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Research Article

Smoothing of Grid-connected Wind-Diesel Power Output Using Energy Capacitor System

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Abstract

This paper presents a small hybrid power system consists of two types of power generation; wind turbine and diesel generation, DG connected to power distribution system. The fluctuations like random nature of wind power, turbulent wind, and sudden changes in load demand create imbalances in power distribution that can affect the frequency and the voltage in the power system. So, addition of Energy capacitor System, ECS is useful for compensation of fluctuating power, since it is capable of controlling both active and reactive power simultaneously and can smooth the output power flow. Hence, this paper proposes herein a dynamic model and simulation of a grid connected wind/DG based-ECS with power flow controllers between load and generation. Moreover, the paper presents a study to analyze the leveling of output fluctuation of wind power with the installation of ECS. To control the power exchanged between the ECS system and the AC grid, a load Following Control, LFC based supervisor is proposed with the aim to minimize variations of the power generated by the diesel generator. The interesting performance of the proposed supervisor is shown with the help of simulations. The computer simulation program is confirmed on a realistic circuit model which implemented in the Simulink environment of Matlab and works as if on line.

Keywords: Wind Power, Diesel generator, Storage system.

1. Introduction

In many remote and isolated communities, electricity is mainly supplied by diesel generators. But diesel generation has some problems, e.g. bad maintainability, unreliable fuel supply and high generation cost [1]. Moreover, the combustion of fuel generates gas emission such as SO_2, No_x and CO_2 which is the main cause of greenhouse effect. Nowadays, many alternative energy sources have been considered for the solution of those problems. One of them is Wind-Diesel generator hybrid power system. Integration of wind power into the power system has been reported e.g. by Binder &Lundsanger [2] and Koch et al. [3]. Economic benefits of combining grid connected wind power with energy storage on open electricity markets has been reported by Bathurst &Strbac [4] and Korpaas et al. [5]. One of the serious problems faced by the Wind-Diesel hybrid power system is that naturally variable wind speed causes power fluctuation problems at the load side. The power fluctuation of wind power generation may bring the voltage fluctuation and/or the frequency deviation in the power system. One way to mitigate the power fluctuation problems is utility-scale energy storage. There are many types of electricity storage, including (but not limited to) conventional batteries, flywheels, Ultra-Capacitors, superconducting magnetic energy storage, flow batteries, pumped hydroelectric energy storage, and compressed air energy storage. The use of energy storage devices and battery energy storage for load leveling application and for improvement of the dynamic performance of power systems has been described by numerous authors, namely A. M. Van Voorden , et all [6] and Muljadi et al. [7]. Electric storage has also been applied to non-grid wind-diesel or autonomous wind storage systems [8,9]. The compensation of fluctuations in a wind-diesel system using fuzzy logic was reported by Leclercq et al. [10]. J. Shi et. al.[11] proposed an application of superconducting magnetic energy storage in the power system integrated with wind farms to control and smooth the active and reactive power flow, and supply dynamic voltage support. The energy capacitor system, ECS a new technology of energy is proposed to be utilized in power systems. Thus, many other applications of the ECS have been reported by numerous authors [12-15]. This paper presents an addition of an energy capacitor system (ECS) to the wind-Diesel power system to improve its performance. The ECS composed of an electric double-layer capacitor with power-electronics devices is useful for compensation of fluctuating power, since it is capable of controlling both active and reactive power simultaneously. The control scheme based on the coordination between the ECS and the DG has been proposed together with computer network. The influence of the computer network failure has been checked and treated in proper way. PI and PID controllers have been used to solve the problem of ECS size limitation and to complete the coordination process. A long process of parameters and gains tuning has been hold based on trial and error

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methodology. The results and the conclusion of the analysis are applicable to any similar hybrid power systems.

