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Enhancement of a Small Power System Performance Using Multi-Objective Optimization

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ABSTRACT Optimal multi-objective design of proportional–integral-derivative controller parameters for a small power system using epsilon multi-objective genetic algorithm (ε-MOGA) has been presented in this paper. The small power system includes a wind turbine generator (WTG), a diesel generator, a battery energy storage system (BESS), and a load. The proposed scheme is applied for controlling the pitch angle system of the WTG to minimize the wind turbine mechanical blades stress, reduce the wind output power deviation, control the system frequency, and decrease the size of BESS by regulating its charging level. The deviations of input wind power are considered in a frequency domain. The low-frequency component is reduced by the pitch angle control system of WTG, while the high-frequency component is mitigated by the charge/discharge of the BESS, respectively. The input of the pitch angle control system of WTG is determined according to the low-frequency component of the input wind power deviation and the BESS state of charge. The output power of BESS is determined according to its state of charge, the high-frequency component of the input wind power deviation, and the frequency deviations. The effectiveness of the proposed controller is confirmed by numerical simulations.

INDEX TERMS Frequency control, multi-objective optimization, pitch angle control, power system stability, wind power generation.

I. INTRODUCTION

There are many isolated islands in the world, and the power is needed everywhere. Most of the remote and isolated communities or technical installations (e.g. meteorological systems, communication relays, farms, tourist facilities, etc.) are not interconnected to the national electric distribution grids and depend on diesel generators to meet the electricity demand [1]. Diesel fuel has several drawbacks: it is expensive because transportation to remote areas adds extra cost. Moreover, it emits sulfur oxide and carbon dioxide by engine exhaust that is harmful to the environment [2], [3]. In addition, diesel generators are inherently inefficient when operating at a low load factor (below 40-50% of their rated capacity) [4], [5]. One of the solutions to these matters is to introduce renewable energy power plants such as wind turbines and photovoltaic systems that are clean and available natural resources. However, the photovoltaic system has some disadvantages as it has low-energy conversion efficiency and it is very costly compared to wind power [6]. Moreover, many suitable regions of wind power generations exist in isolated islands. So, wind turbines have attracted a lot of attention nowadays. The wind-diesel hybrid power system can be installed to the isolated communities to improve their life standard. This hybrid system also can be a part of a micro-grid. It helps to decrease the usage of heavy oils and reduce the associated generation costs in the small power system. In addition, the level of emissions can be minimized [7], [8]. However, wind energy is not constant, and windmill output power is proportional to the cube of wind speed, which causes the fluctuations of the generated output power of WTG that may lead to frequency deviation and voltage flicker inside the power system [9]. Therefore, a new provision is needed in the small power system of the isolated island using pitch angle control. There are various pitch angle methods to control the output power of WTG using Model predictive controls (MPC) [10], Genetic algorithm (GA) [11], [12], Fuzzy logic control (FLC) [13]–[15], GA and Particle swarm optimization (PSO) [16] and Variable structure

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controllers (VSC) [17]. But these methods increase the wind turbine blade stress due to the rapid pitch action. Also, pitch angle control strategy based on FLC is presented in [18]–[20] for variable speed WTG without anything to be mentioned about mechanical blade stress minimization. In [21], individual pitch controller (IPC) based on FLC is discussed for WTG. Blade rotor moment and generator torque are considered as control objectives to mitigate fatigue loads and regulate output power of WTG. However, deciding the type, number of input and output membership functions, and their associated parameters in case of FLC is a time-consuming and complex task that may not often lead to satisfying results. So, in most cases, an optimization tool has to be used to get the best values of these parameters to ensure an optimal performance of the studied power system using FLC. Combined maximum power point tracking (MPPT)-pitch angle control for variable speed WTG using artificial neural networks (ANN) is clarified in [22]. No discussion is presented for the effect of this control scheme on the mechanical blade stress. In addition, the main drawback for applying ANN to wind energy control is the fact that ANN requires substantial amount of training based on predicted scenarios and specific system parameters which conflict with the variable nature of wind speed. Optimization of PID controller parameters for blade pitch system using the Intelligent genetic algorithm (IGA) is studied in [23]. Also, a comparison between PSO and pattern search (PS) algorithm is held in [24] to optimize Proportional-Integral (PI) controller parameters of pitch system for the wind turbine. However, the mechanical stress of the blade is not taken into account as one of the objective functions in these researches. To reduce the blade stress, the control region of the pitch angle and the output power of the WTG should be considered in a frequency domain [25]. H_∞ control method is used in [26] to smooth the output power of WTG but without illustrating the control region of the pitch angle in a frequency domain. Also [27]–[29] present H_∞-based control methods for WTG systems but there are nothing indicated about frequency control strategies. However, the weighting functions in the H_∞ control design cannot be selected easily. Also, the order of the H_∞ controller depends on that of the plant. This leads to a complex structure which is not easy to be realized in practical applications. Most of the industry applications still prefer simple controllers such as PI, PID and lead-lag ones.

To improve the system stability and performance, energy storage devices like superconducting magnetic energy storage (SMES), flywheels, batteries, and ultracapacitors are often used [30]. These serve as backup devices which store excess power when the generation is more than the demand and release power to the grid when the demand is more than the generation. This helps to maintain the safe operation of the power grid and balance the supply and demand sides. Moreover, the integrated energy storage system and WTG system can keep the deviations of frequency in the small power system at acceptable levels. The installation cost of ultracapacitor is very high and flywheel makes high noise especially when it is used with a large capacity range of operation. Also, the operation cost of SMES is very high because it must be maintained at the conduction state. For these reasons, BESS grows rapidly in the energy storage system technologies. The main disadvantage of BESS is its installation cost for large one. If a large BESS has to be installed in a small power system, the system cost will increase with a rapid rate which makes the whole system unfeasible from the economic term. So, it is economically beneficial to utilize small batteries for the output power control of the integrated system.

Therefore, this paper presents a multi-objective control approach for wind turbine and BESS using pitch angle control in a small power system. The proposed method is accessible by implementing PID controller in the pitch angle control system. ε-MOGA algorithm is used to optimize the parameters of the controller. The deviations of the input wind power are considered in a frequency domain. The low-frequency component is reduced by the pitch angle control system of the WTG, while the high-frequency component is reduced by the charge/discharge of the BESS, respectively. The input of the pitch angle control system of the WTG is determined according to the low-frequency component of the input wind power deviation and the BESS state of charge. The output power of BESS is determined according to its state of charge, the high-frequency component of the input wind power deviation and frequency deviations. The superiority of the proposed control approach using frequency domain is validated via the singular value plots of the control loops. The proposed method is compared to conventional one for two cases. Diesel generator dead-band is taken into consideration in the second case study to investigate the robustness of the proposed control scheme. The proposed approach can reduce the output wind power deviation, control the system frequency, mitigate the wind turbine mechanical blades stress and also ensure control of the integrated system by small BESS that is considered as an economical profit. Effectiveness of the proposed method is verified by the numerical simulations in MATLAB® / SIMULINK® environment. The main contributions of the proposed control approach can be summarized a follows:

- 1) The proposed scheme presents a multi-objective control approach for wind turbine and BESS with four conflicting objective functions using pitch angle control of WTG to minimize the wind output power deviations and reduce the wind turbine mechanical blade stress. Also, it controls the system frequency, decreases the size of BESS, and increases it lifetime by regulating its charging level.
- 2) The deviations of input wind power are considered in a frequency domain and the responsibility to smooth these fluctuations are shared between the BESS and the pitch angle control system of WTG to treat the drawbacks of the previous studies that failed to control all these objective functions at the same time. So, in the proposed control approach, BESS smooths only the

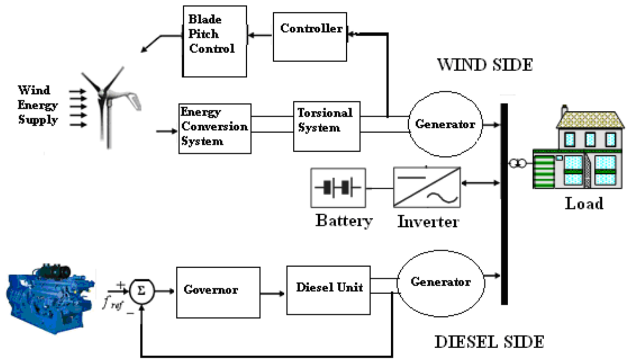

FIGURE 1. Single line diagram of the integrated small power system.

high-frequency component of wind power fluctuations. Therefore, its capacity can be reduced and all the system cost can be minimized. In addition, BESS lifetime can be extended. On the other hand, Wind turbine blade will respond only to the low-frequency component of input wind power fluctuations. So, the mechanical blade stress can be reduced simultaneously.

