Journal of Energy and Power Engineering 11 (2017) 204-213
doi: 10.17265/1934-8975/2017.03.009

Control Scheme of Hybrid Wind-Diesel System with SMES Using NSGA-II

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Received: November 30, 2016 / Accepted: February 01, 2017 / Published: March 31, 2017.

Abstract: Robust control approach of hybrid wind-diesel power system is proposed in this paper. PID (proportional integral derivative) controller is designed in the blade pitch system of wind turbine to improve the system dynamic performance. Furthermore, to minimize the system oscillations, SMES (super-conducting magnetic energy storage) with first order lead-lag controller is implemented to supply and absorb active power quickly trying to reach power generation/demand balance and thereby control system frequency. Minimization of frequency and wind output power deviations are considered as two objective functions for the PID controller of wind turbine. Also, mitigating frequency and diesel output power deviations are presented as two objective functions of the lead-lag controller of SMES. NSGA-II (modified version of non-dominated sorting genetic algorithm) is used to tune the controllers' parameters to get an optimal response. The effectiveness and robustness of the proposed control technique are investigated under different operating conditions using Matlab environment. The simulation results confirm the ability of the controllers to damp all frequency and output powers fluctuations and enhance the stability and reliability of the hybrid power system.

Key words: Wind-diesel system, isolated power system, energy storage, frequency control, blade pitch control, NSGA-II.

1. Introduction

Majority of the isolated and remote areas such as islands depend on diesel generators to meet load demand. Due to economical and environmental effects of diesel generators, efforts have been made to generate electricity from renewable sources such as wind energy. Wind energy is one of the fastest growing sources of electricity at present. Wind power has many advantages including the facts that it produces virtually no pollution of air, water or soil, and it is renewable (non-depletable). However, electric power generated by wind turbines is highly variable depending on wind speed and cannot be predicted. Since wind power varies randomly, there must be a standby power source to meet load demand in case of wind energy shortage. The wind and diesel system is one of the famous hybrid power systems especially for islands utilizing more than one energy source. Wind-diesel system enhances the overall reliability because diesel generator acts as a cushion to take care of variation in wind speed and always provides power equal to load minus wind power [1]. The wind-diesel system is classified as low, medium, and high wind penetration depending on Energy penetration ratio of wind power, which can be defined as [2]:

$$\text{Energy penetration} = \frac{\text{Wind annual energy}}{\text{Annual demand energy}} \quad (1)$$

If energy penetration is less than 20%, wind-diesel system is considered as low penetration. Medium wind-diesel system is classified if energy penetration is between 20% and 50%. While, if the system is capable of shutting down diesel generator during high wind penetration periods, it is classified as high wind penetration. Due to the fact that the output power of wind turbine is related to the cube of wind speed, wind energy diverges quickly from one moment to another.

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Also, load demand of the isolated community changes frequently which affects the system frequency significantly and decreases power quality and system reliability to supply continuous electric power to demand.