2. System Model and Control

The system has two types of generation: the diesel generator and the wind turbine generator. The ECS can act as a load or as a generator depending on the need. The wind turbine has an induction generator with rated capacity of 1000 kW. The diesel engine, which has a rated capacity of 5000 kW, is operated in parallel with the wind turbine to supply the load. The ECS is 300kW of energy storage as a buffer to operate as a load or a source depending on the need. Variable loads are mostly residential and light loads. The block diagram of the integrated overall system is shown in Figure 1. The mathematical model and Matlab representation of each component is described below.

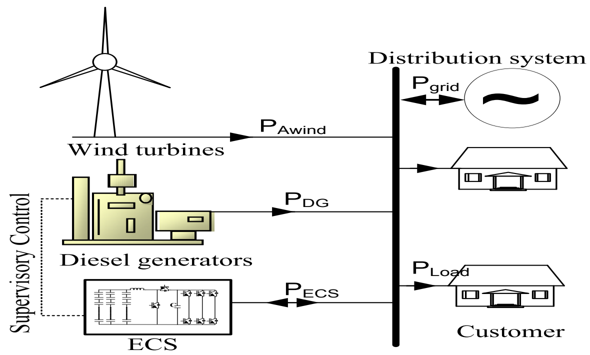

Fig. 1. System under Study

A. WTG model

The characteristic of power output from WTG's can be described by the following formula [1], [16]:

$$P_{wtg}(t) = \begin{cases} 0 & : v(t) < V_c \\ 0.5.C_p \cdot \eta_m \cdot \eta_g \cdot A_w \cdot V^3(t) & : V_c \le v(t) < V_r \\ P_{rated} & : V_r \le v(t) < V_f \\ 0 & : v(t) > V_f \end{cases} \quad (1)$$

Where; v(t) is the wind speed; m/s, $V_c$is the cut off wind speed, m/s, $V_r$is the rated wind speed, m/s, $V_f$is the cut off wind speed, m/s, C_p is the coefficient performance of the turbine,η_m is the transmission efficiency and η_g isthe generator efficiency.P_{rated} is the rated power; kW, A_w is the effective swept area; m^2.Figure 2 illustrates the Simulink block diagram of the wind turbine model and Figure 3 shows the measured wind speed considered in the simulation while Figure 4 shows the total active power from wind turbine generator.

A. ECS model

ECS consists of Super-Capacitors and power electronics. It is used as an energy storage system. The capacitor part of the ECS is a group of electric double layer capacitors with energy/volume obtained (5 Wh/kg or even 15 Wh/kg)[17]. The ECS will supply power to the load when there are surges or energy bursts since ECS can be charged and discharged quickly and it can store and deliver larger amount energy over a longer slower period of time.