- 3) The presented control approach is tested under two case studies and compared to conventional one to validate its effectiveness and robustness over various operating conditions. In the second case study, the performance of the proposed control scheme is evaluated considering the inclusion of governor dead-band of the diesel generator to investigate the ability of the proposed technique to withstand such nonlinear operating condition. Also to validate its capability to decrease all of wind, BESS, diesel output powers and frequency deviations, mitigate the mechanical blade stress, and keep BESS state of charge near its ideal value, versus the conventional method.

This paper is organized as follows: Section II describes the small power system configuration. Section III discusses the proposed ε-MOGA based PID controller design scheme including a brief introduction for ε-MOGA theory. Section IV presents the simulation results for two case studies of the small power system. Section V analyzes the time-domain simulated results of these studied cases of the power system. The specific conclusion is then drawn in section VI.

II. SMALL POWER SYSTEM CONFIGURATION

The single line diagram of the power system under study is shown in Fig. 1. The integrated small power system consists of a WTG, a BESS, a diesel generator and a load. It is assumed that the small power system is disconnected from the grid and it can work independently. The detailed model of the power system is presented in Fig. 2. In this Figure, Δf_w refers to the frequency deviation of wind generation side, Δf_D is the frequency deviation of diesel generation side, ΔP_w is the input wind power deviation, ΔP_L is the load deviation and ΔP_{wtg} is the output power deviation of WTG. Also, the symbols $\Delta\beta$, ΔP_D and ζ are pitch angle deviation, diesel generator output power deviation and BESS state of charge, respectively. The system capacity is 350 KW. The continuous time dynamic behavior of the small power system is modeled by a set of state vector differential equations:

$$X^{\cdot} = AX + BU \quad (1)$$

$$Y = CX + DU \quad (2)$$

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 12^{th} order vector whose its elements are clearly indicated in Fig. 2. While, U and Y can be given as:

$$U = [\Delta P_w \quad \Delta P_L] \quad (3)$$

$$Y = [\Delta f_W \quad \Delta f_D \quad \Delta P_D \quad \Delta P_{Wtg} \quad \zeta \quad \Delta\beta] \quad (4)$$

A. PITCH ANGLE CONTROL SYSTEM

Fig. 3 presents the basic model of the pitch angle control of the WTG system that determines the deviation of pitch angle $\Delta\beta$. From this figure, the input of the control system is determined according to the low-frequency component of the input wind power deviation and state of charge of the BESS. The error signal (e) is then used as input for PID controller whose parameters have to be tuned by ε-MOGA algorithm according to four objective functions as will be discussed in later sections. The time constant of the low-pass filter is chosen as 20s. Actually, the pitch angle control system includes a hydraulic pitch actuator which drives the blades depending on the output signal of the controller. The actuator has nonlinear characteristics, but can be linearized and modeled as shown in Figure 3. $\Delta\beta$ is limited by a rate limiter (±10°/s) and a limiter within the range of 0°-80°. When the wind speed is from zero up to the cut-in value, there is no power generated and the pitch angle is set as $\beta = 90°$. When the wind speed is between cut-in and rated values, respectively, the pitch angle is fixed at $\beta = 10°$ so that the torque controller maximizes the power depending on the wind speed. As the wind speed exceeds its rated value, the proposed pitch angle control system operates between 10°-90° to maintain the rated power of the WTG. Above the cut-out wind speed, the pitch angle is again set as $\beta = 90°$ for safety reasons. The pitch angle control system presented in this paper operates in the area restricted between the rated wind speed and cut-out speed. So, the permissible deviation of pitch angle is within 0° -80°.

B. BESS MODEL

The model of BESS is shown in Fig. 4. A bidirectional power converter controlled by pulse width modulation is assumed in the model. Taking into account the fast response of the power converter, the BESS is modeled as a first-order lag system and the time constant T_b is 0.3 s. The output power of BESS is determined according to its state of charge, the high-frequency component of the input wind power deviation and frequency deviations. The BESS state of charge is indicated as a REL (Remaining Energy Level), which expresses

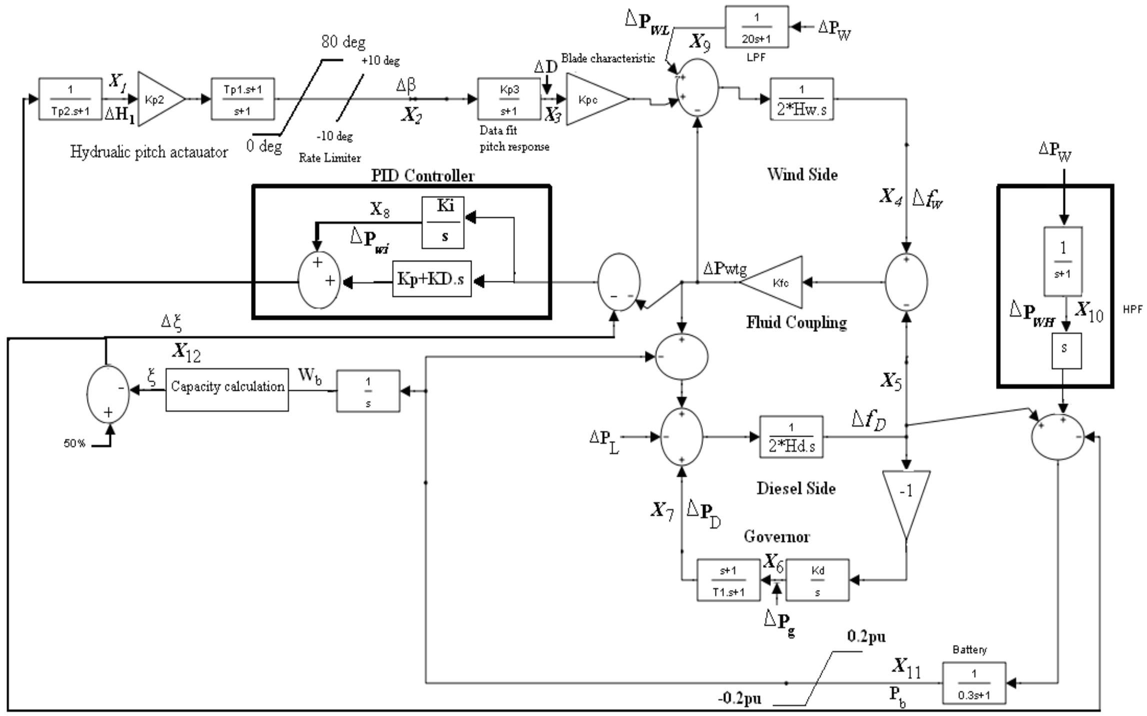

FIGURE 2. Block diagram of small power system.

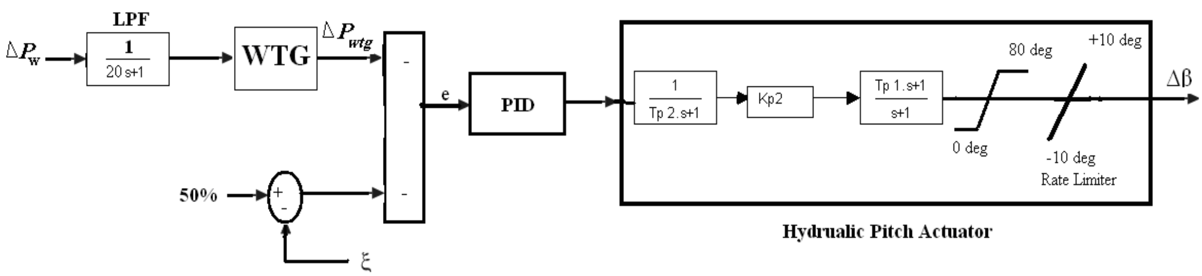

FIGURE 3. Pitch angle control system with hydraulic pitch actuator.