Different strategies are presented to reduce the mismatch between generation and load and hence control the system frequency. One of the most important and effective approaches is to control the blade pitch system of wind turbine to ensure constant supply of wind energy trying to achieve power generation/demand balance which will lead to system frequency control. Wind-diesel system has been the topic of numerous researches in the past decades and various control techniques have been proposed in literature for blade pitch control. Each method is suitable for a specific problem, depending on the nature of the control problem such as ANN (artificial neural network) [3, 4], GA (genetic algorithm) [5-8], FLC (fuzzy logic control) [9-12], PSO (particle swarm optimization) [13, 14], BCO (bee colony optimization) [15], BFO (bacterial foraging optimization) [16], and VSC (variable structure controllers) [17]. However, due to the fact that in wind-diesel problem each control area can have random load changes and random wind speed, many of these methods may not be useful as they require substantial amount of training based on predicted scenarios and specific system parameters such as ANN. Also in some cases defining the method's required parameters, such as membership functions in the case of fuzzy logic, is a long and complex task and may not lead to satisfied results. Also, H_∞ control method is applied to the blade pitch system of wind turbine [18, 19]. However, the weighting functions in H_∞ control design cannot be easily selected that affects the process of design significantly. Also, the order of H_∞ controller depends on that of the plant. This causes a complex structure which is not easy to realize in practical applications especially for large-scale systems. Nowadays, ESS (energy storage systems) are integrated with the renewable sources to maintain the safe operation of the power system and balance the supply and demand sides. These serve as backup devices and store excess power when the generation is more than demand and release power to the system when the demand is more than generation. This action helps in maintaining a steady flow of power irrespective of the load and generation power levels fluctuations. As a result, it guarantees acceptable levels of systems frequency deviations [20, 21]. One of the most efficient ESS is SMES (super-conducting magnetic energy storage). The SMES unit is a device that stores energy in the magnetic field generated by the direct currents flowing through a superconducting coil. Since energy is stored as a circulating current, energy can be drawn from the SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours [22]. The SMES systems have several advantages. The SMES coil has the ability to release large quantities of power within a fraction of a cycle, and then fully recharge in just minutes. The SMES unit can store and discharge DC power at efficiencies of 98% or more and switch between charging and discharging within 17 milliseconds. This quick, high-power response is very efficient and economical. The SMES manufacturers cite controllability, reliability and no degradation in performance over the life of the system as prime advantages of SMES systems. The estimated life of a typical system is at least 20 years [23]. For all these previous reasons, this paper presents a new robust control methodology for hybrid wind-diesel power system. Two controllers are designed to enhance the system stability. Initially, PID (proportional integral derivative) controller is applied in the blade pitch system of wind turbine to keep constant supply of wind energy and thereby control system frequency. Then, SMES with first order lead-lag controller is implemented to absorb the active power fluctuations quickly. Two objective functions are considered for each controller and NSGA-II (modified version of non-dominated sorting genetic algorithm) is utilized to optimize the controllers' parameters to attain the proposed achievement. The ability of the proposed control approach to improve the performance of the hybrid power system is validated using Matlab environment under various operating conditions.

2. Hybrid Wind-Diesel Configuration

Block diagram of the proposed wind-diesel system under study is presented in Fig. 1. Wind turbine generator with rated capacity 150 kW is operated in parallel with 200 kW diesel generator to serve an average load demand of 350 kW. Also, power system parameters are indicated in Table 1 [17]. SMES block diagram consists of two transfer functions connected in series, i.e. the SMES unit model and the controller. Based on Ref. [24], SMES can be modeled by first-order transfer function with time constant T_{sm} =0.03 s. While, controller is represented by a first order lead-lag compensator with single feedback input signal, diesel frequency deviations, Δf_D. The continuous time dynamic behavior of the wind-diesel system is modeled by a set of state vector differential equations:

$$X^{\cdot} = AX + BU \quad (2)$$

$$Y = CX + DU \quad (3)$$

where, X, U, and Y are the state, input, and output vectors, respectively. A, B, C, and D are real constant matrices of the appropriate dimensions associated with the above vectors. X is a 10th order vector whose elements are clearly indicated in Fig. 1. While, U and Y can be given as:

$$U = [\Delta P_w \ \Delta P_{load}] \quad (4)$$

$$Y = [\Delta f_w \ \Delta f_D \ \Delta P_D \ \Delta P_{wtg}] \quad (5)$$

where, ΔP_w, ΔP_{load}, Δf_w, Δf_D, ΔP_D, ΔP_{wtg} are input wind power, load, wind frequency, diesel frequency (system frequency), diesel output power, and wind output power deviations, respectively.

