Maximum Utilization of Wind Energy in a Wind Farm and Diesel Generator-Based Isolated Grid without Energy Storage System

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Abstract

This paper proposes a new frequency control scheme for a wind and diesel generator-based isolated grid, in which neither storage equipment like battery, flywheel, pump storage nor controllable loads are installed. The idea of this proposal is based on the coordination between wind farm and diesel generator to maximize wind energy and minimize amount of fuel consumed by the diesel generator. This investigation is tested in Matlab/Simmulink environment. Simulation results are analyzed and compared to the conventional one.

Keywords: *Wind turbine, frequency control, diesel generator, islanding grid*

1. Introduction

Until now, some distribution grids have been operated autonomously from the large power system due to economic problems. They often occur in remote areas or islands where it is inconvenient to connect to the power system. Take, Catba island, Lyson island, Phuquy island in Vietnam and so on, for examples. In the past, the main distributed generation (DG) units in islanding or isolated grids were diesel generators. Maintaining a constant frequency within those grids was quite simple thanks to the governor system of the diesel generators. However, issues relating to the high cost of fuel and negative impacts on the environment are big challenges to the operator and developer of isolated grids.

Nowadays, exploitation of wind power has gradually become popular in both large power system and island grids and this has contributed to a significant reduction in the use of fossil sources. However, the integration of wind turbine-based DG units in isolated grids put operators and developers under new a challenge due to their power output variation. This can lead to the imbalance of active power within the isolated grid. As a result, frequency in the isolated grid can exceed operating range and the isolated grid can experience an unstable operation period.

This challenge has put researchers under new interests concerning the frequency in the isolated grid or the islanding mode of micro grid. Many papers investigating micro-grid operation in the islanding mode [1-6] and isolated grid [7-13] was published. Generally, in these isolated grids, storage equipments such as flywheel [8], pumped storage hydropower plant [9], batteries [12], and dump load [13] are equipped. With these equipments, maintaining the balance of active power in autonomous grids is quite simple regardless of variation in wind speed. With a suitable size of storage system, it allows wind farm to produce maximum power output as possible. However, the high pre-investment cost for these storage equipments is the biggest difficulty in the installation of storage devices into isolated grids. Therefore, isolated grids with neither storage systems nor controllable loads should be taken into account and the proposal of an effective frequency control scheme is really necessary.

Frequency control ability in an isolated grid based wind – diesel generator without any storage system heavily depends on the type of wind farm, variable speed or fixed speed. From previous researches, variable speed wind farms, which use a variable speed wind turbine associated with a synchronous generator or a doubly fed induction generator (DFIG)-based wind turbine, provide a good frequency control ability [14-19]. As a result, the integration of these wind farms in isolated grids can allow the absence of storage equipments. Reference [6] indicates a method to maintain the frequency in a micro-grid in the islanding mode, which is similar to an isolated grid. In this reference, the wind farm caries out frequency control independently from the diesel generator. Simulation results indicates that the frequency in the micro-grid is retained at normal value after the islanding mode occurs. However, with this method, when the load of micro-grid or isolated grid is changed, both the diesel generator and the wind farm participate in frequency adjustment. As a result, the wind farm rarely reaches the rated value of power despite of high wind velocity. It means that with this method, the objective of frequency controller can be achieved easily but it is not an economical method.

This paper is going to focus on an isolated grid with which wind farm is integrated without any storage systems or controllable loads. A new frequency control scheme is proposed to fully utilize wind energy and to minimize the amount of fuel consumed by diesel generator. This new control scheme is based on the coordination between the diesel generators and the wind farm to ensure that the wind farm is always prioritized in generation. With the offered plan, the operator can save the fuel consumed by the diesel generators as much as possible. This proposal is tested via simulation in Matlab/Simulink. Simulation results will be compared to the conventional scheme offered in [6].

2. Isolated Grid Configuration

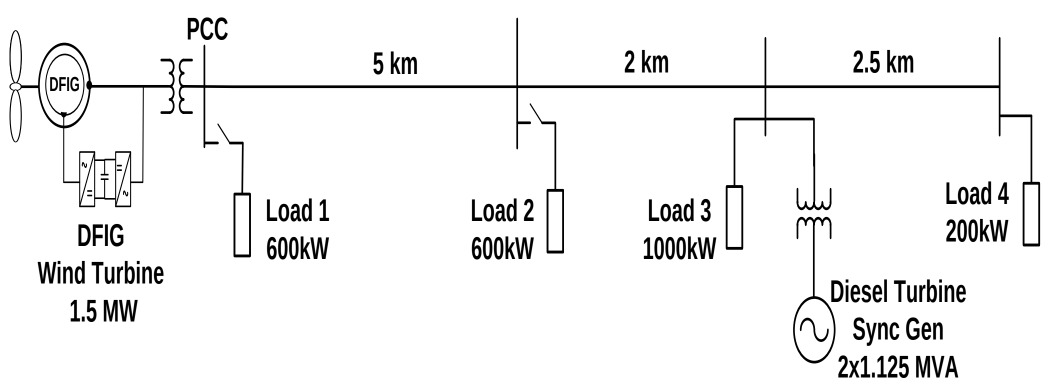


Figure 1. Single-line Diagram of the MG Test System

An islanding grid or an isolated grid is often a distribution system's network, which is isolated permanently from the main grid. It often comprises of several DG units, loads, storage devices and distribution system like transformers, lines and switching equipments and so on. The DG units in the isolated grid are often conventional plants like diesel generators, gas turbine-based generator, and renewable energy ones such as photovoltaic system, wind generators, marine-based generators and so on. The capacity of the DG units can be up to several megawatts.

