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Operation Scheme for a Wind Farm to Mitigate Output Power Variation

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Abstract – Because of the nature of wind, the output power of wind turbines fluctuates according to wind speed variation. Therefore, many countries have set up wind-turbine interconnection standards usually named as Grid-Code to regulate the output power of wind farms to improve power system reliability and power quality. This paper proposes three operation modes of wind farms such as maximum power point tracking (MPPT) mode, single wind turbine control mode and wind farm control mode to control the output power of wind turbines as well as overall wind farms. This paper also proposes an operation scheme of wind farm to alleviate power fluctuation of wind farm by choosing the appropriate control mode and coordinating multiple wind turbines in consideration of grid conditions. The performance of the proposed scheme is verified via simulation studies in PSCAD/EMTDC with doubly-fed induction generator (DFIG) based wind turbine models.

Keywords: Wind farm, wind turbine, Doubly-fed induction generator (DFIG), Active power control, Reliability, Microgrid

1. Introduction

In recent years, the installation of wind power generation has grown significantly over the world. Wind energy currently provides only about 1~2% of the world electricity supply. However, the European Wind Energy Association (EWEA) has set a target to satisfy more than 22% of European electricity demand with wind power by 2030 [1, 2]. The U.S. also has a plan to supply 20% of the nation's electricity from wind by 2030.

With the increasing penetration of wind power, the fluctuating output of wind farms will considerably affect the operation of interconnected grids. The wind speed variation can cause significant variation in the system frequency that may affect frequency protection, resulting in load curtailment or loss of synchronism. Besides, continuous power variation of wind turbines can shorten the life spans of neighboring power generation units and power system facilities [3].

From this point of view, it will become necessary to control the power output of wind turbines considering the frequency regulation and power balance in the grids. Many countries have established standards for wind turbine integration to the grids, namely Grid-Codes [4].

Most conventional methods to regulate the net-power of wind farms are to control the pitch angle of each wind turbines or to stop some part of wind turbines in the wind farms. However, these methods are not quite effective and slow because they are based on mechanical control. Furthermore, they may not stably operate in adverse grid conditions such as island condition or peak demand [5].

This paper proposes an operation scheme for wind farm to reduce power fluctuation by considering grid conditions. In the proposed scheme, three operation modes of the wind farm can be defined: the maximum power point tracking (MPPT) mode, the single wind turbine control mode, and the wind farm control mode. In the MPPT control mode, maximum electric power can be captured from the wind turbines. However, this mode can cause large fluctuation in the power output according to wind speed variation. The single wind turbine control mode uses a hysteresis controller and a rate limiter in the wind turbine controller to reduce output power fluctuation. The wind farm control mode regulates the net active power of a wind farm by hysteresis loop, rate limiter and a rotor speed limit algorithm. The details of the proposed method will be explained in section 3.

Simulation studies in a microgrid consisting of two DFIG type wind turbines, a diesel generator and a battery will verify the performance of the proposed operation scheme.

2. System Modeling

2.1 Wind Turbine Model

A Doubly-Fed Induction Generator (DFIG) is basically a wound rotor induction generator combined with a back-to-back voltage source converter connected to its rotor through slip rings, as shown on Fig. 1.

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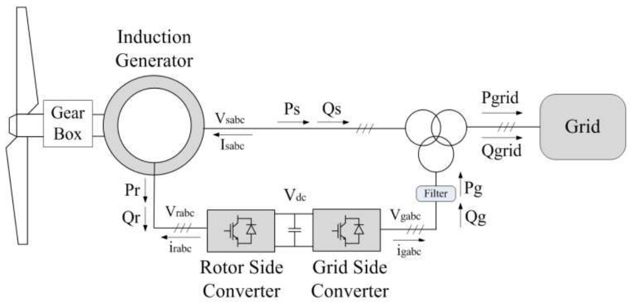


Fig. 1. Structure of DFIG wind turbine

In a DFIG, the stator is directly connected to the grid while the rotor is fed through a variable-frequency dc-link-voltage converter that consists of a rotor-side converter (RSC) and a grid-side converter (GSC). The converters are rated at about 25~30% of the rating of the induction generator. This allows for a reduction in size of the converter, resulting in better system efficiency and lower cost of power electronics. The DFIG can operate with a rotor speed that is between 70~120% of the nominal synchronous speed.