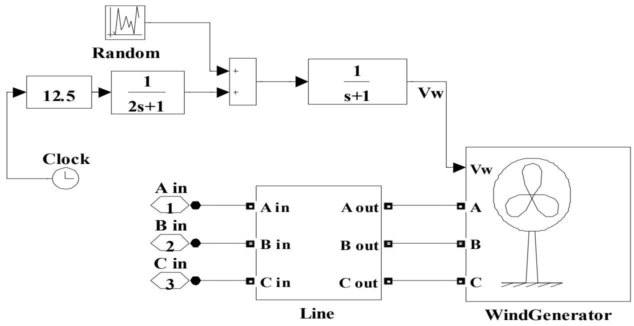

Fig. 2. Simulink Model of WTG

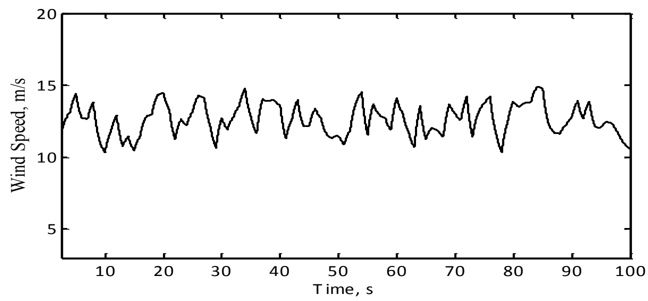

Fig. 3. Measured wind speed considered in the simulation

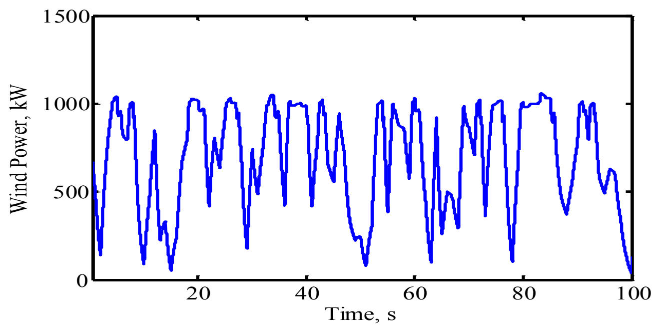

Fig. 4. Active powerfrom WTG

The advantages of Super-Capacitors are[6]:

- Long life cycles (>500,000),
- High capacitive density,
- High cycle efficiency (95% or more),
- Very high rates of charge and discharge continuously,
- Good reversibility,
- Light weight,
- Low toxicity of materials used,
- Large current/power capabilities over a wide range of operating temperatures.

The notable drawbacks to the Super-Capacitors are:

- Low specific energy, Since the amount of energy stored per unit weight is considerably lower than that of an electrochemical battery (3-5 Wh/kg for a super capacitor compared to 30-40 Wh/kg for a battery);
- Wide voltage variations as energy is taken out of or put into the device.
- More expensive than batteries.

The ECS is placed at the AC bus. The primary function of the ECS is to isolate the electric network from fluctuations like random nature of wind power, turbulent wind, and sudden changes in load demand and then improve power quality thereby acting as a shock absorber. Assuming lossless conditions and using the directional power flow conventions in Figure 1, the power exchanged with the electric network, P_{gird}, can be determined by solving the power balance equation:

$$P_{gird} = P_{wtg} - P_{Load} + P_{DG} \pm P_{ECS} \qquad (2)$$

The response time of the ECS, typically on the order of milliseconds, enables it to compensate for fluctuations in wind turbine and load. Therefore, the contribution of the ECS is increasingly important in Wind- diesel power system. The peak power fluctuations of these sources and loads are used to determine the power rating of the ECS.

B. DG model

Conventional generators are normally diesel engines directly coupled to synchronous generators. The frequency of the AC power is maintained by a governor on one of the engines. The governor functions by adjusting the flow of fuel to keep the engine speed and the generator speed essentially constant. The grid frequency is directly related to the speed of the generator, and is, therefore, maintained at the desired level. When power demand fluctuates the diesel generator could vary its output via fuel regulation to its governor. The Matlab/Simulink block diagram of the synchronous generator together with the optional governing system is shown in Figure5, where P_m is the Mechanical power at the machine's shaft and V_f is the field voltage. In this study, the capacity of diesel generator unit is set 5000kW.

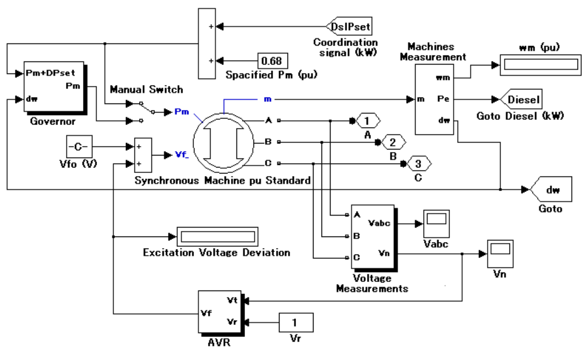

Fig. 5. Matlab block diagram configuration of the DG

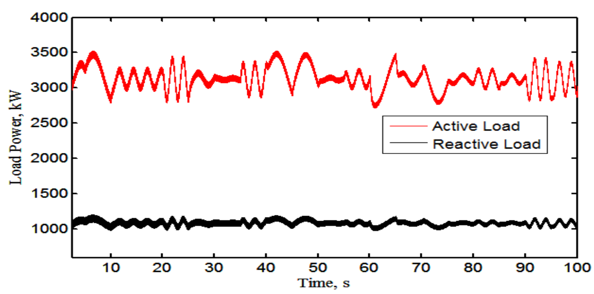

Fig. 6. Variable load

C. Load model

Figure 6 indicates a designed a random pattern of a load for peak values of active and reactive power respectively. The variable load has been added and simulated to the system to make it more realistic model.