3. NSGA-II

NSGA (non-domination sorting based genetic algorithm) is a very effective algorithm but has some drawbacks for its computational complexity, lack of elitism and for choosing the optimal parameter value for sharing parameter. A modified version, NSGA-II was developed, which has a better sorting algorithm, incorporates elitism and no sharing parameter needs to be chosen a priori [25]. In NSGA-II, at any generation, the offspring population Q_t is first created using the parent population, P_t, of size N. Thereafter, the two populations are combined together to form a new population R_t of size $2N$. Then, the new population classified into different non-domination classes. Then, the new population is filled by points of different non-domination fronts, one at a time. The filling starts with the first non-domination front (or class one) and continues with points of the second non-domination front and so on. Since the overall population size is $2N$, not all fronts can be accommodated in N slots available for the new population. All fronts which could not be accommodated are deleted. When the last allowed front is being considered, there may exist more points in the front than the remaining slots in the new population. The points which will make the diversity of the selected

Table 1 Parameters of wind-diesel system.

Inertia constant for wind system, H_W	3.5 s
Inertia constant for diesel system, H_d	8.5 s
Fluid coupling between wind and diesel systems, K_{fc}	16.2 pu kW/Hz
Governor gain, K_d	16.5 pu kW/Hz
Governor time constant, T_1	0.025 s
Gain of hydraulic pitch actuator, K_{p2}	1.25
Time constant of hydraulic pitch actuator, T_{p1}	0.6 s
Time constant of hydraulic pitch actuator, T_{p2}	0.041 s
Gain of data fit pitch response, K_{p3}	1.4
Blade characteristic gain, K_{pc}	0.08 pu kW/deg

