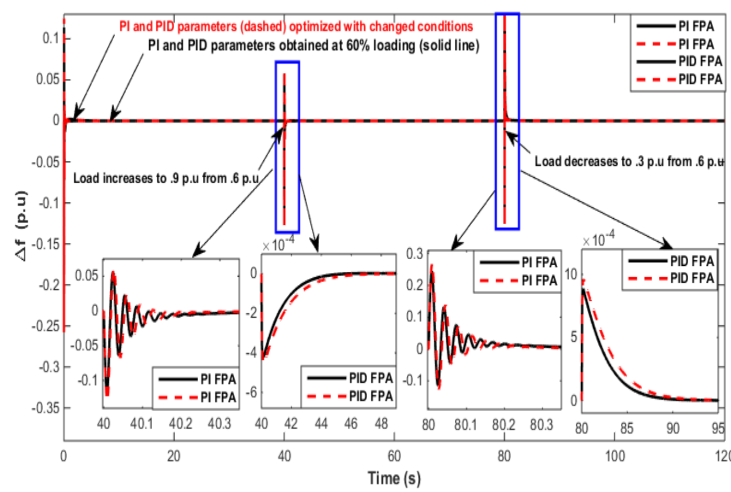


**Fig. 9** Frequency deviation for FPA optimized PI and PID controller, case 3.

*4.4 Sensitivity analysis with Variable, $P_{Load}$, $P_{WTG}$ and $P_{PV}$: Case 4*

The analysis on the dynamic performance of the present model is carried out considering randomly variable characteristics of the wind, solar PV, and load demand respectively. The objective of this study is to examine the performance of the controllers under practical scenario such as variable wind power, solar power and load demand as shown in Fig 10. Under these conditions of variable load demand, $P_{WTG}$ and $P_{PV,}$ the controllers adjust the output power of the BESS, DEG and SMES so that frequency deviancy is minimized and base frequency the system is restored. Fig. 11 shows sensitivity analysis of frequency deviation when employed with FPA optimized PI and PID controllers. In this case, also comparative performance has been presented between the controllers with their optimum gains as obtained in case1 vis-à-vis their counterparts under varying condition. It has been observed that trends of frequency deviation curve remain almost similar. Table 5, presents the peak values of frequency deviation for various operating conditions of the proposed system.

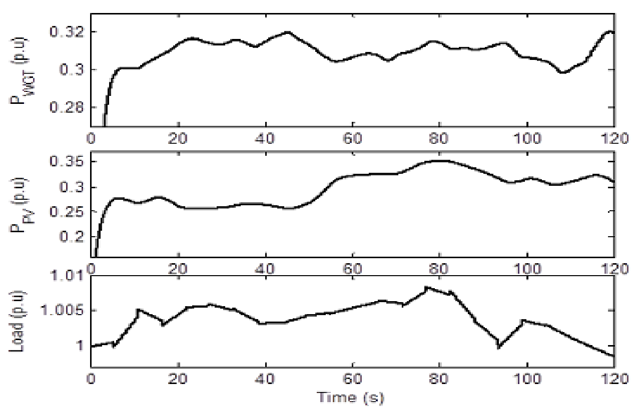


**Fig. 10** Output power of $P_{WTG}$, $P_{PV}$ and load model, case 4

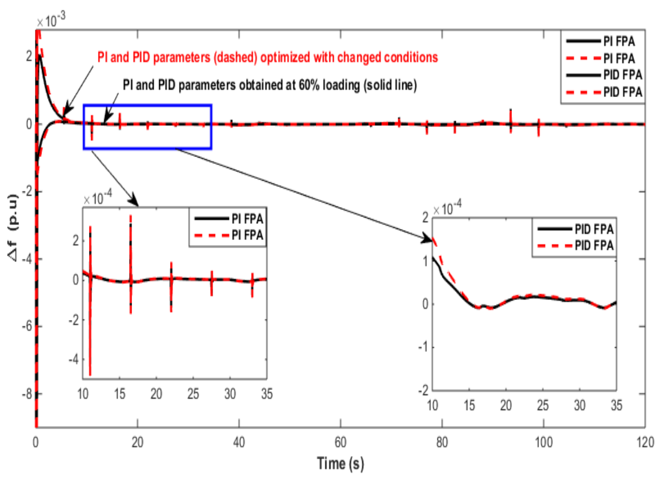


**Fig. 11** Frequency deviation for FPA optimized PI and PID controller, case 4.

Investigation of the responses of case 2, case 3 and case 4 reveals that the performance of the controllers with the optimum gain values controllers obtained at the base loading of 60% does not vary much under changed conditions and hence the gains do not require to be reset for the variation in the system loading or size. However, in all the cases, the performance of PID controller outperforms the PI controller in the view of robustness.

## 5. Conclusion

A comparative performance analysis of FPA optimized PI and PID controllers in an autonomous WTG, PV, SMES, BESS and DEG hybrid power system is carried out. Simulation results show that even though there are quite variations in the output power of $P_{WTG}$, $P_{PV}$ and load; the power generated from DEG, as well as from the energy storage such as BESS and SMES can be effectively controlled to meet the load demand under different conditions. Thus, the present system can effectively maintainthe system frequency within the permissible limit. Simulations results reveal that the response through the FPA optimized PID controller outperforms the PI controller in terms of peak transient deviation and settling time.

Robustness of the controllers has been investigated by sensitivity analysis. For this, the optimum gains of the controllers obtained at the base loading of 60% do not vary much under changed conditions such as ±20% and ±50% from its nominal loading of 60% and hence the gains need do not require to be reset for the variation in the system loading or size. Further, the comparative performance of FPA optimized PI and PID controllers optimized with step changes vis-a-vis their counterparts optimized under randomly varying conditions also revealed the robustness of their optimum gains. Further, the effect of random load on frequency will be more due to the off-grid autonomous operation. Hence, PID controller is a better option for the proposed autonomous hybrid power system.

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