3. Control Strategy

The system is connected to the power system and balancing between generation and load instantaneously and continuously is difficult because loads and generators are constantly fluctuating. So, to smooth and regulate the power supply (P_{grid}) to a prespecified level by the regulated generation on the diesel unit and also by the charging/discharging operation on the ECS under typical variations of power demand and also against the power variation from the wind turbine generation unit, a the load following operation is taken into account. A multi-agent based control system has been proposed on the computer networks for the load following operation [18]. The placement of intelligent agents is illustrated in Figure7. The multi-agents based control system is a computer network composed of many personal computers called agents, which are responsible about sending and receiving data among each others to perform the control strategy and provide the coordination scheme between ECS and the DG. There are two levels of multi-agents based control system, global control and local control are implemented to keep the power supplied from the electric grid smoothen and regulated with power quality[18].

A. Global control [18].

Global control is performed when computer network are available and able to coordinate between the ECS and the DG. The DG receives the required signal from the ECS through the agents to absorb the fluctuations. The controller shown in Figure 8 implements the coordination process between the ECS and the DG. The PI controller used on the ECS side is shown in Figure 9.

B. Local control [18].

This case happens when the computer network fails down due to any reason, in other words, the DG and the ECS system are not coordinated during this period of time i.e. working separately. The performance of the energy capacitor system is clearly degraded and the DG cannot perform the LFO itself, another technique has been used in this case which is modifying the target power to a certain accepted value to improve the performance of the ECS. The local information in the location of the ECS has been implemented. That is called the lower or local control. Figure 10 shows the general configuration of the local control. The target power has been modified as the coordination between the energy capacitor system and the DG is not possible. Hence local information taken from the physical bus bar where the ECS is located is used to improve the performance of the ECS, in other words to keep the ECS in the certain charging and discharging level, not to exceed the top charging level and not to come below the minimum discharging level, thus the target power has been modified.

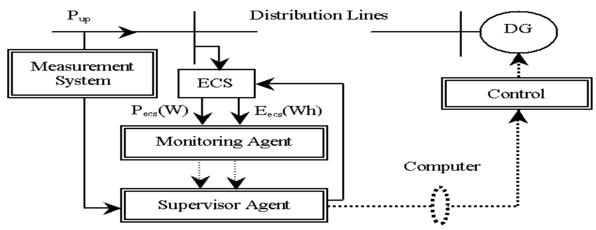

Fig. 7. Global control configuration [18]

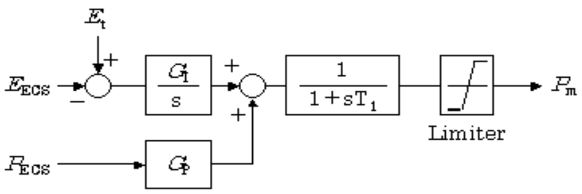

Fig. 8. The representation of the coordination PI controller [18]

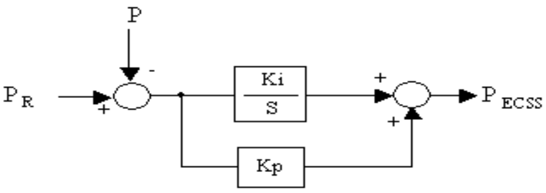

Fig. 9. The representation the PI controllers on the ECS

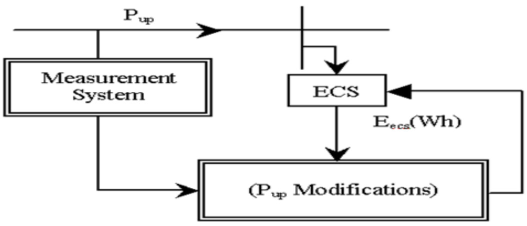

Fig. 10. Local control configuration [18]

