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Frequency deviation control by coordination control of FC and double-layer capacitor in an autonomous hybrid renewable energy power generation system

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ABSTRACT

In this paper, a novel control strategy for frequency control in stand-alone application based on coordination control of fuel cells (FCs) and double-layer capacitor (DLC) bank in an autonomous hybrid renewable energy power generation system is implemented. The proposed renewable energy power generation subsystems include wind turbine generator (WTG), photovoltaic system (PV), FC system and DLC bank as energy storage system. The system performance under different condition has been verified by using real weather data. Simulation results demonstrate the validity of proposed studied hybrid power generation system feeding isolated loads in power frequency balance condition.

1. Introduction

Stand-alone power generation systems are utilized by many communities and remote area around the world that have no access to grid electricity. The renewable energy in grid independent system is growing due to rising fuel prices and environmental warming and pollution [1,2].

Wind and solar power generation are two of the most attractive renewable power generation technologies. In order to integrate renewable energy into such systems and to prevent power fluctuation of wind and solar resources due to weather condition variation, some form of energy storage or additional generation such as FC and battery bank is generally needed [3–5].

FCs systems are one of the promising energy technologies for sustainable future due to their high energy efficiency, environment friendliness and modularity. The main drawback of FCs power generation system is slow dynamics because the FC current slope must be limited in order to prevent fuel starvation problems and to improve its performance and lifetime. The very fast power response, flexible and modular structure of DLC can complement the slower power output of the main source to satisfy load demand completely [6].

In order to prevent fuel starvation problem (over-use) and also to prevent fuel under-use conditions, the excess value of hydrogen fuel flow needs to be controlled rapidly by increasing and decreasing the mass flow into the FC stack, respectively. These operations are restricted by the inertia (dynamic respond) of the actuators. This problem can be controlled by restricting the dynamics of load changes. The different types of FC system have different duration of time delay. Due to this reason the FC system cannot change its power to the desire value.

Due to long duration time delay of FC system, DC link capacitor cannot compensate the variation of load demand and also the voltage variation of DC link capacitor is not in its allowable range for safe operation of inverters. So, DLCs are used to compensate the variation of load demand and FC system power [7,8].

A hybrid power system consists of a combination of two or more power generation technologies to enhance their operating characteristics and efficiencies than that could be obtained from a single power source [9]. The power for the load demand can be effectively delivered and supplied by the proposed hybrid power generation system with proper control and effective coordination among various subsystems.

Several practical arrangements of DLC are used in hybrid power generation. Each of the practical arrangements of double-layer capacitor in hybrid power generation has its advantages and disadvantages relative to operating conditions, control complexity, development cost and fuel economy potential. The usage of the DC/DC converter can maximize the utilization of DLC or batteries during acceleration and cruise and regenerative braking. This structure allows controlling the transient respond of fuel cell by applying different power split strategies such as power-assist or load-leveling control to mitigate the stress on the fuel cell stack [10,11].

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List of symbols

P_{Total}	Total average power generation
P_{WTG}	Power of wind turbine generator
P_{Net}	Net power
K_{WTG}	Gain of wind turbine generator
T_{WTG}	Time constant of wind turbine generator
Δf	System frequency deviation
V_{Wind}	Wind speed
Φ	Solar irradiation
P_{PV}	Power of PV system
K_{PV}	Gain of PV system
T_{PV}	Time constant of PV system
P_{FC}	Power of FC system
K_{FC}	Gain of FC system
T_{FC}	Time constant of FC system
M	Equivalent inertia constant
D	Damping constant
P_W	Mechanical power of wind turbine

A number of literatures have been reported to investigate frequency deviation control and modeling of hybrid renewable energy systems. Among them, Dong Jing and Lee Wang reported the small signal stability analyzed results of a hybrid power generation/storage system connected to isolated load [12,13]. In [14], S. Doolla and T.S. Bhatti investigated the load frequency control of an isolated small-hydro power plant with reduced dump load technique. In [15], dynamic model of FC are simulated as first order lead lag to indicate the exact behavior of FC system in transient event based on experimental data. Output Power Control of Wind Turbine Generator by Pitch angle control is presented in [16] and [17].