In this research, a 22kV-isolated grid is indicated in Figure 1, which none of energy storage equipments or controllable loads are installed. In this grid, a 1.5MW DFIG-based wind farm and two diesel synchronous generators, 1.125MVA for each, are the DG units and they are connected to the grid via 0.69/22kV transformer and 2.4/22kV one, respectively. Loads in this network are represented Load 1, Load 2, Load 3 and Load 4, among which Load 3 and Load 4 are critical loads. It is assumed that the maximum load in this island grid is 2.4MW while the minimum load is 1MW.

2.1. DFIG-based Wind Turbine System

There are two main parts concerning to convert energy from wind energy to electricity one in a wind farm, as shown in Figure 2 [20]. The first part is the blades of the wind turbine and the second one is a generator. These parts are connected together via a shaft system and a gearbox. The blades' radical task is to transform the kinetic energy absorbed from the air into the mechanical energy in order to rotate the generator's rotor. Each wind turbine is presented by a power coefficient C_p that is a function of the tip-speed ratio λ and the pitch angle β. This coefficient reflects the efficiency of energy conversion. In this research, the C_p is expressed in equation (1), where V_w, ω and R stand for the wind speed, the rotor speed and the radius of the blade, respectively.

$$C_p = 0.645[0.00912 + (-5 - 0.4a + 116b)e^{-21b}] \qquad (1)$$

Where

$$a = 2.5 + \beta$$

$$b = \frac{1}{\lambda + 0.08a} - \frac{0.035}{1 + a^3}$$

$$\lambda = \frac{\omega R}{V_w}$$

Generator is used to convert the mechanical energy to the electrical energy. Until now, DFIG has been the most popular generator in the wind industry because of its advantages such as a remarkable ability of active and reactive power control, a small size of converter, and so on [21]. The rotor winding of DFIG is indirectly connected to the grid via an AC/DC/AC converter whereas the stator winding is directly connected to the grid. The duty of AC/DC/AC converter, which includes rotor side converter (RSC) and grid side converter (GSC), is to synchronize between the rotor side and the grid. The GSC is connected to the grid via a filter. Modeling of DFIG and equations describing DFIG are written in detail in [20].

2.2. Diesel Synchronous Generator System

Diesel synchronous generator is a popularly used type in island areas thanks to its convenience such as voltage control ability, power adjustment ability, and installation. However, the high operation cost of diesel engine is a consideration needed problem.

A diesel generator consists of two separate parts. The first part is diesel engine, which produces mechanical energy or motion thanks to burning diesel fuel. The second one is a synchronous generator, which converts the engine-produced mechanical energy to the electricity one. These two components are connected through a crankshaft. In addition, a diesel synchronous generator is often equipped with a governor system and an exciter system to adjust the rotor speed and the terminal voltage of the generator. Their detailed modeling was described in [7, 22].

3. Control System of DG Units in Isolated Grid

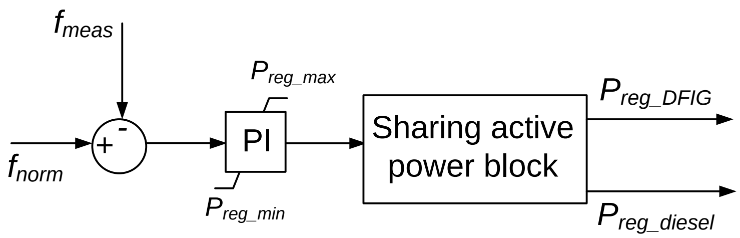
In reference [6], a frequency control method was recommended to maintain the stable operation of micro-grid after the islanding occurrence. This method is based on independent frequency control of diesel generators and wind farm. If this method is implemented in above isolated grid, where storage equipments are unavailable, the wind farm's operation will not be the utmost efficiency. The main reason is that any increase or decrease in the total load leading to a variation of the frequency, both the wind farm and the diesel plant must participate in active power adjustment. As a result, the wind farm cannot generate the MPPT curve while the diesel generator must supply a part of load.