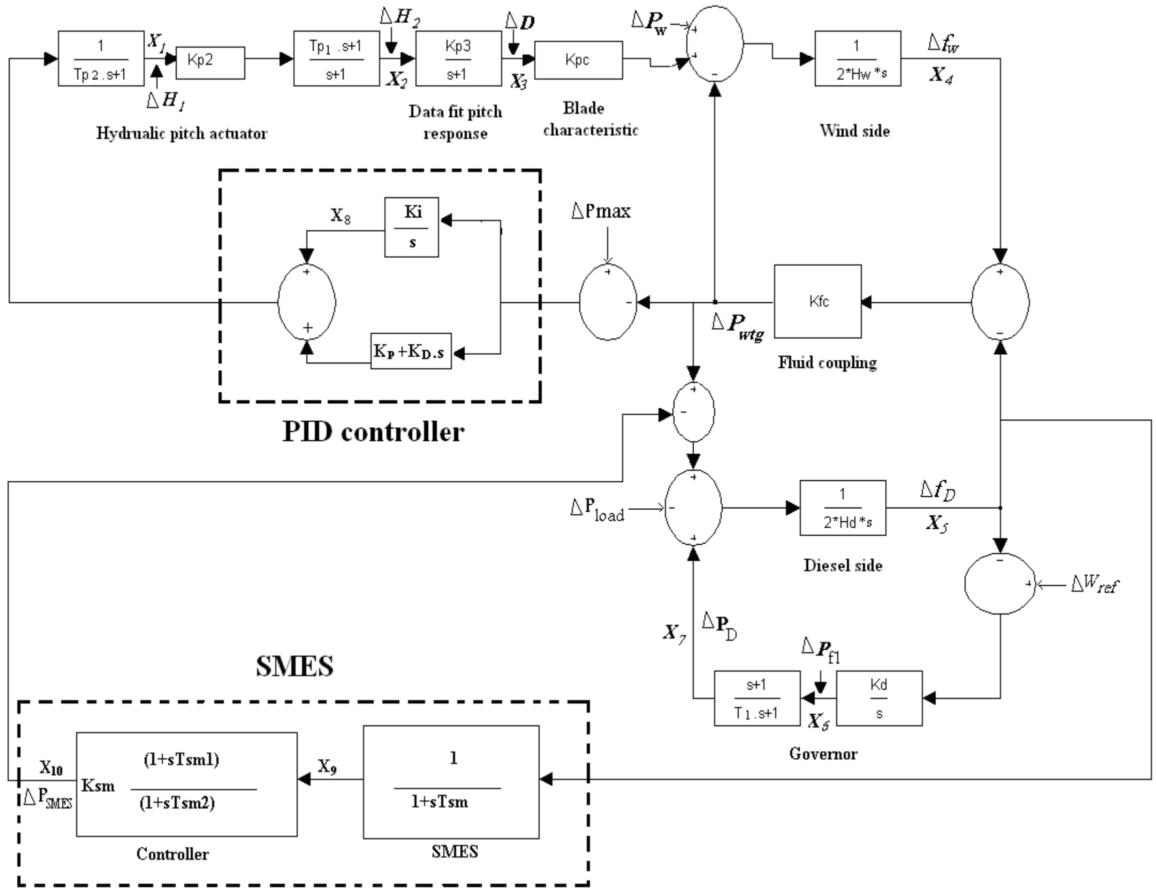


Fig. 1 Block diagram of wind-diesel system.

points the highest are chosen. To ensure diversity, the crowded sorting of the points of the last front which not be accommodated is achieved in the descending order of their crowding distance value and points from the top of the ordered list are chosen. The crowding distance D_M of point M is a measure of the objective space around M which is not occupied by any other solution in the population [26]. The main steps of NSGA-II procedure can be presented in the following steps [27]:

Step 1: Create a random parent population, P_t of size N.

Step 2: Sort the random parent population based on non-domination.

Step 3: For each non-dominated solution, specify a rank equal to its non-domination level.

Step 4: Create an offspring population, Q_t of size N using binary tournament selection, recombination, and mutation operators.

Step 5: From the first generation, creation of each new generation is implemented through the following steps:

(a) Create the mating pool R_t, of size $2N$ by combining the parent population, P_t and the offspring population, Q_t.

(b) Sort the combined population, R_t, according to the fast non-dominated sorting procedure to identify all non-dominated fronts (Fr_1, Fr_2, ..., Fr).

(c) Generate the new parent population, P_{t+1} of size N by adding non-dominated solutions starting from the first ranked non-dominated front, Fr_1. When the total non-dominated solutions exceed the population size N, reject some of the lower ranked non-dominated solutions. This is achieved through a sorting procedure which is done according to the crowded comparison operator based on the crowding distance.

(d) Perform the selection, crossover and mutation operations on the newly generated parent population, P_{t+1} to create the new offspring population, Q_{t+1} of size N.

Step 6: Repeat Step 5 until the maximum number of iterations is reached.

4. Simulation Result

NSGA-II is used to tune the PID controller's parameters of blade pitch control system for wind turbine according to IAE (integral absolute error) criteria based on the following objective functions:

$$F_1(1) = \int_0^t \left|\Delta P_{wtg}\right| \mathrm{dt}. \quad (6)$$

$$F_1(2) = \int_0^t \left|\Delta f_w\right| \mathrm{dt}. \quad (7)$$

Subject to:

$$\mathrm{K}_{\mathrm{p}}^{\min} \leq \mathrm{K}_{\mathrm{p}} \leq \mathrm{K}_{\mathrm{p}}^{\max} \quad (8)$$

$$\mathrm{K}_{\mathrm{i}}^{\min} \leq \mathrm{K}_{\mathrm{i}} \leq \mathrm{K}_{\mathrm{i}}^{\max} \quad (9)$$

$$\mathrm{K}_{\mathrm{D}}^{\min} \leq \mathrm{K}_{\mathrm{D}} \leq \mathrm{K}_{\mathrm{D}}^{\max} \quad (10)$$

Typical range selected for each of K_p, K_i, K_D is [0 to 120].

Also, NSGA-II is applied to optimize the first order lead-lag controller's parameters of SMES according to IAE criteria based on two objective functions can be identified as follows:

$$F_2(1) = \int_0^t \left|\Delta P_D\right| \mathrm{dt}. \quad (11)$$

$$F_2(2) = \int_0^t \left|\Delta f_D\right| \mathrm{dt}. \quad (12)$$

Subject to:

$$\mathrm{K}_{\mathrm{sm}}^{\min} \leq \mathrm{K}_{\mathrm{sm}} \leq \mathrm{K}_{\mathrm{sm}}^{\max} \quad (13)$$

$$\mathrm{T}_{\mathrm{sm1}}^{\min} \leq \mathrm{T}_{\mathrm{sm1}} \leq \mathrm{T}_{\mathrm{sm1}}^{\max} \quad (14)$$

$$\mathrm{T}_{\mathrm{sm2}}^{\min} \leq \mathrm{T}_{\mathrm{sm2}} \leq \mathrm{T}_{\mathrm{sm2}}^{\max} \quad (15)$$

