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Coordination of blade pitch controller and battery energy storage using firefly algorithm for frequency stabilization in wind power systems

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Abstract

Utilization of renewable energy sources (RESs) to generate electricity is increasing significantly in recent years due to global warming situation all over the world. Among RESs type, wind energy is becoming more favorable due to its sustainability and environmentally friendly characteristics. Although wind power system provides a promising solution to prevent global warming, they also contribute to the instability of the power system, especially in frequency stability due to uncertainty characteristic of the sources (wind speed). Hence, coordinated controller between blade pitch controller and battery energy storage (BES) system to enhance the frequency performance of wind power system is proposed in this work. Firefly algorithm (FA) is used as optimization method for achieving better coordination. From the investigated test systems, the frequency performance of wind power system can be increased by applying the proposed method. It is noticeable that by applying coordinated controller between blade pitch angle controller and battery energy storage using firefly algorithm the overshoot of the frequency can be reduced up to -0.2141 pu and accelerate the settling time up to 40.14 second.

Keywords: *battery energy storage, firefly algorithm, pitch angle, wind power system*

1. Introduction

Environmental problems now become a big concern in the world. Climate change due to global warming leads experts to conduct research to control fossil fuel emissions [1]. Controlling pollution, resource efficiency, regulation, and policy have directed and emphasized the world population to shift from fossils fuels to new and renewable energy sources [2]. In Indonesia, fossil fuel reserve includes petroleum, natural gas and coal will be exhausted in the next 50 years. The details are as follows: Oil with 7.7 billion barrels of reserves will be exhausted in 2025. Natural gas with reserves of 165 terra square cubic feet (TSCF) will be exhausted in 2055. Coal with reserves of 18 billion tons, however, has really high pollution level. This condition makes the Indonesia government change the energy policy to increase the application of renewable energy from 17% to 25% [3].

Among numerous types of renewable energy sources (RESs), the wind is becoming more popular as alternative energy sources in power system. Wind power system could provide clean, environmentally friendly, sustainable and renewable electricity to the consumers. Although wind power system gives a positive impact, they also potentially bring negative impact. The majority of wind power system have intermittent power output characteristic due to the uncertainty of the resources. This characteristic might contribute instability on the systems, particularly in frequency stability. Moreover, big concern emerged corresponded to low inertia characteristic of wind power system due to the application of power electronics in wind power system [4, 5].

To handle this problem, designing blade pitch angle of the wind turbine to stabilize the frequency of the system is crucial. Proportional and integral (PI) controller is one the controller that can be used to control blade pitch angle of the wind turbine. However, PI controller itself is not enough to overcome the uncertainty of the wind itself. Hence, an additional controller such as energy storage is important. There are numerous types of energy storages that have been

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used in practical power systems such as capacitor energy storage (CES), superconducting magnetic energy storage (SMES), redox flow batteries (RFB), and battery energy storage (BES) [6-16]. Due to the higher capacity and the fast response, BES is becoming more favourable compared to other energy storage types. Moreover, to get optimal coordination between PI controller and BES, metaheuristic algorithm can be used. Metaheuristic algorithm can be classified into three groups based on the inspiration. Imperialist competitive algorithm and tabu search algorithm fall under socially based inspiration metaheuristic algorithm. In physical based inspiration metaheuristic algorithm there is simulated annealing. While differential evolution algorithm, particle swarm optimization, ant colony optimization, artificial immune system and firefly algorithm are categorized as biological based inspiration metaheuristic algorithm [17-25]. Moreover, firefly algorithm becoming more favourable than other algorithms as it could provide fast and accurate results as well as simplicity. The application of firefly algorithm for solving complex problems has been developed significantly over the years. As reported in [26], the dynamic multidimensional knapsack problems can be handled easily by applying firefly algorithm. The application of firefly algorithm (FA) for solving optimization problem in mechanical sector is reported in [27]. In [26] and [27], FA shows a satisfactory results for solving complex and optimization problems.

The application of improved differential evolution algorithm for designing blade pitch angle of wind turbine for frequency stability enhancement is reported in [28]. In [28], improved differential evolution algorithm can optimized the parameter of blade pitch angle controller of wind turbine. Another research regarding the application of metaheuristic algorithm for designing pitch angle controller of wind turbine is reported in [29]. In [29], the hybrid between particle swarm optimization and differential evolution algorithm is used for optimally design the blade pitch angle controller of wind turbine. However, only used blade pitch angle controller for enhancement of frequency stabilization is not enough indicated by higher overshoot and longer settling time of the wind power system on booth of those research (research on reference [28] and [29]). Hence, in this paper additional devices is proposed.