DFIG is used as a variable speed wind generator and can control active power output and reactive power output independently by ac excitation control in the rotor circuit. In this paper, vector controlled models of the rotor side and the grid side controllers are used [6].

The mathematical relation of the aerodynamic model of the wind turbine for mechanical power extraction from the wind can be expressed as follows [7]:

$$P_{mech} = 0.5\rho\pi R^2 V^3 C_p(\lambda, \beta) \tag{1}$$

where *Pmech* is the extracted power from the wind, ρ is the air density [kg/m^3], *R* is the blade radius [m], *V* is the wind speed [m/s] and C_p is the power coefficient, which is a function of both the tip speed ratio (λ), and the blade pitch angle (β) [deg]. The tip speed ratio λ is generally defined as follows:

$$\lambda = \frac{\omega R}{V} \tag{2}$$

where ω is the rotational speed of the wind turbine. The characteristic of *Cp* will change greatly depending on the wind speed and the tip speed ratio. This means that the wind turbine has optimal power at different wind speeds. Therefore, when the wind speed changes in a variable speed wind turbine, the rotational speed of the wind turbine is controlled to follow the maximum power point trajectory considering equation (2) [8].

2.2 Control of the DFIG

Fig. 2 shows a control block diagram of two converters in the DFIG such as the rotor-side converter and the grid-side converter. The converters are controlled in the dq reference frame aligned to the stator magnetic flux so that the active power and reactive power can be decoupled and controlled independently. The power controller generates the current references for the inner current controllers, which have faster time response.

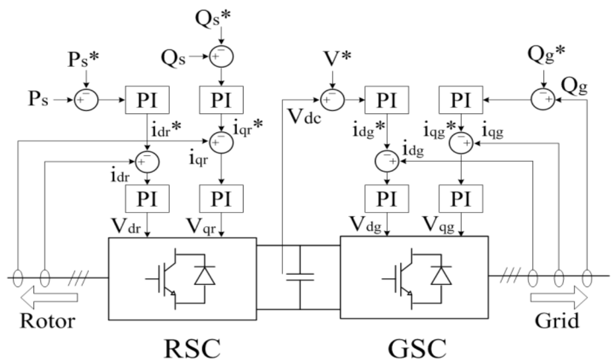


Fig. 2. Control system of the DFIG

2.3 Modeling of microgrid and wind farm

The configuration of the microgrid is shown in Fig. 3.