3.1. Co-ordination Frequency Control

The new frequency control scheme proposed in this paper is based on the coordination between the wind farm and the diesel generators, Figure 2. In this figure, the amount of power needed to compensate for frequency variation P_{reg} is designated by the frequency error between actual value f_{meas} and reference value f_{nom} via a PI controller, Figure 2a. Because the maximum power point tracking (MPPT) curve PMPPT limits the active power adjustment ability of the wind farm while that of the diesel generators is limited by its rating P_{max_diesel}, P_{reg} is limited by P_{reg_max} and P_{reg_min}. These limitations are reliant on the wind farm's current production P_{DFIG}, the output of the diesel generators P_{diesel}, P_{MPPT} , and P_{max_diesel}. Adjusting quantities for the diesel generator ($P_{reg\text{-}diesel}$) and the wind farm ($P_{reg\text{-}DFIG}$) at moment are decided via a sharing active power block, which is described in detail in Figure 2b.

The algorithm in Figure 2b indicates how the active power quantity needing to compensate for the deviation of the frequency is shared between the wind farm and the diesel generator. As can be seen from this flowchart that the DFIG-based wind farm is always prioritized for active power generation as much as possible due to the high fuel cost of the diesel generators. Obviously, when the isolated grid requires the DGs to reduce the power output to decrease the frequency, the diesel generators must be taken first. The wind farm only participates in reducing the power output when P_{reg} is higher than P_{diesel}. In the other situation, in which the grid obliges the DGs to increase the active power output, the wind farm must be prioritized to increase. However, P_{MPPT} curve limits the wind farm's production. Therefore, the diesel generators only shoulder the rest of compensation quantity when P_{reg} is higher than the adjustment ability of DFIG ΔP_{avail}. Note that ΔP_{avail} is the difference of P_{MPPT} and P_{DFIG}.

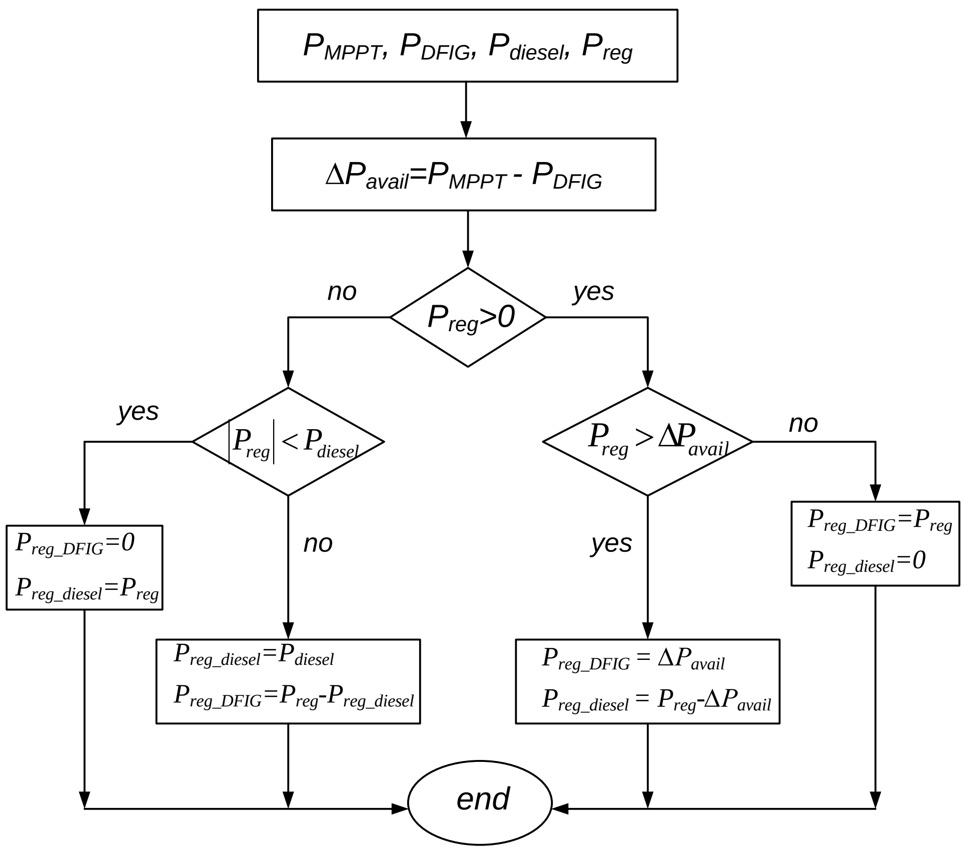
Concerning the voltage at loads in the isolated grid, loads located near the diesel generators is so far from the wind farm. The wind farm cannot adjust the voltage at those loads if the diesel generators are out of service. Therefore, although the diesel generators are not required to generate active power, they must generate or absorb reactive power from the grid in order to maintain the voltage at the local loads. It means that the diesel generators must be connected permanently to the grid.



$$P_{reg\_min} = -(P_{DFIG}+P_{diesel})$$

$$P_{reg\_max} = P_{max\_diesel}+P_{MPPT} -(P_{DFIG}+P_{diesel})$$

(a)



(b)

Figure 2. Frequency Control (a) and Sharing Power between Diesel and Wind Farm (b)

It is noted that because the maximum load is over the diesel plant's capacity, in the period of no wind, both wind farm and the load 1 should be cut off. In this case, only the diesel generators shoulder other loads. This case is not focused in this paper.