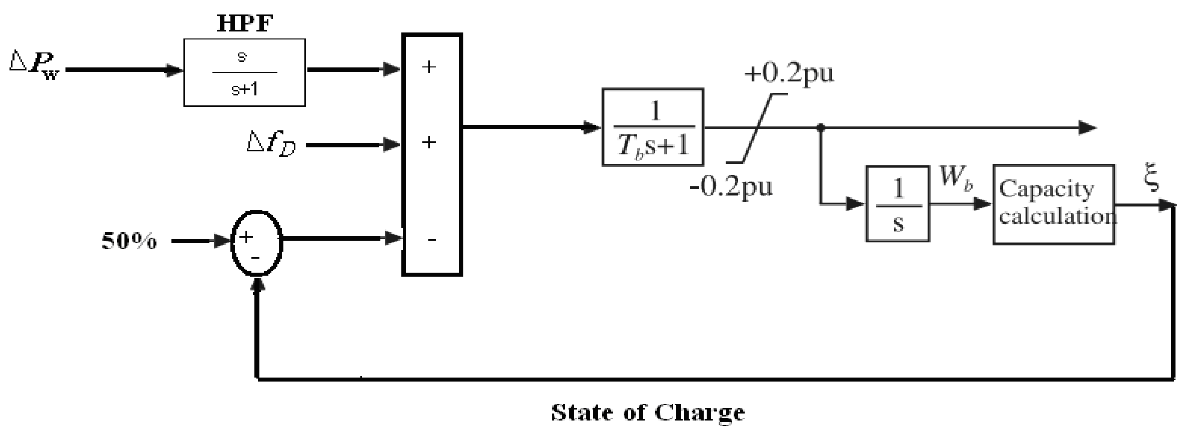

FIGURE 4. BESS model.

dischargeable energy in a percentage of the battery's rated capacity. The REL is obtained by the integral of the BESS output power and its range is within that of the state of charge [31]. The state of charge should always be maintained in its proper range for stable operation. If the deviation of WTG output power is smoothed using BESS without regulating the charging level, it reaches to the lower limit due to losses or to the upper limit by smoothing a large variation of WTG. So, a large capacity BESS is necessary if there is no control method to regulate the charging level which increases the small power system cost significantly. Therefore, one of the objective functions for the proposed PID controller is maintaining the state of charge near 50% to decrease the number of charge/discharge of BESS. Subsequently, reducing the battery capacity of the power system and extending its lifetime. The rated capacity of BESS is 100 KWh and the rated capacity of the power converter is 70 Kw (0.2 pu).

C. INPUT WIND POWER AND LOAD DEVIATIONS MODEL

Wind speed varies with time and also is related to wind speeds of the previous time. Many wind speed models have been used. In this paper, wind speed, and thus input wind power deviation, is presented using autoregressive and moving average (ARMA) time-series model [32]. Also, load deviation is modeled using the same approach. The ARMA time series model y_t is:

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + .. + \phi_n y_{t-n} + \alpha_t - \Theta_1 \alpha_{t-1} - \Theta_2 \alpha_{t-2} - .. - \Theta_m \alpha_{t-m} \quad (5)$$

where ϕ_i (i=1,2,..,n) , Θ_J (j=1,2,..,m), and α_t are the autoregressive parameters, moving average parameters, and a normal white noise process with zero mean, respectively. The simulated input wind power and load deviations values S_t can be calculated using the following equation [32]:

$$S_t = \mu_t + \sigma_t y_t \quad (6)$$

where μ_t and σ_t are the average and the standard deviation values of input wind power and load deviations, respectively.

III. ε-MOGA BASED PID CONTROLLER DESIGN

A. CONTROLLER DESIGN APPROACH

In this study, parameters of the pitch angle-PID controller will be tuned using ε-MOGA algorithm to meet the proposed performance. Four objective functions are introduced using integral absolute error (IAE) criteria as follows:

$$F(1) = \int_0^t |\Delta f_w| \, .dt \quad (7)$$

$$F(2) = \int_0^t |\Delta P_{wtg}| \, .dt \quad (8)$$

$$F(3) = \int_0^t |\zeta - 50| \, .dt \quad (9)$$

$$F(4) = \beta_{act} = \int_0^t |\Delta\beta| \, .dt \quad (10)$$

Subject to

$$K_p^{min} \le K_p \le K_p^{max} \quad (11)$$

$$K_i^{min} \le K_i \le K_i^{max} \quad (12)$$

$$K_D^{min} \le K_D \le K_D^{max} \quad (13)$$

Typical range selected for each of K_p, K_i and K_D is [0 to 100]. The weight of all objective functions is equal in this study. β_{act} is a performance index used for mechanical blades stress. If β_{act} is large, it means that the pitch action and therefore the mechanical blades stress is large and vice versa. The four objective functions have clear conflict especially between minimization of wind output power deviation and wind turbine mechanical stress reduction. That is why ε-MOGA algorithm was chosen. The advantage of ε-MOGA over the other multi-objective approaches is its capability to keep the diversity over the optimization process by inserting every solution in isolated box as will be discussed in details with the next section. This action widens the search space so it can reach to good results that cannot be achieved by other techniques. Also, ε-MOGA requires little memory resources. In addition, its running time is small compared to other multi-objective schemes with the same number of objective functions.

B. ε-MOGA THEORY

ε-MOGA is an elitist multi-objective evolutionary algorithm based on the concept of epsilon-dominance, which is used to control the content of the archive A(t) where the result of the optimization problem is stored. ε-MOGA obtains an ε-pareto set, Θ_p^* (which is not unique), that converges toward the pareto optimal set, Θ_p in a smart distributed manner around the pareto front $\mu(\Theta_p)$ with limited memory resources. Moreover, it adjusts the limits of the pareto front dynamically and prevents the solutions belonging to the ends of the front from being lost [33]–[35]. To reach this goal, the objective space is split into a fixed number of boxes n_box_i. So, for each dimension i ϵ [1....n], n_box_i cells of ε_i width are created [35], [36]. Where

$$\varepsilon_i = (\mu_i^{max} - \mu_i^{min})/n\_box_i, \quad \mu_i^{max} = max\, \mu_i(x), \quad \mu_i^{min} = min\, \mu_i(x) \text{ and } x \epsilon \Theta_p^* \quad (14)$$

This grid preserves the diversity of $\mu(\Theta_p^*)$ since each box can be occupied by only one solution. For a solution x ϵ solution space, $box_i(x)$ can be defined by

$$box_i(x) = ([(\mu_i(x) - \mu_i^{min})/(\mu_i^{max} - \mu_i^{min})] * [n\_box_i]) \times \forall i \epsilon [1.....n] \quad (15)$$

A solution x^1 with value $\mu(x^1)$ ε-dominates the solution x^2 with value $\mu(x^2)$, denoted by $x^1 <_\varepsilon x^2$, if and only if

$$box(x^1) < box(x^2) \vee (box(x^1) < box(x^2) \wedge x^1 < x^2), \quad box(x) = \{box_1(x), \ldots, box_s(x)\} \quad (16)$$

Hence, a set $\Theta_p^* \subseteq \Theta_p$ is ε-pareto, if and only if

$$\forall x^1, x^2 \epsilon \Theta_p, x^1 \neq x^2, box(x^1) \neq box(x^2) \wedge box(x^1) >_\varepsilon box(x^2) \quad (17)$$

Therefore, ε-MOGA updates A(t) by saving only ε-dominant solutions that do not share the same box. When two mutually ε-dominant solutions compete, the solution that remains in A(t) is the closer to the center of the box. So, preventing solutions belonging to adjacent boxes and increasing diversity of solution can be achieved. The algorithm is composed of three populations [35], [37]: the main population, P(t), which explores the search space D_s during the iterations and its population size is $Nind_p$. The auxiliary population G(t) and its size is $Nind_G$, which must be an even number. The last one is the archive, A(t), which stores the solutions Θ_p^* and its size is $Nind_A$ that is variable but bounded by:

$$Nind\_max\_A = \frac{\prod_{i=1}^{s}(n\_box_i + 1)}{n\_box_{max} + 1} \quad (18)$$

where $n\_box_{max} = \max[n\_box_1, \ldots, n\_box_s]$.