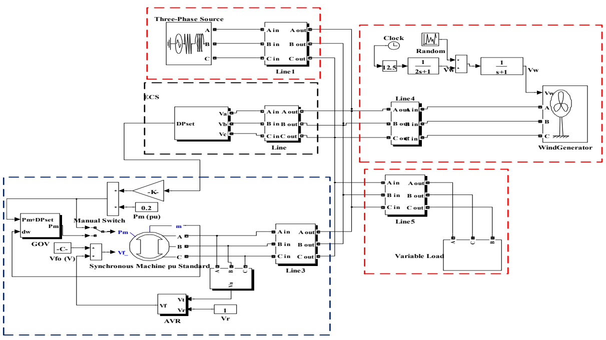

Fig. 11. Matlab Simulink of three-phase instantaneous-value based model of the target system

4. Simulation results

The simulation evaluation has been conducted on the system shown in Figure 1 using MATLAB/SIMULINK. Matlab general representation of the system under study is shown in Figure 11. The wind turbine drives a 1 MWand DG has a rated capacity of 5 MW. The charging and discharging level of the ECS was specified from 0.9 kWh to 3 kWh. The external power grid that the WTG connected is represented as a voltage source rated at 6.6 kV. The dynamic model used for simulations is highly nonlinear and has a stiff structure, and it done by Intel(R) Core(TM)2 Duo CPU, T8300@ 2.4 GHz, With 4GB RAM. Consequently, a 100-s duration is used for the simulations with all wind speed. The operation of the system is simulated with and without ECS under different control strategies.Based on trial and error methodology, the parameters of the PI controllers used at different control strategies scheme have been tuned until the optimum values obtained to achieve the desired result. Table 1 shows the tuned parameters under different strategies to control the real power of the system under study.The wind signal driving the wind turbine is simulated as a group of random wind, as shown in Figure 3. From Figure 4, It can be seen that the output active power of WTG fluctuate with the variation of wind speed which will induce voltage instability. Figure 12 illustrates the grid power according to different control strategies. From this figure it can be see that, first one when ECS is not in service and no control action is performed which results in a very fluctuated and distorted power delivery from the utility grid as shown with the dotted line in the figure. Secondly by introducing global control and there is a coordination control condition between both the DG and the ECS, the active power which is delivered to the power grid can be smoothen, as shown with the solid line in the figure. Finally, by introducing a local control and the DG is not supporting the ECS due to computer network failure. The output power and energy of the ECS under different operation is shown in Figs. 13 and 14.

Table 1. Controller tuned parameters in case of LFO

Strategy	Parameters	On the ECS	On the DG	Coordination controller
Global control parameters	P	0.5	15	0.1645
	I	700	0.8	0.006
	Gain	1	0.06	-
Local control parameters	P	0.7	8	0.015
	I	700	0.6	0.008
	Gain	0.065	0.06	-