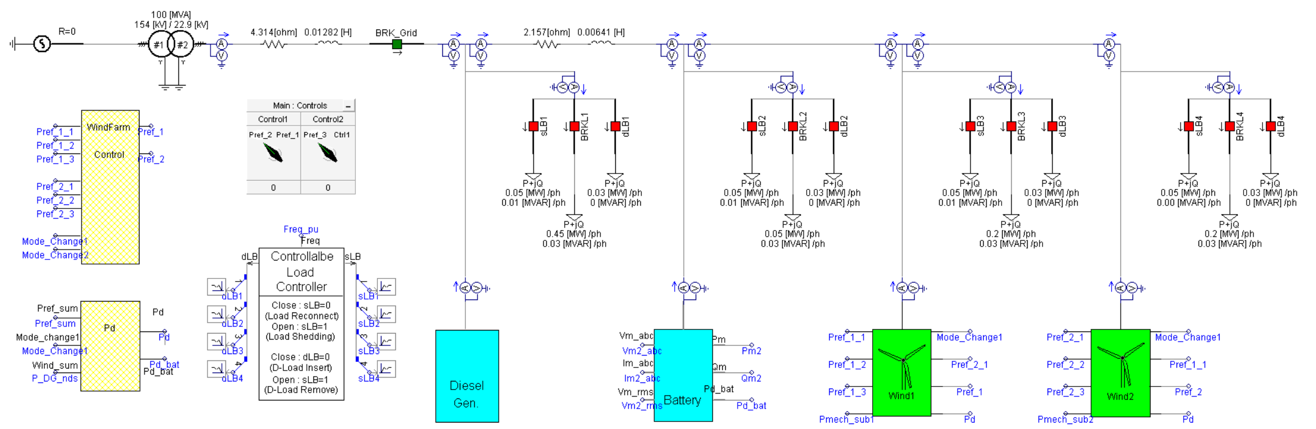


Fig. 3. Configuration of the wind farm in microgrid

The microgrid consists of a wind farm with two 2MW-DFIG wind turbines, a 3MW-diesel generator and a 1MW-battery energy storage system (BESS). The microgrid can be connected to the electric power grid or operate separately. The controller of diesel generator and battery utilize the droop control scheme to operate the microgrid in island mode [9].

3. Operation Scheme of Wind Farm

3.1 MPPT mode

Every wind turbines are basically operated in MPPT mode. If wind speed changes, the MPPT block automatically calculate the optimal rotor speed reference or optimal tip speed ratio. The rotor side converter in DFIG controls the rotor speed to follow this reference so that the efficiency of wind turbine is maximized.

3.2 Single wind turbine control mode

To achieve this operation, basically we use the method of hysteresis control as shown in Fig. 4 [10]. The purpose of hysteresis control is to reduce the power fluctuation during small wind speed changes.

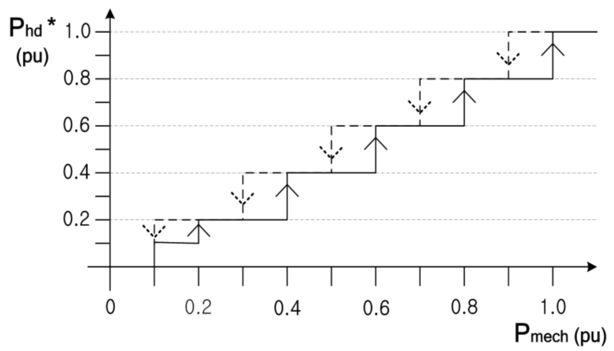


Fig. 4. Reference setting using hysteresis loop

The reference value through the hysteresis, P_{hd}*, is determined according to the mechanical power input P_{mech}. P_{hd}* set points are fixed in a certain range where wind speed deviation is small. If the mechanical power input to the wind turbine changes more than a specific level due to wind speed change, P_{hd}* moves to a higher set point.

Frequent change of P_{hd}* can be prevented by using the hysteresis loop.

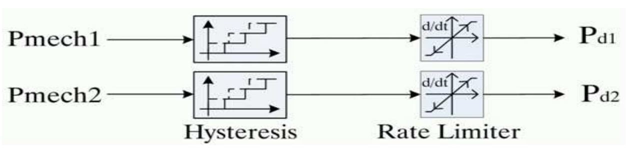


Fig. 5. Control diagram of single wind turbine control mode

To smooth the power output, a rate limiter is added to the hysteresis controller. Both the increasing and decreasing rates of the active power can be controlled in each wind turbine. A basic control diagram of the single wind turbine control mode is shown in Fig. 5.

$$J\frac{d\omega_m}{dt} = P_{mech} - P_d \quad (3)$$

J : Rotational Inertia of the generator
ω_m : Rotor Angular Velocity
P_{mech} : Mechanical power input
P_d : Demand power output

In this control mode, the final output reference of wind turbine is P_d*. Therefore, the continuous mismatch between P_{mech} of the mechanical input and P_d* of the electrical demand output can cause the rotor speed variation, as shown in (3). For this reason, when the rotor speed exceeds a certain limit, the overall reference power set point should be moved by using the rotor speed limit algorithm in Fig. 6. If the rotor speed exceeds 25% of its nominal value, then pitch control is activated first to reduce rotor speed and the reference power set point is increased. If the rotor speed is below 25% of its nominal value, only the reference value is decreased. These actions will make the rotor speed remain in the boundary.