In the previous works, the authors used the diesel generators and battery bank to control frequency deviation control with different control strategy. The main contribution of this research is that a novel control strategy for frequency deviation control of stand-alone autonomous hybrid power generation based on coordination of FC and DLC is proposed to enhance power quality. Also studied hybrid power generation is investigated under real weather data to analysis the effective of proposed control strategy. The simulation results show the validity of the proposed control strategy.

This paper is organized as follows: in Section 2, system descriptions and methodology are explained, power management and proposed control strategy is described in Section 3. Simulation and results discussion are presented in Section 4 and the research will be concluded in Section 5.

2. System configuration and description

The generalized block diagram of the proposed hybrid power generation/energy storage system is shown in Fig. 1. The power generation subsystems include a WTG, a PV, an FC system and DLC bank is employed as energy storage system. DLC is assumed to have enough capacity to store surplus energy generated subsystem. In the proposed system a PV and a WTG system are used as primary energy power generation and have priority to produce power to satisfy load demand.

To detailed study of proposed hybrid power generation/storage system precisely, should employ high order mathematical models with nonlinearity. In this case to simulate and investigate all part of such systems with this complexity, simplified model as linear first order transfer function are generally employed. Therefore, the system nonlinearities have not been taken into account and the system simulated in simplified model. The mathematical models of the different components are presented in sub-section.

2.1. Wind power generation model

The output power of wind turbine generators depends upon the wind speed. The mechanical power of the wind turbine is given by [16]

$$P_{Wind} = \frac{1}{2}\rho A v^3 C_p(\lambda, \theta) \quad (1)$$

where ρA, C_p are the air density, swept area of blades and power coefficient which is a function of tip speed ratio.

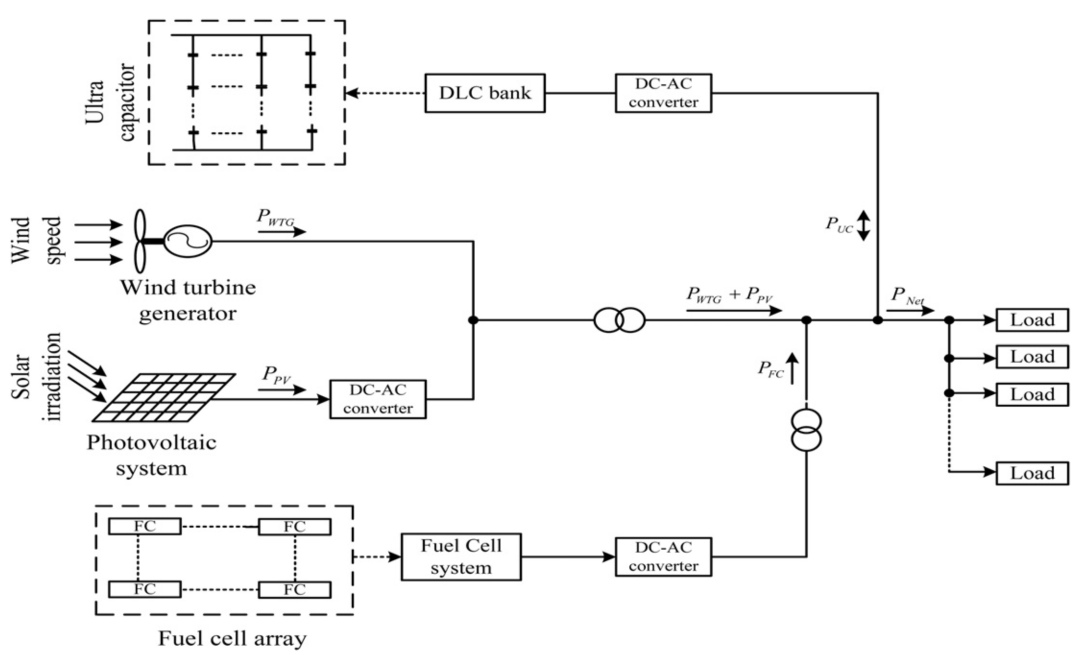


Fig. 1 Overall system configuration of the hybrid power generation and energy storage system.