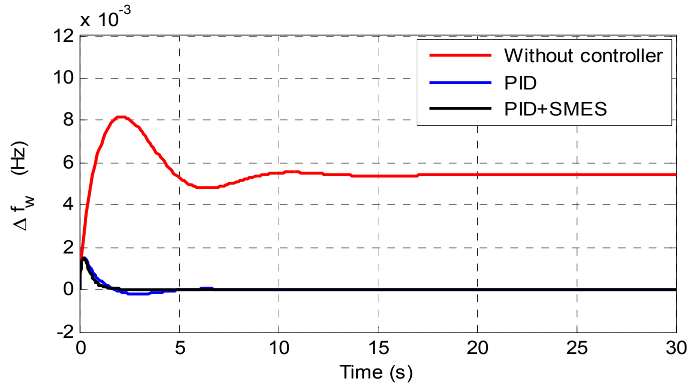
where, ranges selected for K_{sm}, $\mathrm{T}_{\mathrm{sm1}}$, and $\mathrm{T}_{\mathrm{sm2}}$ are [10 to 40], [0.1 to 2], and [0.01 to 0.1], respectively. Three case studies are considered in this section to confirm the effectiveness and robustness of the proposed control approach. NSGA-II based control scheme for wind turbine and SMES is then compared with conventional ones. Conventional methods are presented as wind-diesel system without any control action, and with PID controller only in the blade pitch system of wind turbine, respectively.

4.1 Case 1

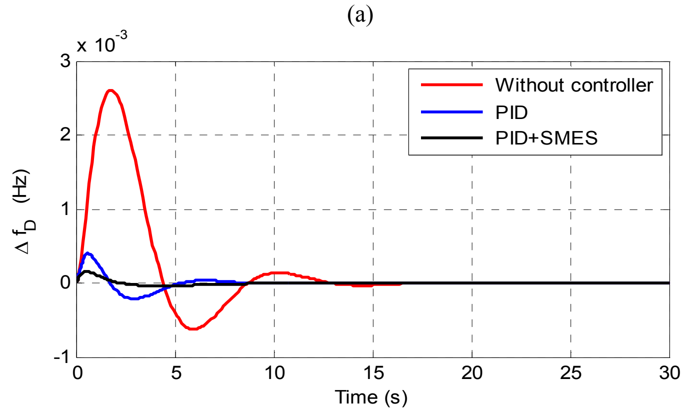
10% increase of input wind power is presented in this case study. The time-domain results of wind-diesel system under this operating condition are then shown in Fig. 2. The system transient response results indicated in Fig. 2 clarify the ability of the proposed control scheme to damp wind and diesel frequency deviations, decrease settling time, and reduce overshoot significantly. In addition, it succeeded to mitigate the fluctuations of diesel and wind output powers with settling time less than 5 s and clear minimized overshoot compared to power system without control action, and with PID controller only, respectively.

4.2 Case 2

In this case, the stability of the wind-diesel system with the proposed control approach is checked under harsh operating condition to confirm its effectiveness. The operating condition is represented as 25% increase in load power with 10% rise in the input wind power and 50% reduction in K_{fc} value. K_{fc} is chosen because it is the most sensitive parameter in the system. It means that the control response of the power system is very sensitive for K_{fc} changes [6]. The simulation results are presented in Fig. 3. The system dynamic response results show that the NSGA-based control scheme can withstand this severe operating condition, damp all



(a)