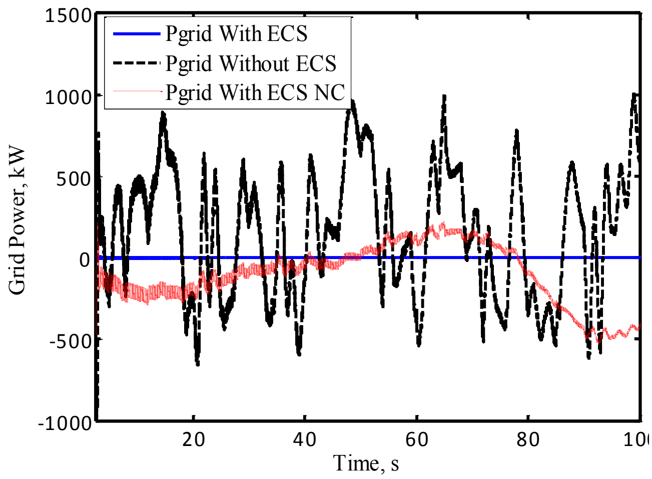

Fig. 12. Grid Power under different operation

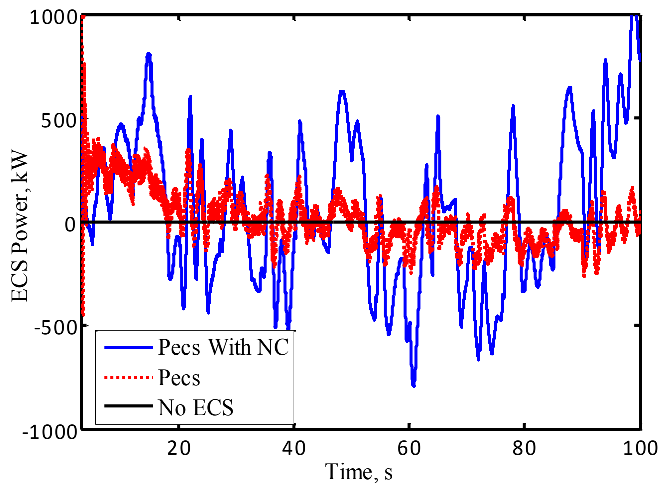

Fig. 13. Output and input power of ECS under different operation

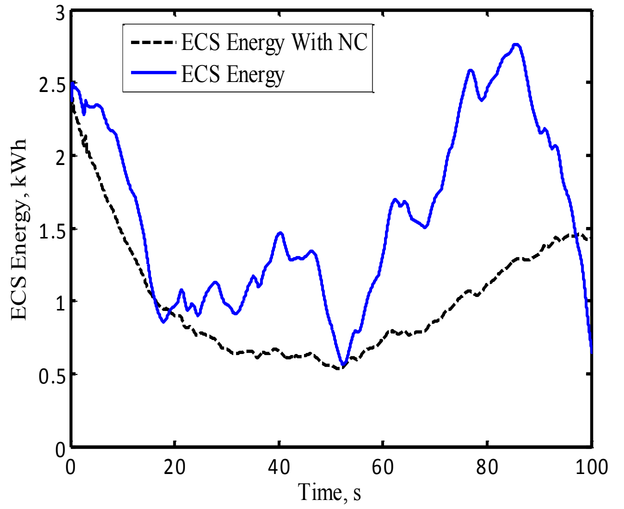

Fig. 14. ECS Energy under different operation

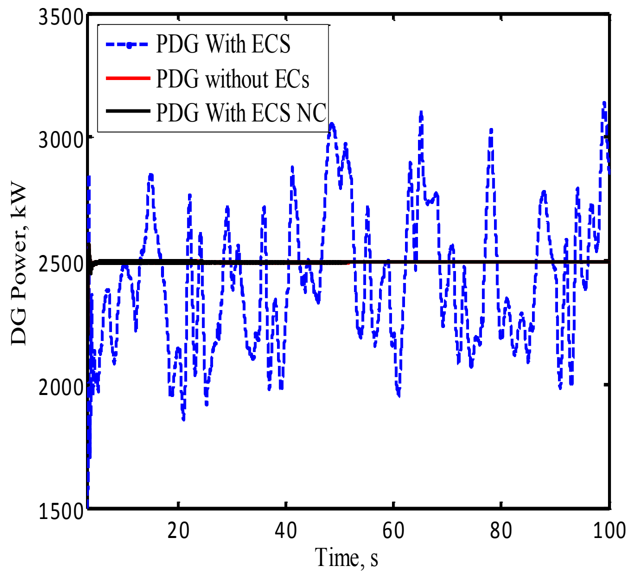

Fig. 15. DG power under different control strategy

The output active power generated by the DG under different operation is shown in Figs. 15. From this figure, it can be seen that the DG power with ECS under local control and without ECS are constant and equal to 2.5MW. On the other hand, the DG output power fluctuated with ECS under global control to regulate the power from utility grid.