The main steps of the proposed algorithm are as follows [35], [38]:

- Step1. Begin and create empty A(t).
- Step2. P(0) is initialized with $Nind_p$ individuals that have been randomly selected from D_s.
- Step3. Calculate the fitness value of each individual in P(t).
- Step4. Check individuals in P(t) that might be included in A(t), as follows:
  - 1) Non-dominated individuals in P(t) are detected, Θ_{ND}.
  - 2) Pareto front limits μ_i^{max} and μ_i^{min} are calculated from μ(x),$\forall$ x ϵ Θ_{ND}.
  - 3) Individuals in Θ_{ND} are analyzed and those which are not ε-dominated by individuals in A(t), are included in A(t).
- Step5. Create G(t) as follows:
  - 1) Two individuals are randomly selected, x^p from P(t), and x^A from A(t).
  - 2) A random number u ϵ [0-1] is generated.
  - 3) If u > $P_{c/m}$ (probability of crossing/mutation), x^p and x^A are crossed over by means of the extended linear recombination technique.
  - 4) If u < $P_{c/m}$, x^A and x^p are mutated using Gaussian distribution and then included in G(t).

  This procedure is repeated $Nind_p/2$ times until G(t) is filled up.
- Step6. Calculate the fitness value of each individual in G(t).
- Step7. Check, one by one, which individuals in G(t) must be included in A(t) on the basis of their location in the objective space.
- Step8. Update P(t) with individuals from G(t). Every individual x^G from G(t) replaces an individual x^p that is randomly selected from the individuals in P(t) which are dominated by x^G. However, x^G will not be included in P(t) if there is no individual in P(t) dominated by x^G.

Finally, individuals from A(t) compose the smart characterization of the pareto front, Θ_p^* . Then ε-MOGA was applied to solve the multi-objective optimization problem to search for the PID controller parameters of the pitch angle control system. The parameters of the algorithm were set to:

- $Nind_G = 8$, $Nind_p = 20000$, $P_{c/m} = 0.2$.

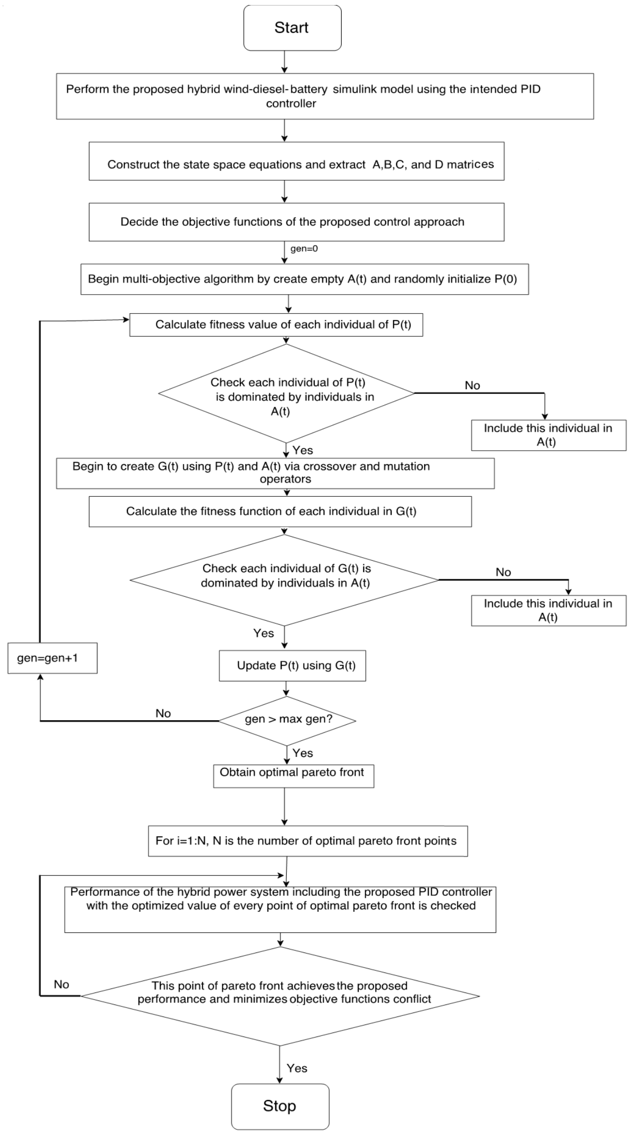

FIGURE 5. Flowchart of ε-MOGA based PID controller design process.

- Number of generation=1000.
- $n\_box_1 = n\_box_2 = n\_box_3 = n\_box_4 = 500$.

After simulation running of the proposed optimization approach, The final pareto front of ε-MOGA is achieved which consists of 126 points. Each point contains one value for K_p, K_i, and K_D, respectively of the PID controller for the blade pitch system of WTG. The performance of the small power system with these values of the PID controller parameters associated to each point is then investigated individually using SIMULINK environment to get the best operating point that can minimize the conflict among the four objective functions. Finally, among all these points of pareto front, the best one that can ensure adequate performance of the small power system and at the same time minimize the conflict among the objective functions has PID controller parameters as follows: $K_p = 1.2252$, $K_i = 0.7535$, and $K_D = 0.6854$. The flowchart of the complete design process for the proposed ε-MOGA based PID controller is presented in Fig. 5. The singular

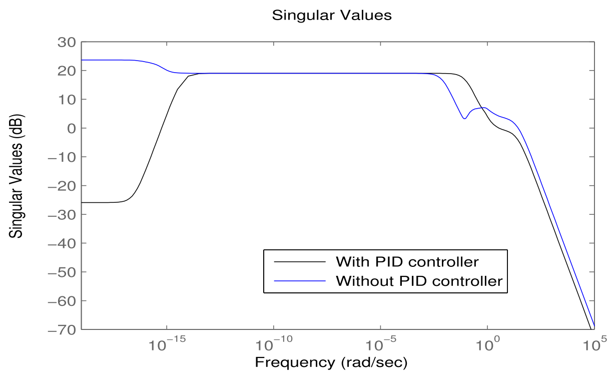

FIGURE 6. Singular values plot of pitch angle control loop.

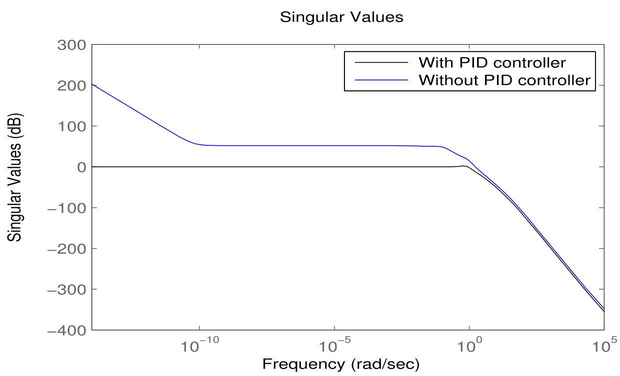

FIGURE 7. Singular values plot of state of charge control loop.

values plots of the control loops with/without the proposed controller are shown in Figs. (6-8). In Fig. 6, the singular values plot of the pitch angle control loop indicates that there is a high gain in the low-frequency domain without using the proposed controller. Due to this high gain, the pitch action for the output power fluctuations of WTG may increase at the low-frequency domain which increases the blade pitch mechanical stress. Also, there is a resonance point as shown in the figure. The resonance frequency can be calculated and the value is 0.0803 rad/sec. The resonance point may affect the blade pitch control in the small power system. The state of charge control loop is shown in Fig. 7. From this figure, the singular values plot has an integral characteristic at the low-frequency domain without utilizing the proposed control approach. Because of this, the state of charge keeps increasing so that the characteristic can be eliminated. On the other hand, in the frequency control loop, a high gain in the low-frequency domain (below 1 rad/sec) is clarified without implementing the proposed control scheme as shown in Fig. 8. Therefore, the frequency fluctuations due to the input wind power and load deviations may increase at the low-frequency domain.

IV. SIMULATION RESULTS

To confirm the effectiveness of the proposed control approach, some simulations are performed in the Simulink environment of MATLAB software. The simulation parameters of the integrated power system are given in Table 1.

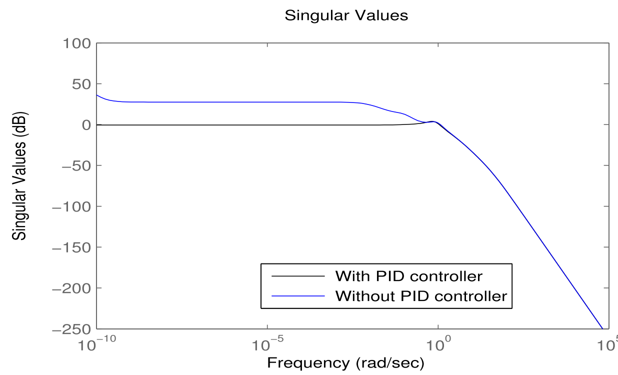

FIGURE 8. Singular values plot of frequency control loop.