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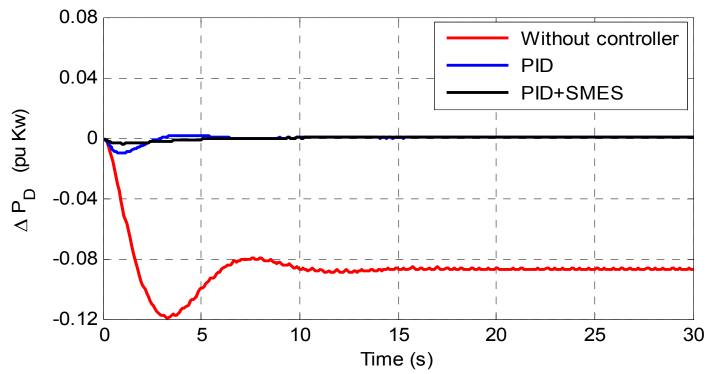
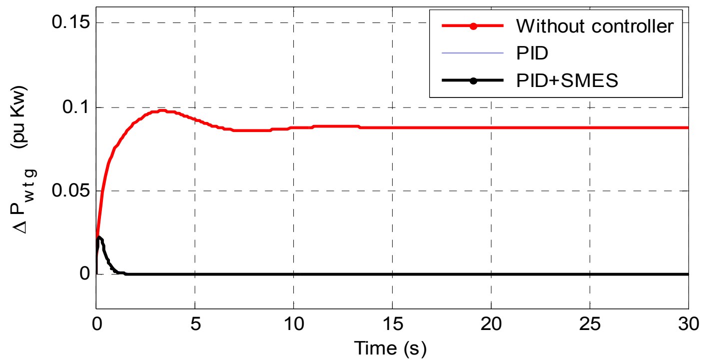


(c)



(d)

Fig. 2 System transient response curves for (a) wind frequency deviations; (b) diesel frequency deviations; (c) diesel output power deviations; (d) wind output power deviations for 10% input wind power increase.