The balance of the active power between grid, wind generation and diesel generator in the presence or absent ECS is shown in Figure 16 and Figure 17 respectively. The balance of active power is maintained by the governor of the diesel generator. It can bee seen that the grid power in Figure 17 is very smooth than in Figure 16. When the load demands more power than the wind turbine and storage energy in ECS then a control signal from ECS send to diesel engine to compensate the deficit power. For example at time equal to 20 s, the wind turbine is very high due to high wind speed as shown in Figure 3. The load demand at this time is 3.2273MW, The output active power from WTG is 1MW and the ECS power is 104.9kW. Hence the DG power is 2.09MW on the other hand the power to grid is 2.5kW. As it can be seen also, when wind speed is low at time 30 sec the output from WTG is 738.4kW, the DG is 2.689 MW, ECS power is 160.32kW and grid power is 2.2kW to feed the load demand 3.53MW.

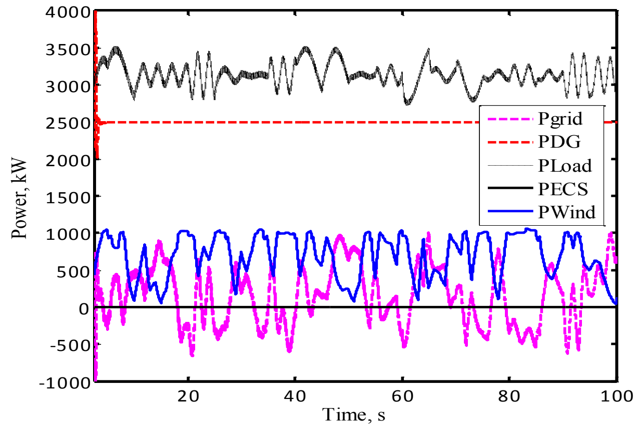

Fig. 16. Powers for Each Unit Under No Control without ECS

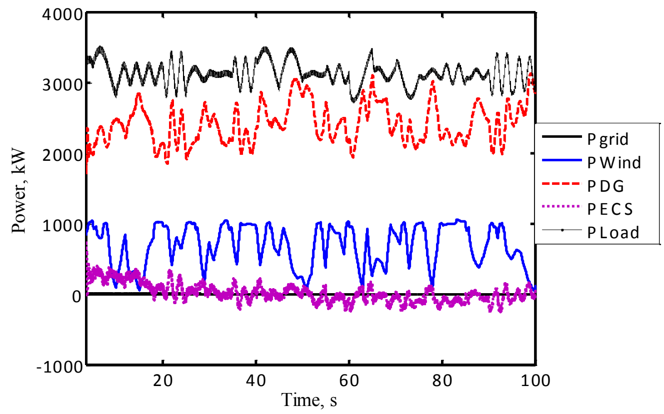

Fig. 17. Powers for Each Unit with ECS

The evaluation index to calculated the power deviation from the utility grid and to evaluate the LFO scheme for the different strategies can be expressed as follow [18]:

$$\boldsymbol{Index} = \frac{\sum |P_{grid} - P_t|}{N} \tag{3}$$

Where P_{grid} is the power from the grid, P_t the target power, and N is the number of entered data. The obtained indices according to the different control strategy are shown in Table 2. The smaller index gives better result as shown n this table which is 1.325kW for global control strategy.

Table 2. LFO indices for different control strategy

Control strategy	Index
No control	210
Global control	1.325
Local control	150.25

5. Conclusions

In this paper, a dynamic modeling and a control strategy of a ECS system associated with a diesel generator and a wind turbine generator connected to grid has been proposed. ECS element has been considered with the target to smooth of grid power. The control of the power exchanged between the ECS system and the DG is achieved with the help of a load following operation based supervisor to minimize variations of the power from utility grid. The PI controller of ECS, DG and coordination is designed for the improvement of power quality of the power system integrated with the wind farm. The simulation results show that the ECS can respond very quickly to the active power demand from the wind farm, and the power quality of power grid integrated with wind power can be improved considerably. Multi-agent based load following operation control have been proposed to regulate the power flow. Global control is better than local control. Comparing the simulation results, it has been noticed that, ECS has a very good response of absorbing fluctuations.

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