This paper novelty is design coordination between blade pitch angle controller (PI controller) and BES using firefly algorithm to enhance the frequency performance on wind power systems. Furthermore, the paper is organized as follows: Section 2 provides a brief explanation about modeling wind power system for frequency stability study and modeling battery energy storage. Section 3 provides a method for designing the coordinated control between blade pitch angle controller and BES using FA. Result and discussion of the proposed method are presented in section 4. Section 5 highlight the contribution, conclusions and future directions of the research.

2. Pleminaries

2.1. Wind Power System Model

For frequency stability study, a mathematical representation of wind power system is crucial. When sudden wind speed change emerged, the rotor speed of the generator is accelerated or de-accelerated resulting in frequency change in the system. This phenomenon could be captured by using (1) [30].

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H_{\omega}}\left(\Delta P_m + \Delta P_w\right) \tag{1}$$

Where H_w and ΔP_w are the constant inertia of the wind turbine and wind power input from the generator system, respectively, while $\Delta\omega$ and P_m are frequency constant and mechanical power from the turbine respectively. Figure 1 illustrates wind power system for frequency stability study [30].

The purpose of fluid coupling as shown in Figure 1 is to transfer the difference between the angular velocity of the turbines and the frequency of the generator into power. That block connected to blade pitch angle controller consists of PI controller. That block can be presented using (2) [30].

$$\frac{d\Delta x_2}{dt} = K_{p2}\frac{d\Delta x_1}{dt} + K_{p2}\Delta x_1 \quad (2)$$

where

$$\Delta x_1 = \Delta P_{\max} - \Delta P_{wtg} \quad (3)$$

and

$$\Delta P_{wtg} = K_{FC}\Delta\omega_2 \quad (4)$$

Moreover, substitute ΔP_{wtg} and ΔP_{max} ($\Delta P_{max} = 0$). Hence, the calculation can be represent as (5) [30].

$$\frac{d\Delta x_1}{dt} = -K_{FC}\frac{d\Delta x_2}{dt} \quad (5)$$

furthermore, the rest of the calculation can be presented in (6-8), and (9) [30].

$$\frac{d\Delta x_2}{dt} = -\frac{K_{FC}K_{p2}}{2H_{\omega}} + \left(\Delta P_w + \Delta P_m - \Delta P_{load}\right) - K_{FC}K_{p1}\Delta\omega_2 \quad (6)$$

$$\frac{dx_3}{dt} = K_{p1}T_{p1}\frac{d\Delta x_2}{dt}K_{p2}\Delta x_2 - \Delta x_3 = \frac{-K_{p1}T_{p1}K_{FC}K_{p2}}{2H_{\omega}}\left(\Delta P_w + \Delta P_m - \Delta P_{load}\right) \quad (7)$$
$$-K_{p1}T_{p1}K_{FC}K_{p2}\omega_2 + K_{p1}\Delta x_2 - \Delta x_3$$

$$\frac{d\Delta x_4}{dt} = \frac{1}{T_{p2}}\left(\Delta x_3 - \Delta x_4\right) \quad (8)$$