3.2. Control Strategy for Rotor Side Converter

To maintain the normal frequency in the grid, at moment, the sharing block will send P_{reg_DFIG} to the wind farm's controller and the wind farm must regulate among that quantity. It means that the DFIG plant must generate a reference power P_{ref} that is the summation of P_{MPPT} and P_{reg_DFIG}. Beside, the wind farm must also keep the rated voltage at the point of common coupling (PCC). Therefore, RSC is controlled to generate P_{ref} and maintain the PCC voltage at a constant.

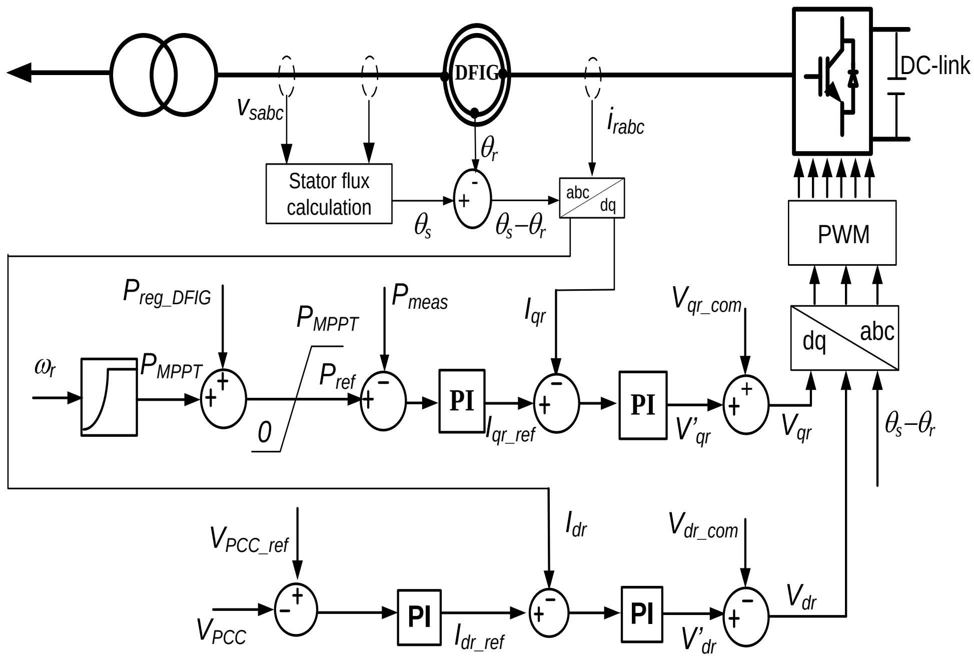


Figure 3. Controlling Diagram for RSC of DFIG

With *dq* frame chosen the same as that in [23], which d-axis is oriented with the stator flux and q-axis is 90^o head of d-axis respect to direction of rotation, controlling diagram applied to RSC is indicated in Figure 3. In this figure, it comprises of two cascaded control loops. The outer control loop adjusts the reference active power and the PCC voltage V_{PCC}, independently. The outputs of this loop are the reference currents, I_{qr_ref} and I_{dr_ref}, for the inner loop, which regulates q-axis and d-axis rotor current components, I_{dr} and I_{qr}, independently. The output signals of this loop are the voltage signals V'_{qr} and V'_{dr}. These two voltage signals (V'_{qr} and V'_{dr}) are compensated by the corresponding cross coupling terms (V_{qr_com} and V_{dr_com}) to form the *d-q* voltage signals, V_{qr} and V_{dr}, which are used by the PWM module to generate the IGBT gate control signals to drive the rotor-side IGBT converter. V_{qr_com} and V_{dr_com} are expressed in equations (2) and (3) where L, ω, s, θ and I represent inductance, angle speed, rotor slip, phase angle and current, subscripts *PCC, d, q, abc, s, r* and *m* stand for the PCC point, d-axis, q-axis, instantaneous three-phase, rotor side and stator side, mutual between the rotor side and the stator one. Noted that i_{dr} and i_{qr} are transformed from the instantaneous three-phase rotor currents i_{rabc} via the stator-flux oriented reference frame.