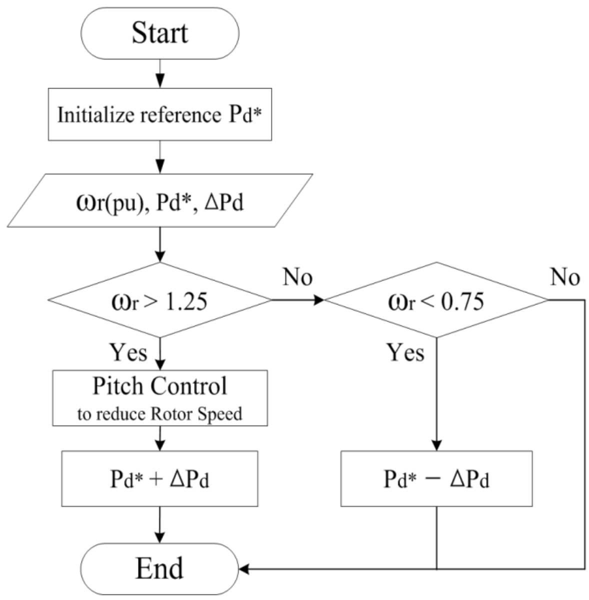


Fig. 6. Flowchart of rotor speed limit algorithm.

3.3 Wind farm control mode

The wind farm control mode is to regulate the net active power of a wind farm. The wind farm control mode also uses hysteresis loop, a rate limiter and a rotor speed limit algorithm. In the first step, it calculates the expected maximum value of total active power in the wind farm from the wind speed of each wind turbine. This value passes through a low pass filter to reduce the high frequency variation of the output power before hysteresis control. In the next step, the P_{mech} value is revised considering real active power of the wind farm by using the reference revision algorithm in Fig. 8.

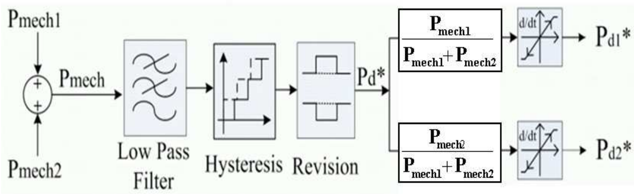


Fig. 7. Control diagram of wind farm control mode

Finally, the P_d* value is distributed considering the ratio of each active power in the total active power of the wind farm, as shown in (4) and (5).

$$P_{d1}^* = P_d^* \times \frac{P_{mech1}}{P_{mech1}+P_{mech2}} \quad (4)$$

$$P_{d2}^* = P_d^* \times \frac{P_{mech2}}{P_{mech1}+P_{mech2}} \quad (5)$$

The reference revision algorithm is similar to the rotor speed limit algorithm in terms of adjusting of P_d*. But, the reference revision algorithm discerns between P_{mech} and Pd* to avoid an excessive demand difference. By using the rate limiter, the repeated fluctuation of P_d* around P_{mech} can be prevented.

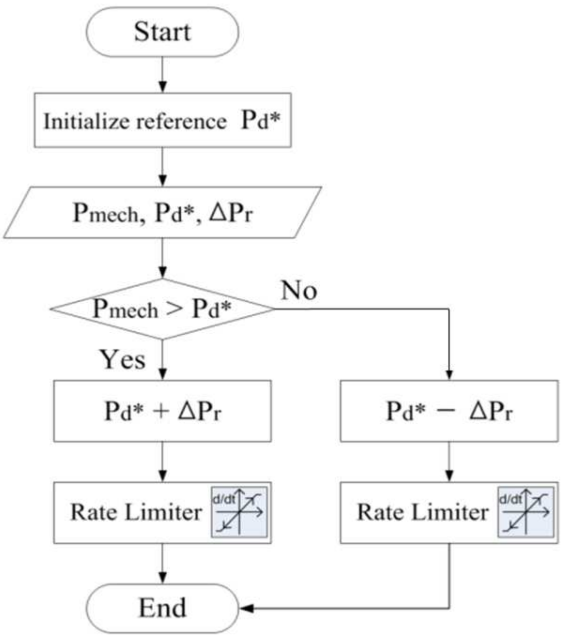


Fig. 8. Flowchart of reference revision algorithm.