TABLE 1. Simulation parameters.

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.

TABLE 2. PI controller parameters.

	P gain K_p	I gain K_i
Pitch angle control system	2	0.1
State of charge	0.01	0
Frequency deviation	8	0.1

The proposed PID controller method is compared with conventional control scheme presented in [39]. In the conventional approach, three PI controllers are implemented: first in the pitch angle control system, second in the BESS state of charge closed loop while the third is set in the frequency deviation closed loop. The parameters of the PI controllers are listed in Table 2. In the proposed study, the ARMA(3,2) model are used to present input wind power and load deviations as follows [40]:

$$y_t = 1.7901y_{t-1} - 0.9087y_{t-2} + 0.0948y_{t-3} + \alpha_t - 1.0929\alpha_{t-1} + 0.2892\alpha_{t-2} \quad (19)$$

where the average input wind power deviation are considered as 0.35pu taking into account the average annual wind speed in the isolated island of Okinawa, Japan, which is from 8.5 to 10 m/s. However, the average value of load deviation is presented as 0.3pu. Input wind power and load deviations are shown in Figs. 9 and 10. Simulation of the small power system is performed for 20 minutes.

A. CASE 1

This case is considered as the base one. The output powers of WTG system for the conventional and proposed methods are shown in Fig. 11. This figure clearly confirms that the

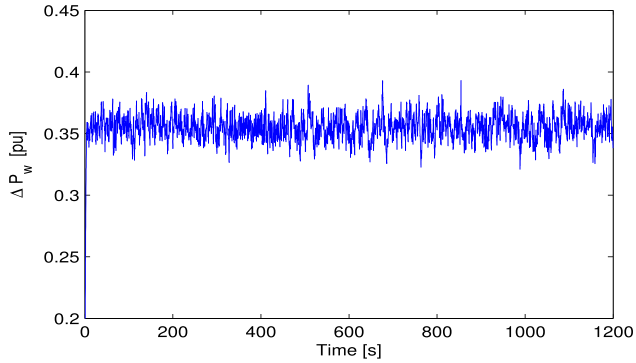

FIGURE 9. Input wind power deviation.

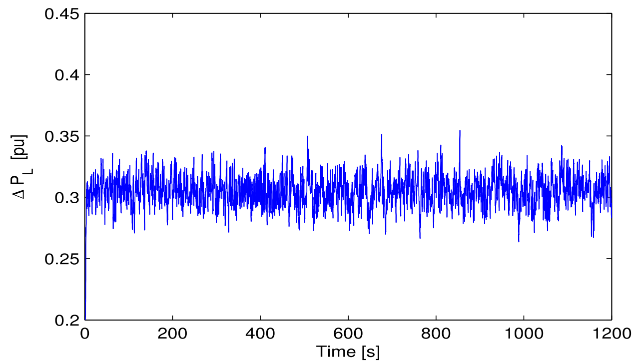

FIGURE 10. Load deviation.

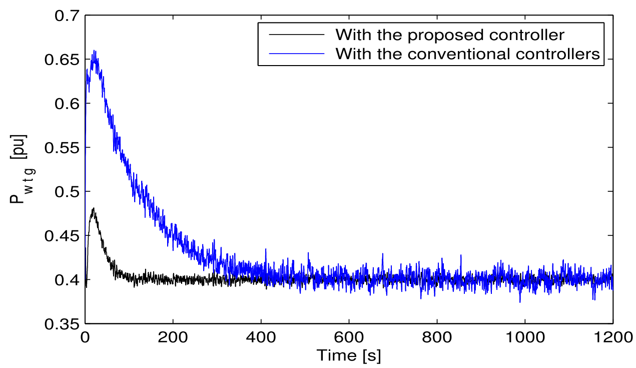

FIGURE 11. Output power of WTG.

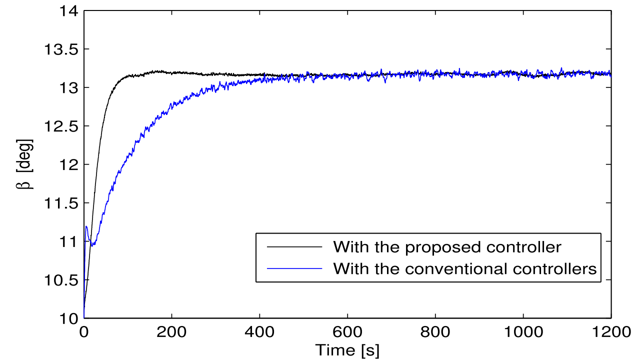

FIGURE 12. Pitch angle.

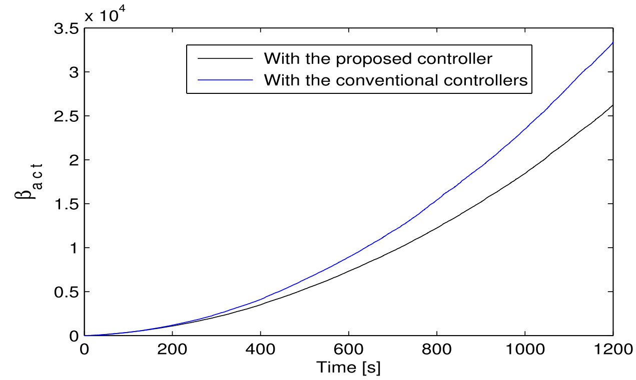

FIGURE 13. Performance index β_{act}.

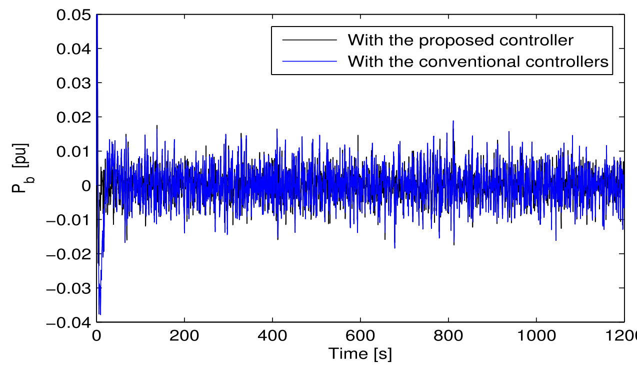

FIGURE 14. Output power of BESS.

output power fluctuation of WTG with the proposed method is smaller than that of the conventional one and with significantly reduced overshoot. Figs. 12 and 13 indicate the pitch angle and the performance index β_{act}, respectively. From these figures, it is obvious that the system with the proposed controller has a speed of response faster than that with conventional ones. It makes more pitch actions but with less swing from the nominal value of the pitch angle. So, the wind turbine mechanical blade stress is decreased using the proposed controller which is confirmed with the performance index figure. Hence, the proposed control approach with that values of the PID controller parameters selected from the pareto front succeeded to decrease the conflict between the output power of WTG and the mechanical blade stress. Figs. 14 and 15 show the output power of BESS and its state of charge for both methods. From these figures, it is proved that BESS with conventional method charges and discharges with more fluctuations than those with the proposed controller. Besides, the state of charge with conventional method deviates slightly from fifty percent level with larger fluctuations as compared to that with the proposed one. Diesel generator output power with the conventional and proposed approaches is pointed out in Fig. 16 which shows the capability of both control approaches to keep the fluctuations of diesel generator output power within the acceptable limits. However, there are little more overshoots using the proposed scheme due to diesel generators trials to

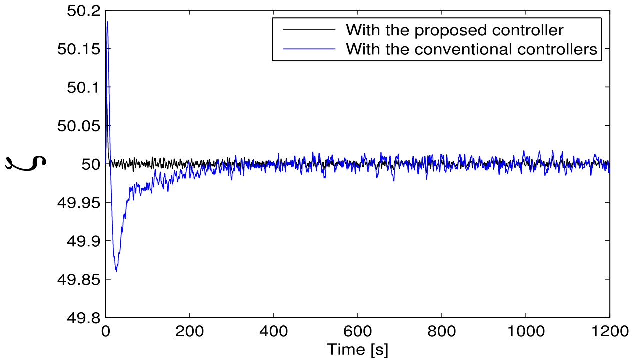

FIGURE 15. State of charge.