$$\frac{d\Delta P_m}{dt} = K_{P3}K_{PC}\Delta x_4 - P_m \quad (9)$$

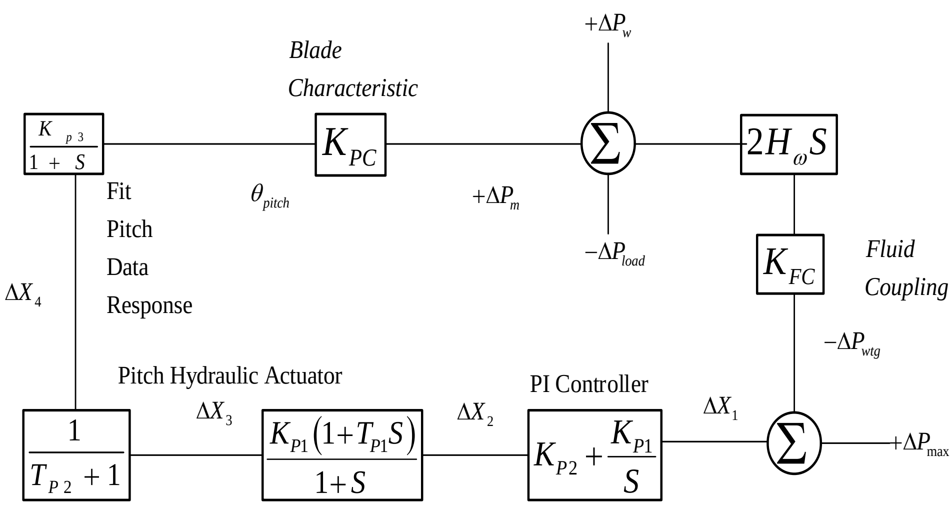

Figure 1. Block diagram of wind power system

2.2. Battery Energy Storage Model

In the last few decade, application of BES in power system is increasing significantly. BES can be used for storing and releasing energy to the grid. In this study, BES is used as an additional device to maintain the frequency stability in wind power system due to the wind speed variation. The dynamic of battery cells, converter and the controller is considered in this BES model as shown Figure 2 [31]. From Figure 2 it is noticeable that the converter and the associated controller is modeled as first order differential equation with gain constant. Furthermore, the dynamic behavior of battery cells is captured by second order differential equation considering gain constant. It is noticeable that to control the output of BES, the gain constant of the converter is played important role. Hence, it this paper, to get the best output of BES, the gain controller of BES converter is optimized by using FA.

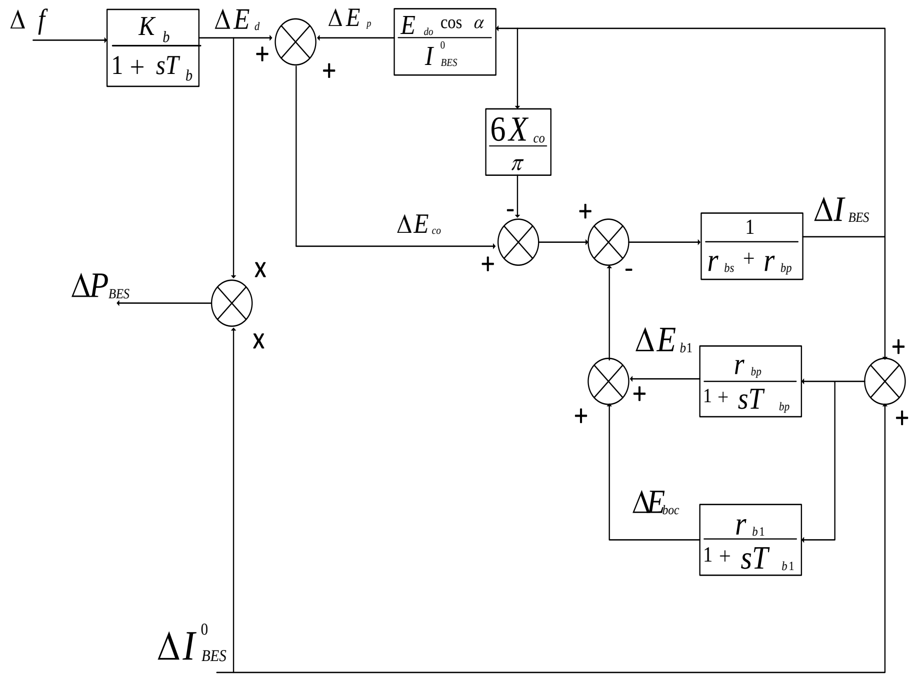

Figure 2. Block diagram of BES

3. Proposed Method

3.1. Firefly Algorithm

In 2009, a researcher from Cambridge University developed new algorithm that inspired by the behavior of fireflies. That algorithm is called as firefly algorithm (FA). There are three basic baselines of FA for finding the convergence value. The first baseline is the assumption that all of firefly is unisex. Hence, regardless of their gender, each fireflies is attracted each other. The second baseline is the value of attractiveness is related to the brightness of the fireflies. Considering that statement, the fireflies with dimmer brightness will move toward the fireflies with brighter brightness. Furthermore, when the distance increase the brightness of fireflies is decrease. Moreover, the fireflies will move randomly if there are no fireflies with the brightest brightness. The last baseline is the objective function of the fireflies are indicating the brightness of the fireflies [32, 33].

The most important parts in FA is the intensity and attractiveness function. In this paper, the attractiveness is assumed to be influenced by the degree of light intensity. This can be captured mathematically by using (10). The level of light intensity on *x* fireflies that proportional to the objective function *(f(x))* is described by *i*.

$$I(x) = f(x) \tag{10}$$

The attractiveness coefficient (β) of fireflies has a relative value depending on the light intensity that will be assessed by other fireflies. Hence, the assessment of firefly is depending on the fireflies distance. Moreover, due to the air factor (γ), the light intensity will decrease from the source. Hence, the attractiveness function can be captured into mathematical representation using (11). Furthermore, the distance between fireflies *i* and *j* at the location *x*, *xi* and *xj* can be determined by using (12).