$$v_{qr\_com} = s\omega_s(\delta L_r i_{dr} + \frac{L_m^2}{L_s} i_{ds}) \quad \text{and} \quad v_{dr\_com} = -s\omega_s \delta L_r i_{qr} \quad (2)$$

$$\delta = 1 - \frac{L_m^2}{L_s L_r} \quad (3)$$

3.3. Control Strategy for Grid Side Converter

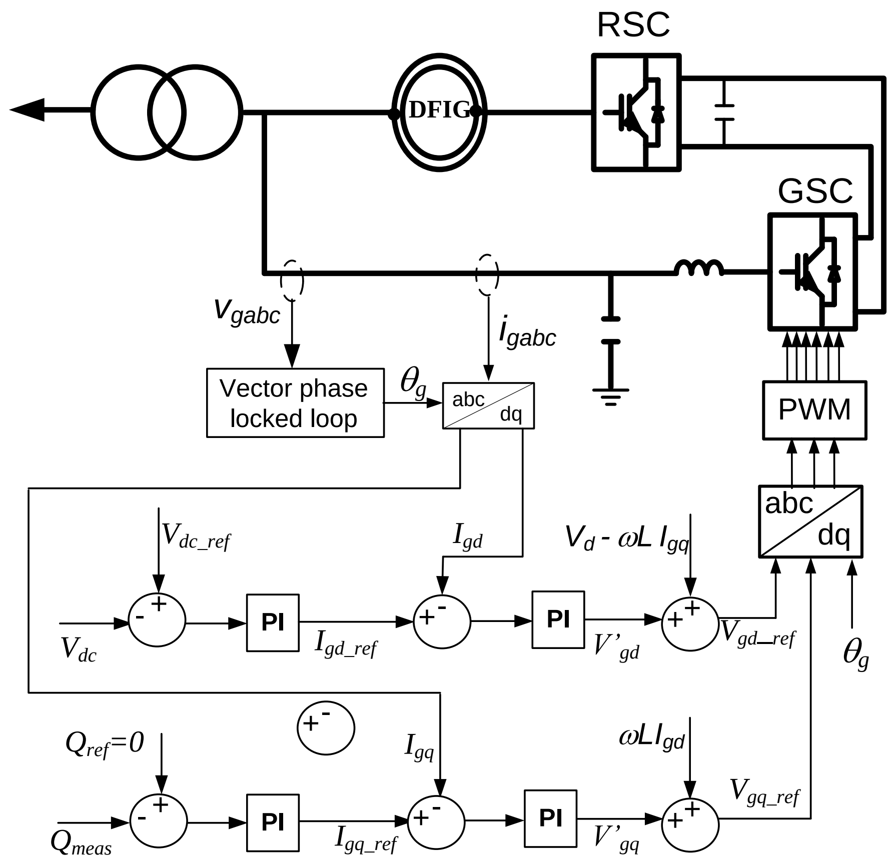


Figure 4. Controlling Diagram for GSC of DFIG

The duty of the grid side converter (GSC) is to maintain a constant voltage on DC link and a zero reactive power output at the grid side of GSC. With *dq* frame chosen the same as that in [23], which *d*-axis is aligned with the vector voltage V_g while *d-axis* lags behind *d-axis by* 90^o, controlling diagram applied to GSC is demonstrated in Figure 4. The d-axis and q-axis current components are used for the DC voltage and the unity power factor control, respectively. In this figure, *V, I, Q,* ω, θ, and *L* correspondingly represent voltage, current, reactive power, angle speed, phase angle and the inductance of filter installed in the AC side of the inverter. The subscripts *dc, g, ref, d* and *q* stand for the dc side, the grid side of the inverter, reference value, *d* and *q* components, respectively.

This diagram consists of two control loops. The outer one is to adjust the DC voltage on DC link and reactive power, independently. The output currents of this loop are considered as the reference currents, I_{gd_ref} and I_{gq_ref}, for the inner loop, which regulates I_{dr} and I_{qr} components among their reference values, independently. The output voltage components of inner loop, V'_{gd} and V'_{gq}, are compensated by voltage drop on the inductance. The *d-q* reference voltages, V_{gd_ref} and V_{gq_ref}, are used by the PWM module to generate the IGBT gate control signals to drive the rotor-side IGBT converter.

3.3. Governor System of Diesel Generator

To regulate P_{reg_diesel} as expected, this quantity is converted to ω_{reg} via a PI controller. The reference rotor speed of governor system is the summation of ω_{reg} and the rating speed of diesel, ω_{rated}=1pu. This reference value is provided to the governor system in order to produce a mechanical power P_{mec}. Figure 5 indicates how the reference speed for the governor system of the diesel generator is computed. The modeling of a governor system is described in detail in [7, 22].