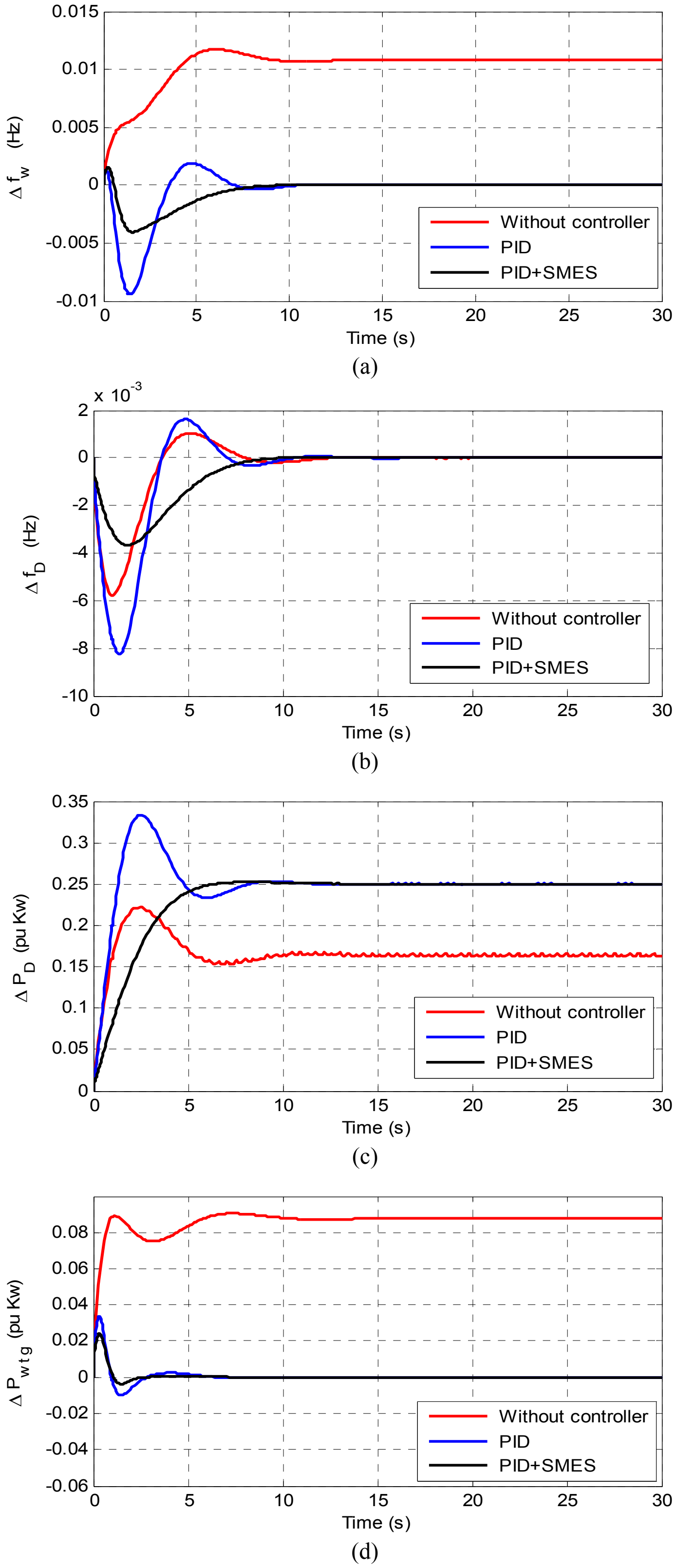


Fig. 3 System transient response curves for (a) wind frequency deviations; (b) diesel frequency deviations; (c) diesel output power deviations; (d) wind output power deviations for 25% load power increase with 10% rise in the input wind power and 50% decrease in K_{fc} value.

fluctuations of wind frequency, diesel frequency, diesel output power, and wind output power, decrease settling time, and minimize overshoot compared with the conventional methods.

4.3 Case 3

Wind gust shown in Fig. 4. is presented as random input wind power to investigate the robustness of the proposed control mechanism. The performance curves of wind-diesel system under this operating condition are then shown in Fig. 5. The system transient response curves clearly indicate the superiority of the proposed control scheme with SMES even in such severe operating condition. It can minimize oscillations of frequency and output power for diesel generator and wind turbine significantly compared to conventional methods without any control action or with PID controller in pitch angle system of wind turbine only, respectively.

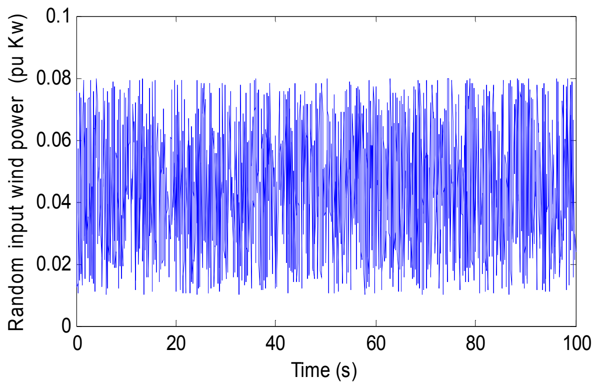


Fig. 4 Wind gust.