$$\beta(r) = \beta_0 * \exp\left(-\gamma r^m\right), \left(m \geq 1\right) \tag{11}$$

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{12}$$

In (13) can be used to mathematically describe the movement of fireflies toward best level of light intensity. Where x_1 indicated the initial position of fireflies located at *x*, while alpha is a variable that has a range between 0 and 1. All the variables formed on (17) ensure the fast algorithm work toward the optimal solution. Moreover, the complete mathematical equation as well as the parameter of FA can be found in [32, 33].

$$x_i = x_i + \beta_0 * \exp\left(-\gamma r_{ij}^2\right) * \left(x_j - x_i\right) + \alpha * \left(rand - \frac{1}{2}\right) \tag{13}$$

3.2. Procedure of Designing the Controller

Comprehensive damping index (CDI) is used as the objective function for designing blade pitch controller and BES simultaneously using firefly algorithm. The CDI can be described mathematically using (14). Where, n is the number of state variable of the total system and ξ is the damping of each eigenvalue [34].

$$CDI = \sum_{i=1}^{n} (1 - \xi_i) \tag{14}$$

subject to:

$$\begin{aligned} K_p^{\min} &\leq K_p \leq K_p^{\max} \\ T_i^{\min} &\leq T_i \leq T_i^{\max} \\ K_b^{\min} &\leq K_b \leq K_b^{\max} \end{aligned} \tag{15}$$

In addition to the objective function and upper and lower bond given in (14) and (15), constraint related to minimum damping (5%) is used. Furthermore, minimizing the value of CDI is considered as the objective function of the FA. Furthermore, The procedure of designing coordinated controll of blade pitch angle controller and BES using FA includes the following steps:

Step 1 Input parameter of FA (number of firefly, max generation, alpha, beta, gamma, detailed explanation regarding alpha, beta, and gamma can be found in [32, 33]), data of wind turbine and BES.
Step 2 Add BES in the wind turbine power system.
Step 3 Start firefly initialization by putting a random number in the search area.
Step 4 Evaluate the objective function by using equation (14).
Step 5 Rank the firefly based on the fitness value (CDI value) and find the best fitness (the minimum CDI value) from the firefly.
Step 6 Update firefly movement using equation (13)
Step 7 Update the best fitness (check the CDI value again)
Step 8 Update the firefly value (determining with CDI value)

Step 9 Determine if the criterion is satisfied (the maximum iteration). If not go back in step 3.
Step 10 Print the results (K_p, T_i from blade pitch controller and K_b from BES)

4. Results and Analysis

The effectiveness of the proposed method (coordination of PI controller and BES using FA) is being analyzed through two cases study. MATLAB/SIMULINK environment was used to simulate the cases study. Wind power system model, BES model, were performed within SIMULINK. While the MATLAB m-file was used to design the FA. The first section on this result shows the blade pitch angle deviation due to wind speed variation. While the second section provides frequency performance due to wind speed changing. Table 1 illustrates the optimization parameters of BES and PI controller using FA while the convergence graph of FA was shown in Figure 3. FA find the objective value in the iteration number 9.

Table 1. Optimized Parameter

Variable	Value
Kbes	44.7280
Kp	2.4243
Ti	1.7500

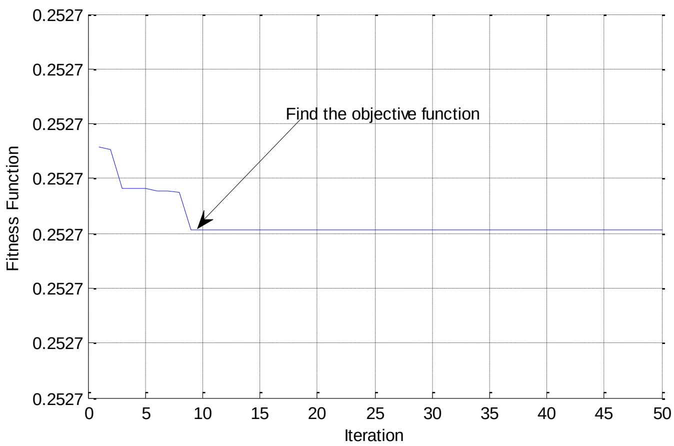

Figure 3. Convergence graph of FA

4.1. Pitch Angle Response

In this section, pitch angle wind turbine response against wind speed variation was observed. The wind speed variation was set from 3 m/s to 9 m/s with 1 m/s step. Table 2 shows the pitch angle overshoot response of wind turbine due to wind speed variation. It was observed that the proposed method could reduce the overshoot of pitch angle. This condition could happen due to the optimal parameter of PI controller and BES that could provide fast and precise signal control and active power to the system. Hence, the overshoot of pitch angle can be reduced. Furthermore, deeper observation must be conducted by looking at the frequency response of the system due to wind speed variation and analyze the impact of the proposed method.