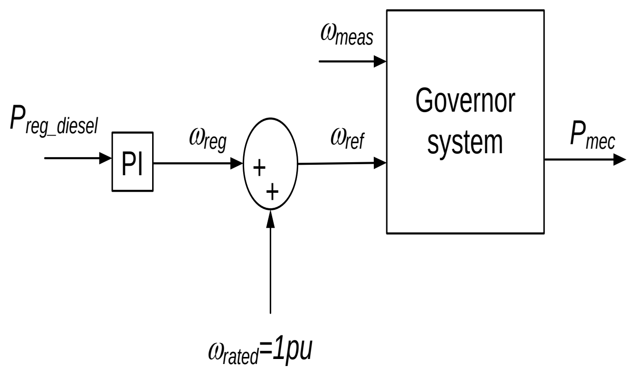
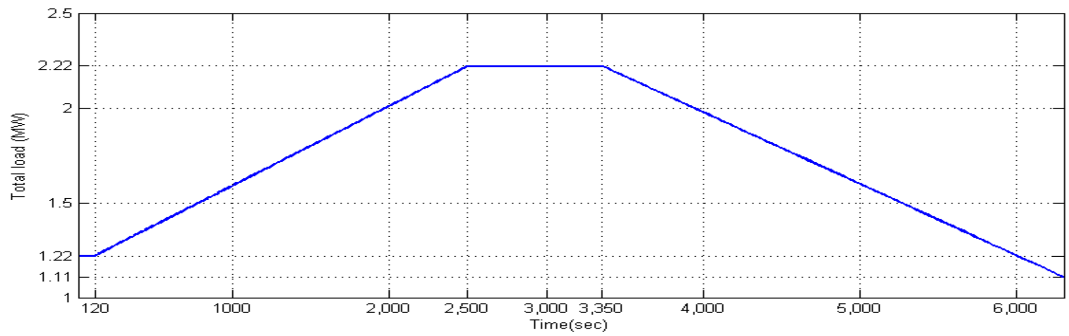


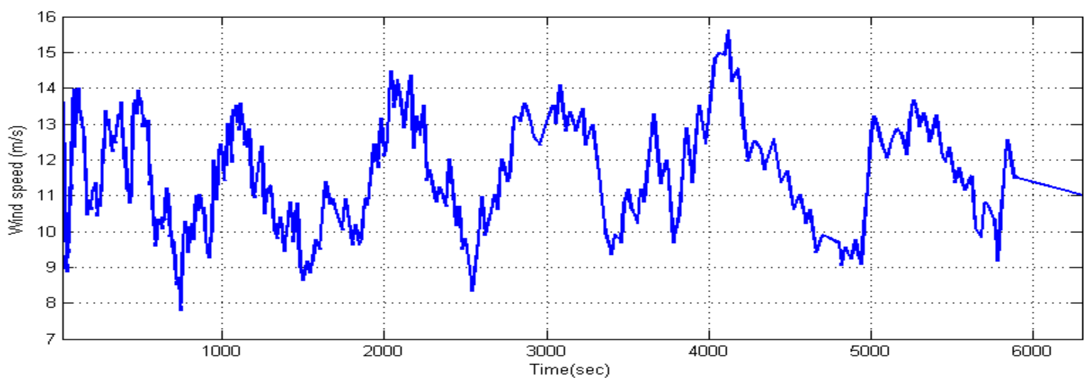
Figure 5. Reference Speed for the Governor System of Diesel Generator

4. Simulation Results and Discussion

To test the recommended scheme, two scenarios of load, load increase and load decrease are investigated. The first one is the total load in the grid increases from 1.22MW to 2.22MW within around 40minutes, from 120s to 2500s, and the second one is a decrease in load, from 2.22MW to 1.11MW, occurring from 3350s to 6200s, as Figure 6a. From 2500s to 3350s, the demand is remained at a constant, 2.22MW. This test is carried out under Matlab/Simulink environment. The wind speed profile used for this simulation is demonstrated in Figure 6b.



(a)



(b)

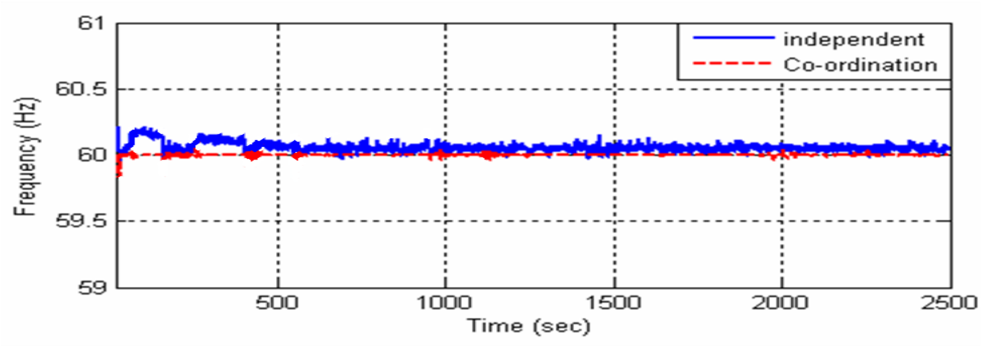
Figure 6. Total Load (a) and Wind Velocity Profile (b)