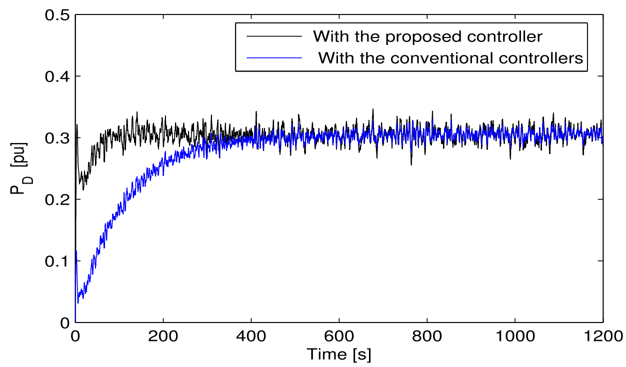

FIGURE 16. Diesel generator output power.

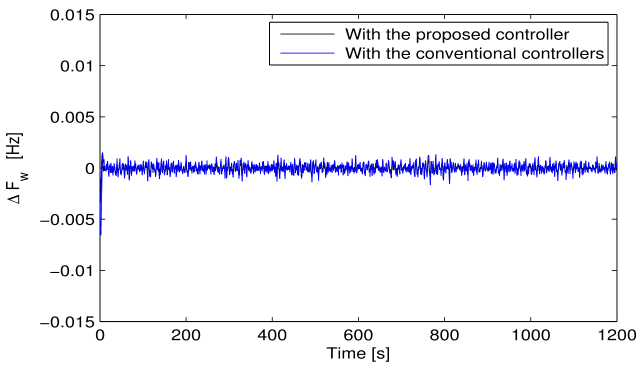

FIGURE 17. Frequency deviation.

meet the load demand variations from moment to another. This action appears only in the proposed approach as a result of the controller effect to ensure constant wind output power and regulate the charged/discharged power of BESS. Fig. 17 shows the frequency deviation which clarifies the superiority of the proposed control scheme to mitigate frequency fluctuations compared to the conventional method.

B. CASE 2 (PERFORMANCE EVALUATION USING DIESEL-GENERATOR DEAD-BAND)

The previously considered case study of the small power system model is linear in nature. However, taking into account the nonlinearity in the form of inclusion of the governor

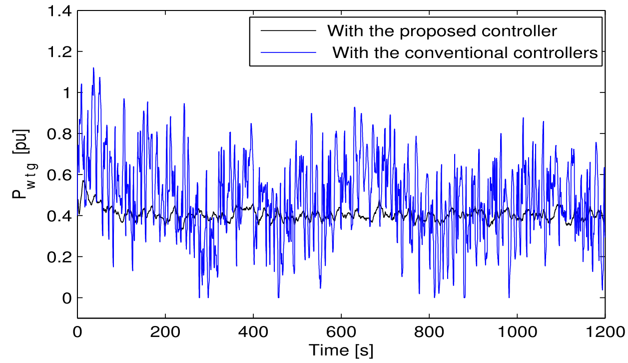

FIGURE 18. Output power of WTG.

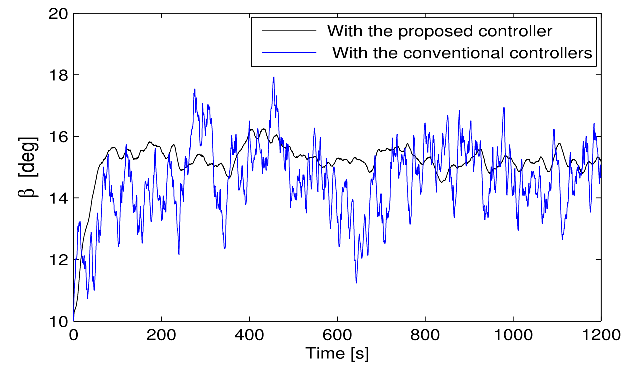

FIGURE 19. Pitch angle.

dead-band for the diesel generator is crucial for this type of research work to investigate the effectiveness of the proposed control scheme. In the model, the dead-band block is included in the governor system of diesel-generator. The dead-band control does not let the system to respond to the frequency deviations that lie within a predefined range. So, the governor is inactive within these dead-band limits. North American Electric Reliability Corporation (NERC) standards require the plant to have a dead-band not more than 0.036 Hz. Hence, the dead-band range in this case study is chosen to be ±0.01 Hz. The time-domain simulations are performed using the same input wind power and load deviations of case 1 for 20 minutes including the dead-band of diesel generator.

The output powers of the WTG system for the conventional and proposed methods are pointed out in Fig. 18. The proposed approach still has the ability to withstand this harsh operating condition and can keep the output power of WTG around its nominal value (0.4pu). However, the conventional method has larger fluctuations which move away from this value. The pitch angle with the proposed, conventional methods and the performance index β_{act}, are shown in Figs. 19 and 20, respectively. These figures confirm precisely the capability of the proposed scheme to guarantee less wind turbine mechanical blade stress even with the diesel generator dead-band implementation. This action can increase the wind turbine lifetime significantly. Figs. 21 and 22 show the output power of BESS and its state of charge for both

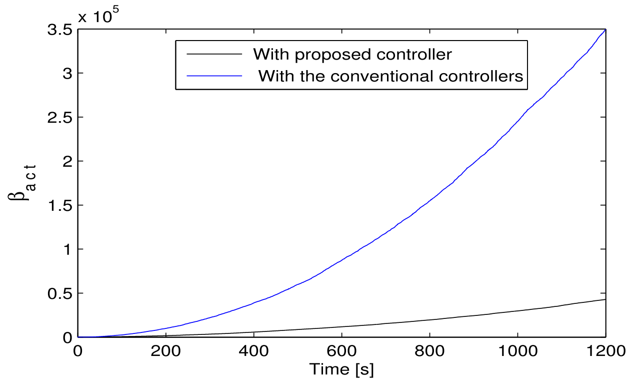

FIGURE 20. Performance index β_{act}.

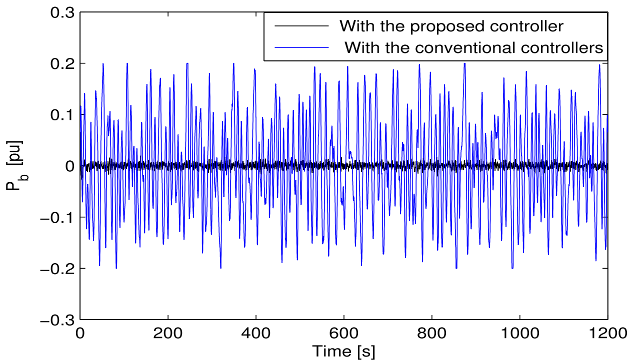

FIGURE 21. Output power of BESS.

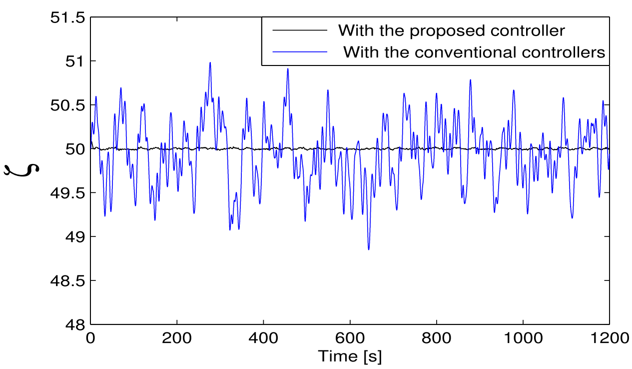

FIGURE 22. State of charge.

techniques. From these figures, BESS with the conventional method cannot charge and discharge many times due to the capacity limit. So, larger battery capacity will be required which will increase the system cost significantly. Also, it is evident from the simulation results that the ramp rate of charge/discharge is very high for BESS with the conventional approach that affects the BESS lifetime. On the other hand, the proposed method still ensures well-regulated charged/discharged power of the BESS within the acceptable limits and adequate charge/discharge ramp rate. Also, the state of charge deviation with the conventional method increases from the ideal level (50%) with larger fluctuations

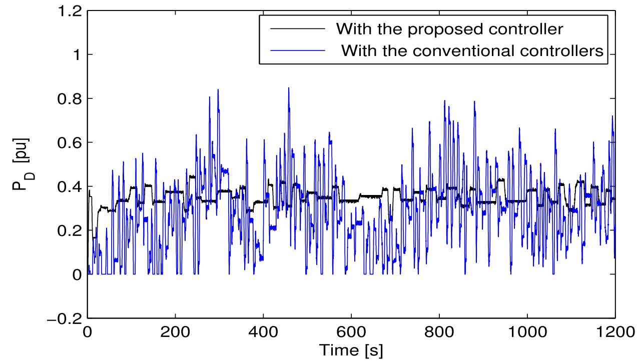

FIGURE 23. Diesel generator output power.