3.4 Operation scheme of the whole wind farm

In Fig. 9, the overall operation scheme is shown in detail. P* is the reference stator power and determined from three different control modes, MPPT mode, single wind turbine control mode and wind farm control mode. If there is no restriction in grid condition, individual wind turbine and wind farm are operated in MPPT mode. If the grid condition changes, for example, from normal state to alert state, control mode becomes single wind turbine control mode. Alert state may include the situation with less spinning reserve or tripping of fast acting generator. Finally, when the grid condition becomes severe such as island operation in microgrid or peak demand period in summer or winter peak season, the wind farm is operated in wind farm control mode and produce more smoothed output.

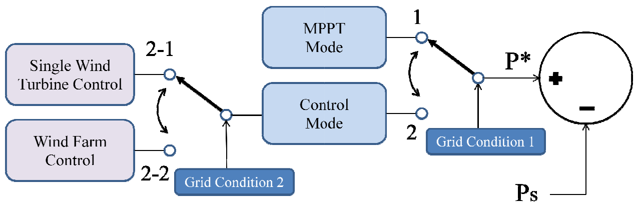


Fig. 9. Proposed operation scheme of the whole wind farm

4. Simulation Results

4.1 Output power of wind farm

The wind speed profiles applied to each wind turbine in the simulation are shown in Fig. 10. The wind speeds vary in a range of ±2 m/s from the average value of 10 m/s.

The process of setting the reference P_d* is shown in Fig. 11. P_d* is obtained from the value of expected total active power in the wind farm (P_{mech}) and from the smoothed value through low pass filter (P_{d_LPF}). Eventually, this value can be the reference value of wind farm by the process of wind farm control, as shown in Fig. 8.

The simulation results of the proposed control scheme depicted in Fig. 12 show the difference between P_{mech} and P_d*. Each wind turbine generates active power of P_{grid}. And the rotor speed (W_{pu}) changes according to the difference

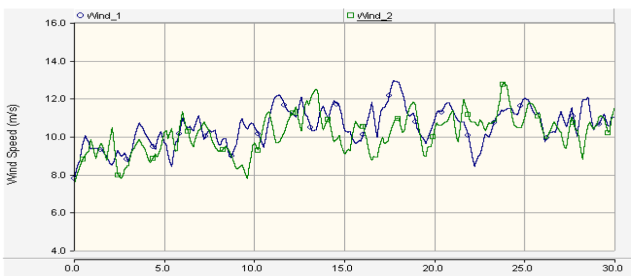


Fig. 10. Wind speed profiles in the wind farm.

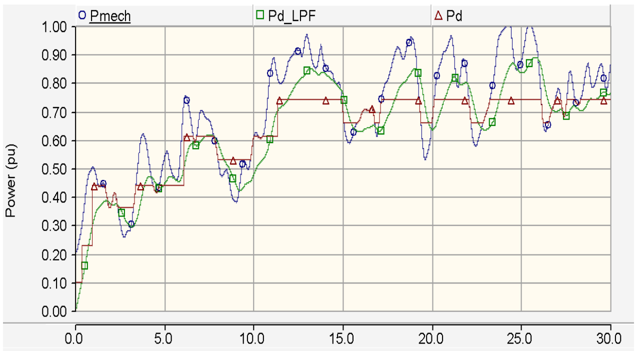
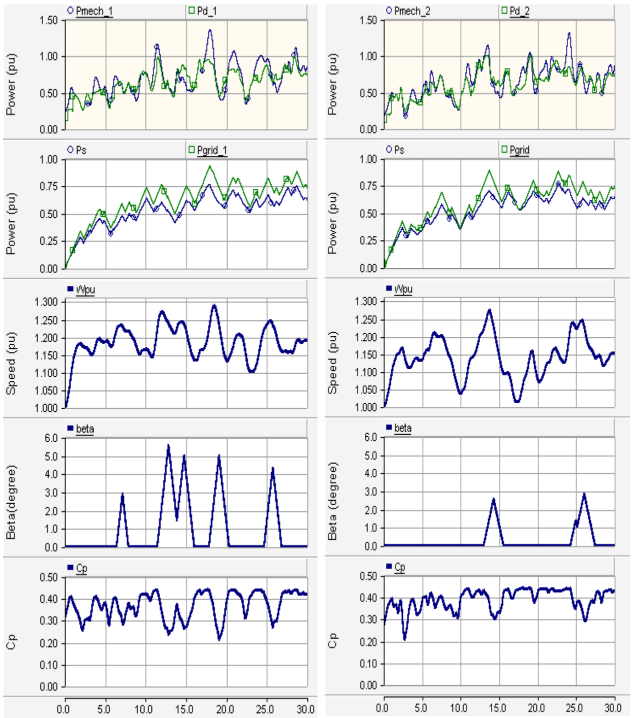


Fig. 11. Reference setting in wind farm control mode.