4.1. Load Increase

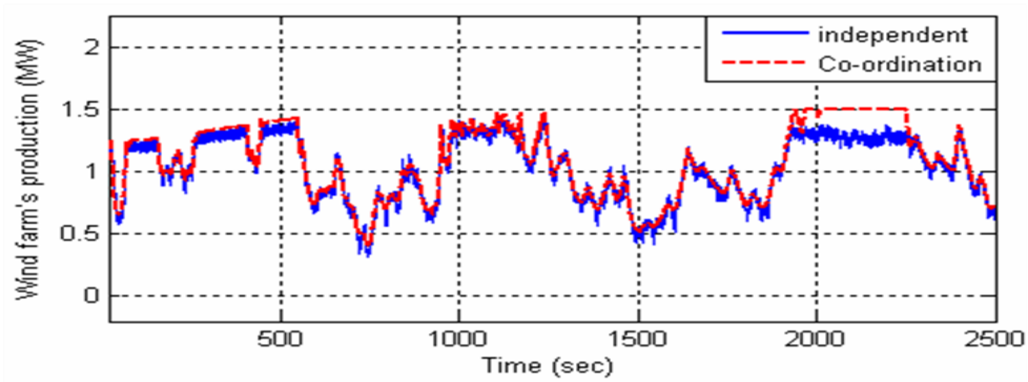
It is assumed that the load increases from 1.22MW at 120s to 2.2MW at 2500s, as shown in Figure 6a. Simulation results are demonstrated in Figure 7. As can seen from Figure 7a, with the co-ordination controller, the frequency in the isolated is maintained at 60Hz during simulation stage. The independent controller also keeps the frequency in operation range, from 59.5 to 60.5.

Figure 7b indicates that the production of the wind farm increases among the load when the total load increases from 1.22MW to 1.5MW. The diesel generators only supplies active power to the grid, Figure 7c, when the wind farm's available power is below the demand. Otherwise, the diesel generator's production is equal to zero. By contrast, in the case of the independent controller, both the diesel generators and the wind farm supply active power to the grid in spite of high wind velocity period. As can be seen from Figure 7b and 7c, in the period of high wind speed, the diesel generators must supply active power while the wind farm has not yet approached the MPPT curve. Take from 480s to 520s for example.

Next period, the demand is over the wind farm's capacity, the co-ordination controller allows the wind farm to generate maximum power as much as possible while the diesel generators only shoulder the rest of demand. On the other hand, for the independent controller, when load increases, both the wind farm and the diesel generators must increase in active power output. As a result, the wind farm is hard to generate maximum power, as expected. Therefore, with conventional controller, the diesel generators must supply a higher active power compared to the case of new controller. For example, form 1900s to 2250s, the wind farm's production reaches 1.5MW with the proposed controller while it is only around 1.4MW with the conventional one. The diesel generators in the case of independent controller must generate 0.15MW higher compared to that of the co-ordination one.



(a)



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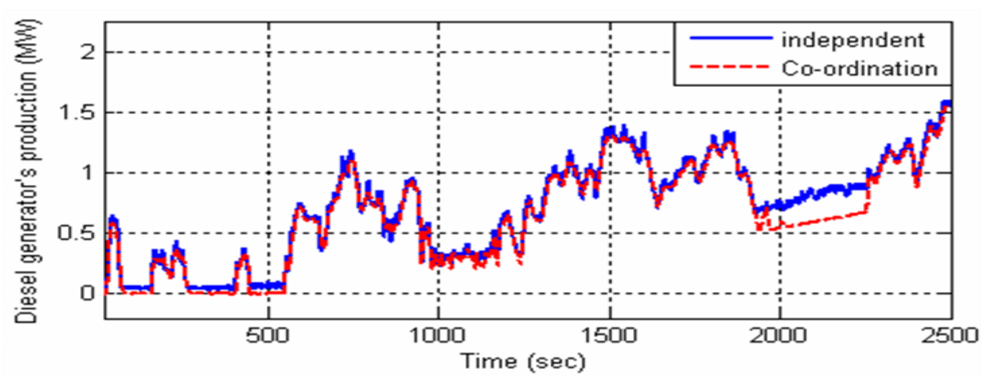
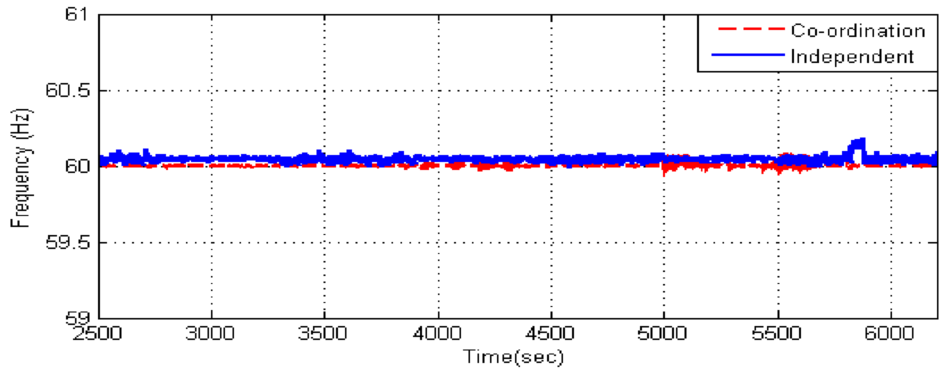