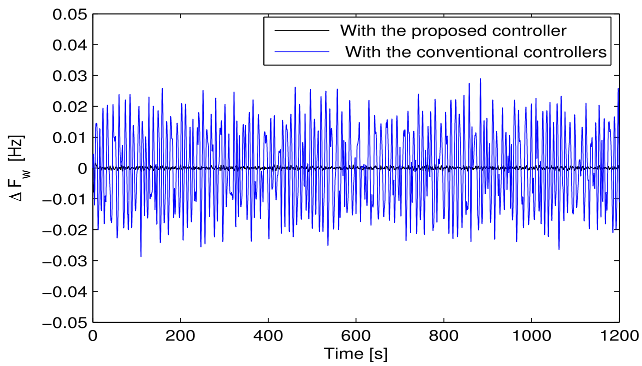

FIGURE 24. Frequency deviation.

as compared to that with the proposed scheme. Diesel generator output power with the conventional and proposed schemes is clarified in Fig. 23 which indicates the ability of the proposed approach to withstand the effect of the governor dead-band inclusion damping all oscillations with a high speed of response. However, the conventional control technique fails to keep the system stability having large swings compared to the proposed one. Fig. 24 confirms the superiority of the proposed control scheme for damping frequency fluctuations while the conventional one seems to be unstable with high-frequency oscillations.

V. RESULTS ANALYSIS

Detailed analysis of the time-domain simulation results is held here for the two case studies presented in the previous section

- 1) Case 1 represents the implementation of the proposed multi-objective ε-MOGA based PID control scheme for the pitch angle control system of WTG in the small power system. Simulation is performed for 20 minutes. As a result, the proposed technique can reduce the output power fluctuations of WTG and decrease its overshoot significantly as shown in Fig. 11. While the conventional method still has very high overshoot near 0.65 pu. Also, the proposed technique succeeded to mitigate the pitch angle fluctuations and accordingly reduce the mechanical blade stress performance index β_{act}

compared to the conventional method that can be extracted from Figs. 12 and 13. So, the proposed control scheme overcomes the main drawbacks of the previous studies and can decrease the significant conflict between the wind output power fluctuations and mechanical blade stress thanks to considering the input wind power deviations in a frequency domain and sharing its smoothing responsibility between BESS and pitch angle control system of WTG. This action decreases the duty cycle of both elements and thus achieves the proposed performance. Also, the BESS can charge/discharge with fewer fluctuations using the proposed control technique having state of charge almost constant at its typical value (50%) compared to the conventional method as shown in Figs. 14 and 15. On the other hand, due to the achievement of the proposed control approach for keeping the output wind power almost constant and regulating the charged/discharged power of BESS, diesel generator tries to meet the load demand variations from one moment to another. So, the diesel generator output power has a little more overshoot fluctuations compared to the conventional technique as shown in Fig. 16. Also, the proposed control scheme succeeded to damp the frequency variation and decrease its magnitude compared to the conventional method as presented in Fig. 17.

- 2) In the second case study, the inclusion of the governor dead-band of the diesel generator is considered and the performance of the proposed control scheme is evaluated for 20 simulation minutes to validate its capability to withstand such nonlinear operating condition. The results confirm the ability of the proposed control technique to keep the WTG output power near its nominal value (0.4 pu) while the conventional method has high fluctuations reach to 1 pu. Also, the proposed scheme can mitigate the pitch angle fluctuations significantly and decrease the mechanical blade stress by an enormous amount compared to the conventional method which has high pitch angle fluctuations as indicated in Figs. 19 and 20. Besides, the proposed method succeeded to damp the deviations of the charged/discharged power of BESS significantly with an almost constant state of charge at its recommended value (50%). However, BESS with the conventional approach stopped charging/discharging many times due to reaching to the capacity limit (0.2 pu) with high fluctuations. So, larger battery capacity will be required if this method is practically implemented in the small power system. Hence, the total cost of the power system will increase dramatically. Also, the conventional technique has clear deviations for the state of charge compared to the proposed one as presented in Fig. 22. On the other hand, the proposed approach still can regulate the output power of diesel generator while the conventional method fails to keep the system stability with high fluctuations of the diesel generator output power reaches to 0.9 pu as shown in Fig. 23. Also, the proposed control scheme guarantees its superiority to control the system frequency and damp its fluctuations as shown in Fig. 24. In contrast, the conventional method appears to lose its stability with high frequency oscillations.

VI. CONCLUSION

Multi-objective frequency domain approach has been applied to a PID controller design process for a small power system in this paper. The small power system consists of WTG, diesel generator, BESS, and load. ε-MOGA algorithm is used to optimize the gains of the controller in the pitch angle system of WTG. The deviations of the input wind power are considered in a frequency domain. The low-frequency component is reduced by the pitch angle control system of the WTG, while the high-frequency component is minimized by the charge/discharge of the BESS, respectively. Four objective functions are considered in the controller design approach. The proposed method is compared to the conventional one in two case studies. To confirm the robustness and effectiveness of the proposed control approach, the diesel generator dead-band is considered in the second case. From simulation results, for the first case, the proposed approach can reduce the wind output power deviation and control the system frequency. Furthermore, it can minimize the wind turbine mechanical blades stress, decrease the size of BESS and increase its lifetime by regulating its charging level that is taken into account as an economic profit. In addition, for the second case, the proposed control scheme can bear diesel generator dead-band inclusion and ensure system stability with reducing all of the wind, BESS, diesel output powers, and frequency deviations. Also, it clearly minimizes the mechanical blade stress and keeps the BESS state of charge near its ideal value (50%). However, the conventional method fails to keep system stability having large oscillations for all of the system components output powers and frequency. Also, it has high mechanical blade stress and BESS ramp rate of charge/discharge that decrease dramatically the lifetimes of the wind turbine and BESS, respectively. Overall, the performance of the small power system is enhanced significantly using the proposed technique.

REFERENCES

[1] H. Ibrahim, R. Younès, T. Basbous, A. Ilinca, and M. Dimitrova, "Optimization of diesel engine performances for a hybrid wind–diesel system with compressed air energy storage," *Energy*, vol. 36, no. 5, pp. 3079–3091, May 2011.

[2] R. Hunter and G. Eillot, *Wind-Diesel Systems. A Guide to Technology and its Implementation*. Cambridge, U.K.: Cambridge Univ. Press, 1994.

[3] H. Nacfaire, *Wind-Diesel and Autonomous Energy Systems*. New York, NY, USA: Elsevier, 1989.

[4] A. Khelif, A. Talha, M. Belhamel, and A. H. Arab, "Feasibility study of hybrid Diesel-PV power plants in the southern of Algeria: Case study on AFRA power plant," *Int. J. Elect. Power Energy Syst.*, vol. 43, no. 1, pp. 553–564, Dec. 2013.

[5] B. Sedaghat, A. Jalilvand, and R. Noroozian, "Design of a multilevel control strategy for integration of stand-alone wind/diesel system," *Int. J. Elect. Power Energy Syst.*, vol. 35, no. 1, pp. 123–137, Feb. 2012.

[6] T. Senjyu, E. Omine, D. Hayashi, H. Sekine, and T. Funabashi, "Application of decentralized control for remote power system stabilization by installing renewable energy power plant," *IEEJ Trans. Elect. Electron. Eng.*, vol. 3, no. 5, pp. 473–481, Sep. 2008.

[7] A. M. Kassem and A. M. Yousef, "Robust control of an isolated hybrid wind-diesel power system using Linear Quadratic Gaussian approach," *Int. J. Elect. Power Energy Syst.*, vol. 33, no. 4, pp. 1092–1100, May 2011.