(a) Wind turbine 1 (b) Wind turbine 2

Fig. 12. Various characteristics of individual wind turbine

between P_{mech} and P_d*. If the rotor speed exceeds a specific limit, the rotor speed is reduced by the control of the pitch angle (β). The power coefficient (Cp) also changes due to the tip speed ratio and the pitch angle.

Fig. 13 shows the active power output in each control mode of the wind farm. In the MPPT mode, the wind-speed variations in the wind farm result in significant fluctuations in total active power output. In the single wind turbine mode, the controller regulates increasing or decreasing active power from the ramp or gust wind speed in each wind turbines. Therefore, the pattern of the total active power output in the single wind mode is smoothed more than that in the MPPT mode, and this mode can limit ramp rate of active power.

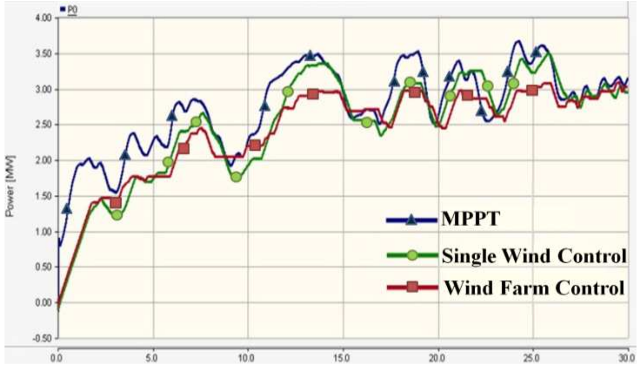


Fig. 13. Active power of each control mode

Finally, with the same wind speed conditions, the total active power output can be regulated most by the wind farm control mode. Although the active power of each wind turbine is not smoothed, the total active power output is smoothed. It improves not only the power quality and reliability but also the distributed generation(DG) operation and life cycle in weak power systems like microgrid

4.2 Output power of wind farm in microgrid

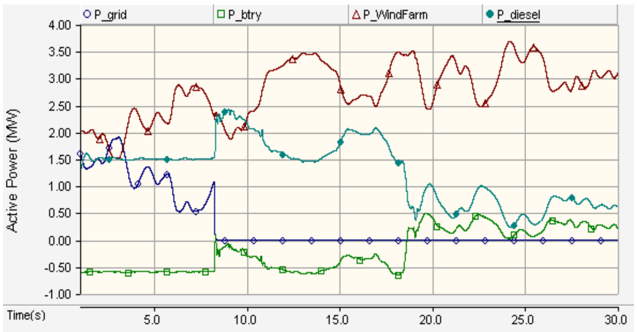
The penetration of wind power has been increasing rapidly, active power fluctuations, hereby, could bring severe problems to grid operation. Therefore, the simulation studies have been carried out in microgrid in order to verify the effect of active power fluctuations of wind farm.

The microgrid is interconnected to the main grid for eight seconds and then disconnected from the main grid as shown in Fig. 14. During grid-connected mode, from 0s to 8s, output powers of the DGs are unchanged and the grid balances the load. In the island mode, after 8s, there is no power from the grid and DGs must follow the local loads. The coordination between DGs can be achieved by droop characteristics of the DGs.

The battery is operated considering the state of charge (SOC). Therefore, if the SOC of the battery is either over 90% or below 20%, the battery mode will change either from charge mode to discharge mode or vice versa.

Fig. 14 shows the output power and frequency of the microgrid in MPPT mode. In the grid-connected mode, the fluctuation of wind farm does not affect the microgrid operation due to robustness of the main grid. However, in the islanded mode the DGs balance the local loads and the fluctuating power of the wind farm affects microgrid operation. Therefore, the fluctuation not only negatively affects power quality and reliability but also DG operation and life cycle. The effect of fluctuation on frequency is shown in Fig. 14(b).