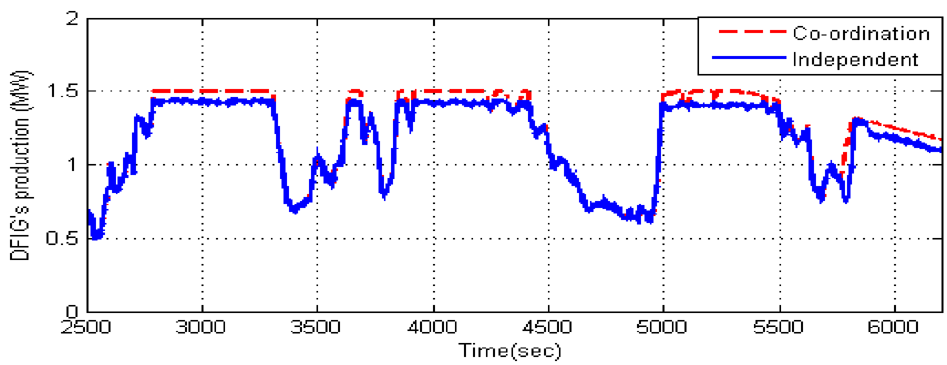
(c)

Figure 7. Simulation Results in the Case of Increase in Load: Frequency in the Grid (a), Power Output of Wind Farm (b), Power Output of Diesel Generators (c)

4.2. Load Decrease



(a)



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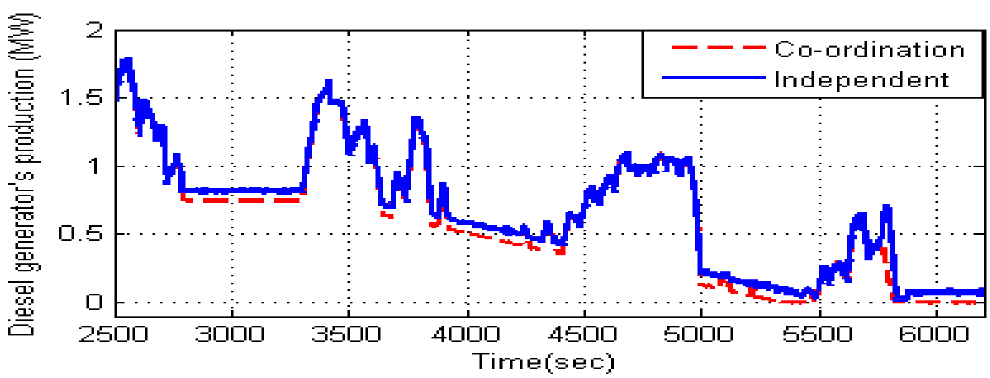

(c)

Figure 8. Simulation Results in the Case of Decrease in Load: Frequency in the Grid (a), Power Output of Wind Farm (b), Power Output of Diesel Generators (c)

It is assumed that a reduction of load from 2.22MW at 3350s to 1.11MW at 6200s, Figure 6a. Simulation results in a 1-hour period, from 2500s to 6200s, are shown in Figure 8. Generally, both controllers, the frequency in the isolated grid can be maintained at around 60Hz, in the allowable frequency range. In the case of independent controller, the grid's frequency is a little higher than that of co-ordination controller, Figure 8a.

Concerning the wind farm's production, Figure 8b, before 5300s, the total load is higher than the wind farm's capacity so the co-ordination controller designates the wind farm to supply maximum power as possible. This is hardly seen in the case of the independent controller, Figure 8c. After 5300s, the total load is below the capacity of the wind farm, during high wind speed period, take between 5300s and 5500s as an example, the wind farm's production satisfies all load of the grid. The main reason is that the co-ordination controller prioritizes the wind farm to generate active power. In the case of independent controller, both the diesel plant and the wind farm participate in the active power control, so the wind farm cannot shoulder all load despite high wind speed interval.

Figure 8c indicates that during high wind speed period, in the case of the co-ordination controller, the diesel generators must produce a higher active power compared to that of the independent one. This can be seen in the period from 5800s to 6200s. In this interval, total load is below than the available power of the wind farm, so the wind farm shoulder all load and the diesel generators' production is equal to zero. By contrast, in this period, in the case of the independent controller, the diesel generator must shoulder a part of load.

From above-analysis, the proposed scheme allows the wind farm to generate maximum power as much as possible. It means that the wind energy source is utilized the utmost and amount of fuel using for the diesel generators can be saved. This is the benefit of the co-ordination controller. Note that this proposed frequency control scheme can implement in the case of a PMSG-based wind farm.

5. Conclusion

This research focused on an isolated grid where a DFIG-based wind farm is integrated without any storage equipments or controllable loads. A co-ordination control scheme, which coordinates between the diesel generator and the wind farm in active power adjustment, to maintain the frequency in the operating range or the balance of active power within the isolated grid is offered. The objective of this method is to utilize the wind energy fully and to minimize the fuel consumed by the diesel generator. From the simulation results, it is clear that with the proposed controller, the wind energy is utilized the utmost compared to the case of independent controller. This allows saving the fuel consumption for diesel generators.

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