[8] J. G. Slootweg and W. L. Kling, "Is the answer blowing in the wind?" *IEEE Power Energy Mag.*, vol. 1, no. 6, pp. 26–33, Nov. 2003.

[9] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and C.-H. Kim, "A coordinated control method for leveling PV output power fluctuations of PV–diesel hybrid systems connected to isolated power utility," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 153–162, Mar. 2009.

[10] J. Pahasa and I. Ngamroo, "Coordinated control of wind turbine blade pitch angle and PHEVs using MPCs for load frequency control of microgrid," *IEEE Syst. J.*, vol. 10, no. 1, pp. 97–105, Mar. 2016.

[11] A. N. C. Supriyadi, H. Takano, J. Murata, T. Goda, and T. Hashiguchi, "Adaptive frequency control for hybrid wind-diesel power system using system estimator," in *Proc. IEEE Int. Conf. Power Syst. Technol. (POWERCON)*, Oct. 2012, pp. 1–6.

[12] A. Supriyadi and A. Nandar, "Robust PI control of smart controllable load for frequency stabilization of microgrid power system," *Renew. Energy*, vol. 56, pp. 16–23, Aug. 2013.

[13] M. Tarkeshwar and V. Mukherjee, "A novel quasi-oppositional harmony search algorithm and fuzzy logic controller for frequency stabilization of an isolated hybrid power system," *Int. J. Elect. Power Energy Syst.*, vol. 66, pp. 247–261, Mar. 2015.

[14] A. Lasheen and A. Elshafei, "Wind-turbine collective-pitch control via a fuzzy predictive algorithm," *Renew. Energy*, vol. 87, pp. 298–306, Mar. 2016.

[15] C. Viveiros, R. Melício, J. Igreja, and V. M. F. Mendes, "Performance assessment of a wind energy conversion system using a hierarchical controller structure," *Energy Convers. Manage.*, vol. 93, pp. 40–48, Mar. 2015.

[16] S. R. Gampa and D. Das, "Real power and frequency control of a small isolated power system," *Int. J. Elect. Power Energy Syst.*, vol. 64, pp. 221–232, Jan. 2015.

[17] D. Das, S. K. Adityaa, and D. P. Kothari, "Dynamics of diesel and wind turbine generators on an isolated power system," *Int. J. Elect. Power Energy Syst.*, vol. 21, no. 3, pp. 183–189, 1999.

[18] T. L. Van, T. H. Nguyen, and D. C. Lee, "Advanced pitch angle control based on fuzzy logic for variable-speed wind turbine systems," *IEEE Trans. Energy Convers.*, vol. 30, no. 2, pp. 578–587, Jun. 2015.

[19] H. Slah, D. Mehdi, and S. Lassaad, "Advanced control of a PMSG wind turbine," *Int. J. Modern Nonlinear Theory App.*, vol. 1, no. 1, 2016, Art. no. 64119.

[20] Z. Civelek, M. Lüy, E. Çam, and N. Barişçi, "Control of pitch angle of wind turbine by fuzzy PID controller," *J. Intell. Autom. Soft Comp.*, vol. 22, no. 3, pp. 463–471, 2016.

[21] B. Han, L. Zhou, F. Yang, and Z. Xiang, "Individual pitch controller based on fuzzy logic control for wind turbine load mitigation," *IET Renew. Power Generat.*, vol. 10, no. 5, pp. 687–693, 2016.

[22] A. Dahbi, N. Nait-Said, and M.-S. Nait-Said, "A novel combined MPPT-pitch angle control for wide range variable speed wind turbine based on neural network," *Int. J. Hydrogen Energy*, vol. 41, no. 22, pp. 9427–9442, 2016.

[23] Z. Civelek, E. Çam, M. Lüy, and H. Mamur, "Proportional–integral–derivative parameter optimisation of blade pitch controller in wind turbines by a new intelligent genetic algorithm," *IET Renew. Power Generat.*, vol. 10, no. 8, pp. 1220–1228, 2016.

[24] S. Behera, B. Subudhi, and B. B. Pati, "Design of PI controller in pitch control of wind turbine: A comparison of PSO and PS algorithm," *Int. J. Renew. Energy Res.*, vol. 6, no. 1, pp. 271–281, 2016.

[25] A. M. Howlader, Y. Izumi, A. Uehara, N. Urasaki, T. Senjyu, and A. Saber, "A robust H_∞ controller based frequency control approach using the wind-battery coordination strategy in a small power system," *Int. J. Elect. Power Energy Syst.*, vol. 58, pp. 190–198, Jun. 2014.

[26] R. Sakamoto *et al.*, "output power leveling of wind turbine generator by pitch angle control using H_∞ control," *Elect. Eng. Jpn*, vol. 126, no. 4, pp. 17–24, 2008.

[27] A. D. de Corcuera, A. Pujana-Arrese, J. M. Ezquerra, E. Segurola, and J. Landaluze, "H_∞ based control for load mitigation in wind turbines," *Energies*, vol. 5, no. 4, pp. 938–967, 2012.infini

[28] B. E. Muhando and R. W. Wies, "Nonlinear H_∞ constrained feedback control for grid-interactive WECS under high stochasticity," *IEEE Trans. Energy Convers.*, vol. 26, no. 4, pp. 1000–1009, Dec. 2011.

[29] A. N. C. Supriyadi, I. Ngamroo, S. Kaitwanidvilai, A. Kunakorn, T. Hashiguchi, and T. Goda, "Robust pitch controller design in hybrid wind-diesel power generation system," in *Proc. 3rd IEEE Conf. Ind. Electron. Appl.*, Jun. 2008, pp. 1054–1059.

[30] H. Jiayi, J. Chuanwen, and X. Rong, "A review on distributed energy resources and microgrid," *Renew. Sustain. Energy Rev.*, vol. 12, no. 9, pp. 2472–2483, Dec. 2008.

[31] K. Yoshimoto, T. Nanahara, G. Koshimizu, and Y. Uchida, "New control method for regulating state-of- charge of a battery in hybrid wind power/battery energy storage system," in *Proc. IEEE PES Power Syst. Conf. Expo.*, Oct. 2006, pp. 1244–1251.

[32] P. Wang and R. Billinton, "Reliability benefit analysis of adding WTG to a distribution system," *IEEE Trans. Energy Convers.*, vol. 16, no. 2, pp. 134–139, Jun. 2001.

[33] J. Herrero, "Non-linear robust identification using evolutionary algorithms," Ph.D. dissertation, Polytech. Univ. Valencia, Valencia, Spain, 2006.

[34] M. Laumanns, L. Thiele, K. Deb, and E. Zitzler, "Combining convergence and diversity in evolutionary multiobjective optimization," *Evol. Comput.*, vol. 10, no. 3, pp. 263–282, 2002.

[35] M. E. Lotfy, T. Senjyu, M. A.-F. Farahat, A. F. Abdel-Gawad, and A. Yona, "A frequency control approach for hybrid power system using multi-objective optimization," *Energies*, vol. 10, no. 1, p. 80, 2017.

[36] J. M. Herrero, G. Reynoso-Meza, M. Martínez, X. Blasco, and J. Sanchis, "A smart-distributed Pareto front using the ev-MOGA evolutionary algorithm," *Artif. Intell. Tools*, vol. 23, no. 2, pp. 145002-1–145002-22, 2014.

[37] J. Herrero, X. Blasco, M. Martínez, and J. Sanchis, *Multiobjective Tuning of Robust PID Controllers Using Evolutionary Algorithms* (Lecture Notes in Computer Science). Berlin, Germany: Springer, 2008, pp. 515–524.

[38] J. M. Herrero, X. Blasco, J. V. Sánchez-Pérez, and J. Redondo, "Design of sound phase diffusers by means of multiobjective optimization approach using ev-MOGA evolutionary algorithm," *Struct. Multidisciplinary Optim.*, vol. 53, no. 4, pp. 861–879, 2016.

[39] A. Howlader *et al.*, "A minimal order observer based frequency control strategy for an integrated wind-battery-diesel power system," *Energy*, vol. 46, no. 1, pp. 168–178, Oct. 2012.

[40] T. Senjyu, T. Nakaji, K. Uezato, and T. Funabashi, "A hybrid power system using alternative energy facilities in isolated island," *IEEE Trans. Energy Convers.*, vol. 20, no. 2, pp. 406–414, Jun. 2005.

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