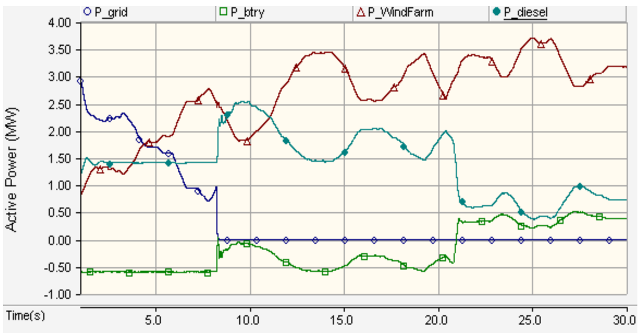
Figs. 15 and Fig. 16 show the output power and the frequency of the microgrid in single wind turbine mode and wind farm control mode, respectively. As the mode changes from the MPPT mode to the single wind mode or from the single wind mode to the wind farm mode, there is



(a) Oxutput power of the wind farm and DGs.

(b) Frequency in microgrid.

Fig. 14. MPPT mode simulation results in microgrid



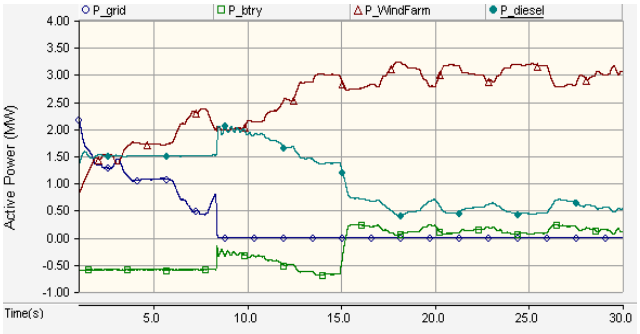
(a) Output power of the wind farm and DGs

(b) Frequency in microgrid.

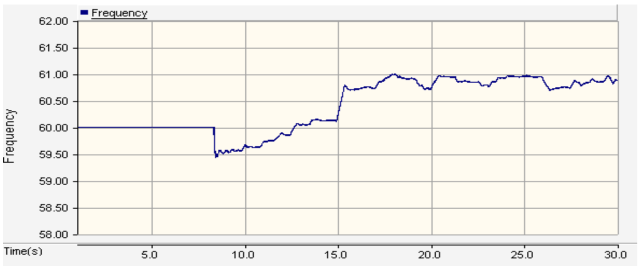
Fig. 15. Single wind turbine mode simulation results in microgrid

a reduction in the fluctuating power of the wind farm and variation of frequency of the microgrid.

Consequently, it is clear that the active power of the wind farm can be smoothed well by means of the proposed operation scheme. Furthermore, the proposed algorithm reduces DG output changes and frequency changes in



(a) Output power of the wind farm and DGs.



(b) Frequency in microgrid.

Fig. 16. Wind farm control mode simulation results in microgrid

microgrid. Although there is slight energy loss in single wind turbine mode and wind farm control mode compared to MPPT mode, the reduction in fluctuation is more helpful in reliability and power quality.

5. Conclusion

In this paper, an operation scheme to control the active power of wind farm has been proposed. In this scheme, the control mode of the wind farm can be chosen by considering the grid conditions. To achieve this control, the operation scheme uses hysteresis loop, a rate limiter and a reference revision algorithm proposed in this paper. Operation scheme of the wind farm includes three operating modes, the MPPT mode, the single wind turbine mode and the wind farm control mode. As mode is changed from the MPPT mode to other control modes, it is no longer possible to achieve maximum active power, but there is a reduction in fluctuation of active power output of the wind farm and frequency in microgrid. As a result, the power quality, reliability, the DGs operation performance and life cycle can be improved through output power control in wind farm in weak power system like microgrid.

Simulation studies have been carried out in PSCAD/ EMTDC and have shown that the proposed operation scheme enables the wind farm to actively participate in active power regulation of the grid. The proposed operation scheme enables high penetration of wind energy. The proposed scheme will be suitable for weak power system like microgrid.

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