Table 2. Pitch Angle Overshoot of the Wind Turbine

Wind speed	PI controller	PI BES	PI BES FA
3	-7.721	-3.436	-1.801
4	-10.18	-4.578	-2.401
5	-13.05	-5.691	-3.001
6	-15.66	-6.862	-3.600
7	-18.26	-8.020	-4.201
8	-20.81	-9.153	-4.791
9	-22.94	-10.31	-5.012

4.2. Frequency Response

In this section, observation of the frequency response of the system was performed. To analyze the frequency deviation of the wind power system, a small perturbation was made by giving 9 m/s wind speed changes. Figure 4 illustrates the frequency response of the system while detailed overshoot and settling time of wind power system frequency response was shown in Table 3 from Figure 4 it was noticeable that adding BES in the system could damp the overshoot and also accelerate the settling time of the frequency. By looking at the smallest overshoot and fastest settling time, it could be stated that the best frequency response was the proposed method (coordination between PI controller and BES using FA). This condition could happen because of BES could supply additional active power to the system when wind speed changing. The PI controller is also play important role for changing the pitch angle of wind turbine to stabilize the frequency when wind speed variation is emerge.

Table 3. Overshoot and Setting Time of the cases

Variable	PI controller	PI BES	PI BES FA
Overshoot (pu)	-0.8342	-0.3749	-0.2141
Settling time (s)	56.69	50.09	40.14

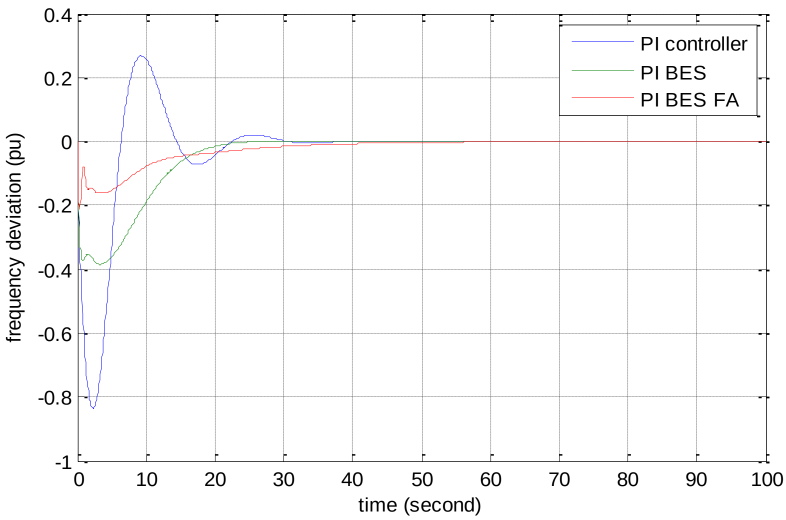

Figure 4. The frequency response of the cases

It could be seen from Table 3, by using the proposed method (PI controller and BES tune with FA) the overshoot and settling time of the wind power system frequency can be reduced up to 0.6201 pu and 16.55 s when the wind speed become 9 m/s. Furthermore Table 4 illustrates the frequency response comparison of the proposed method with the well-established algorithm. It was observed that the proposed response provides a better response in term of small overshoot and fastest settling time. This condition could happen because of BES could supply additional active power to the system when wind speed changing. The PI controller is also play important role for changing the pitch angle of wind turbine to stabilize the frequency when wind speed variation is emerge.

Table 4. Overshoot and Settling Time of the Cases

Variable	With traditional mathematical approach	With Hybrid DE-PSO	Proposed method
Overshoot (pu)	-0.7241	-0.6141	-0.2141
Settling time (s)	53.29	50.00	40.14

5. Conclusion

The present study proposes a coordination between blade pitch angle controller (PI controller) and battery energy storage system using firefly algorithm. From the investigated case studies it was found that the proposed can reduce the overshoot of blade pitch angle response of the system. It was also found that BES could enhance the frequency response of the wind power system when wind speed variation emerges. The proposed method has the best performance regarding small overshoot and fastest settling time. Further research is required to understand the frequency performance of the wind power system with PI controller and BES connected into the existing grid (transmission line or distribution line). Another metaheuristic algorithm or traditional optimization approach can be used to design coordinated controller between blade pitch controller (PI controller) and BES. Moreover, the significant impact of BES could also investigated through comparative study with another energy storage.

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