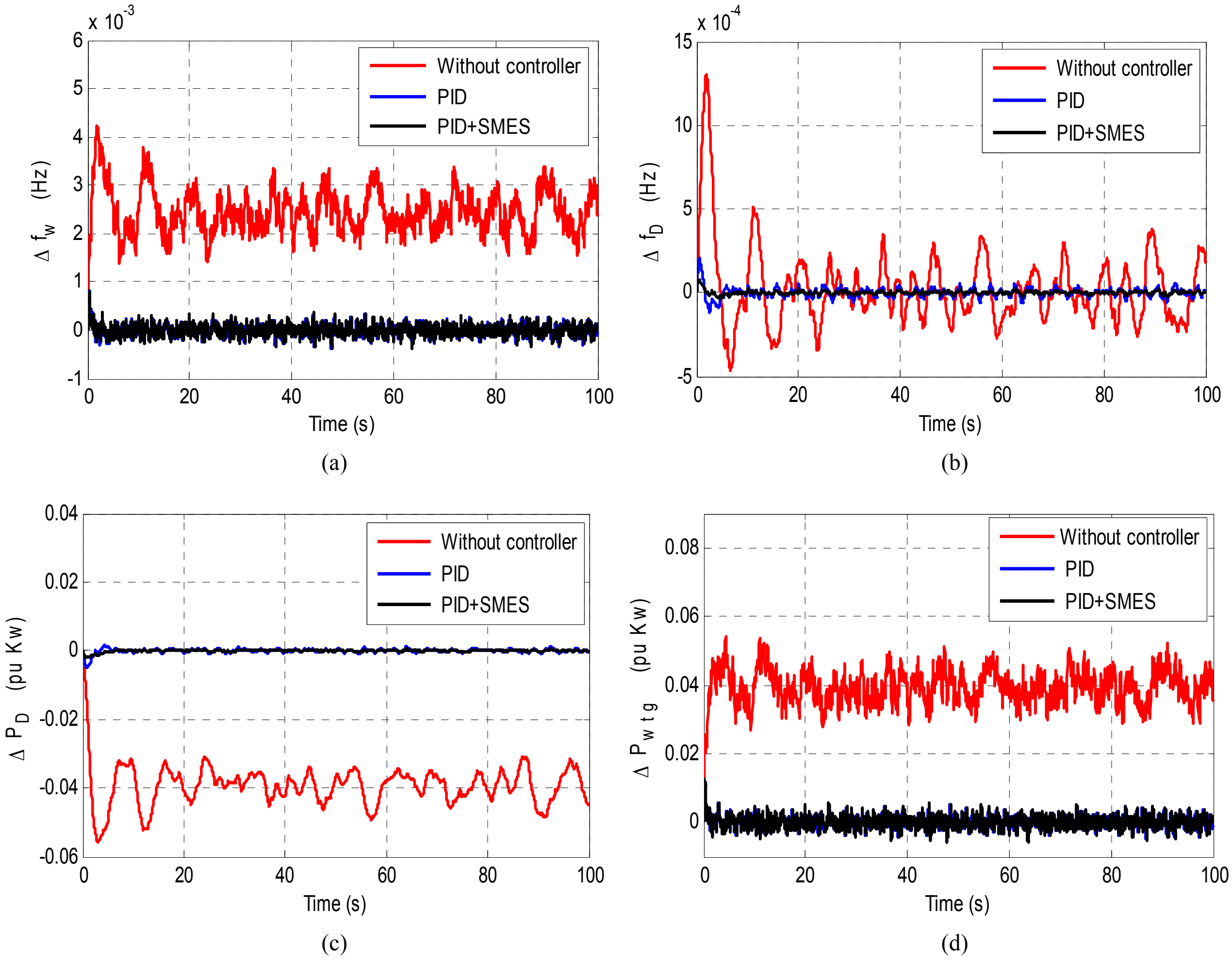


Fig. 5 System transient response curves for (a) wind frequency deviations; (b) diesel frequency deviations; (c) diesel output power deviations; (d) wind output power deviations for wind gust.

5. Conclusions

NSGA-based control approach for hybrid wind-diesel system is presented in this paper in two phases. Firstly, PID controller is utilized in the blade pitch system of wind turbine to ensure constant supply of wind energy trying to meet power generation/demand balance that drives to system frequency control. In the second stage, SMES with first order lead-lag controller is implemented to absorb the active power fluctuations quickly and hence control system frequency. Two objective functions are considered for each controller and NSGA-II is used to optimize the controllers' parameters to get an optimal performance. Three case studies are considered to validate the effectiveness and robustness of the proposed control technique under severe operating conditions such as system parameters variations and wind gust. The system transient response results confirm the superiority of the proposed control scheme over the conventional methods to damp the fluctuations of frequency and output power of diesel generator and wind turbine, decrease settling time, and minimize overshoot clearly. Overall, the performance of the wind-diesel system is enhanced significantly using the proposed control approach.

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