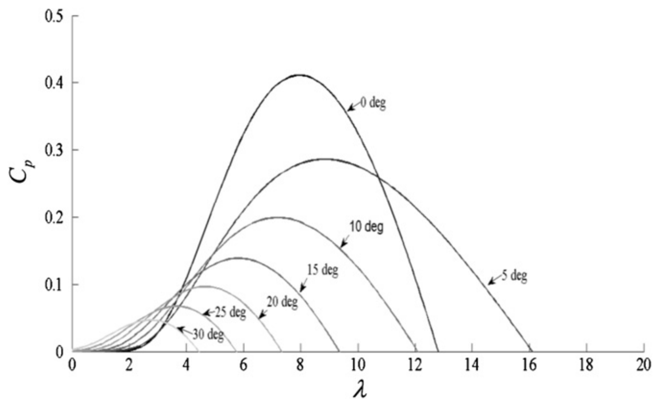


Fig. 2 $C_p - \lambda$ characteristics of the Wind turbine generator at different pitch angles (θ).

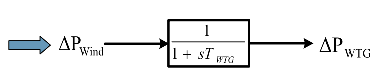
The maximum rotor efficiency C_p is obtained at a special, λ which depend on the aerodynamic design of a given turbine. To keep λ constant at the optimum level at all times, the rotor must turn at high speed at high wind, and at low speed at low wind. Fig. 2 indicates $C_p - \lambda$ characteristics of the Wind turbine generator at different pitch angles (θ).

Fig. 3 expresses the output power of the wind turbine generators in comparison with wind speed. This figure indicates that the output power is maintained constant when wind speed is higher than the rated wind velocity. This is done with the aim of the pitch angle control to protect the electrical system and to prevent the rotor from over speeding.

In this study, when wind speed is greater than the cut out speed (25 m/s), the system is taken out of operation for safety of its components and when wind speed is greater than cut-on wind speed, the output power of WTG is constant at its maximum value by the pitch angle control. However, when wind speed is smaller than cut in speed 4 m/s, the output power of the WTG is zero.

The transfer functions of the WTG shown in Fig. 1 is represented by a first order lag as

$$\frac{\Delta P_{Wind}}{\Delta P_{WTG}} = \frac{1}{1+sT_{WTG}} \tag{2}$$



where T_{WTG} is called Time constant of wind turbine generator.

2.2. PV power generation model

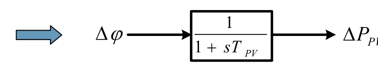
A PV system consists of one or several photovoltaic generators connected in series and parallel to provide the desired voltage and current. PV generation systems are currently considered to be one of the most promising energy sources. PV generation is a flexible and environmental friendly power generation method. The electrical data of photovoltaic modules are influenced by solar radiation, solar cell temperature and area of PV array. The output power of the PV system can be express as follow [13]:

$$P_{PV} = \eta S \varphi (1 - 0.005(T_a + 25)) \tag{3}$$

The PV power extracted from the solar irradiation mainly depend upon four quantities namely, conversion efficiency of PV array (η), measured area of PV array (S), solar irradiation (φ), ambient temperature (T).

The transfer function of PV can be represented by a simple linear first order lag as:

$$\frac{\Delta \varphi}{\Delta P_{PV}} = \frac{1}{1+sT_{PV}} \tag{4}$$



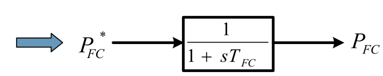
where T_{PV} is called time constant of PV system.

2.3. Fuel cell power generation system

Fuel cells are static energy conversion devices that use hydrogen and oxygen to convert chemical energy into electrical energy. However, the main drawback of fuel cell is slow dynamic due to their slow dynamic in the fuel supply system, which contains pumps, valves [15].

The transfer function of FC can be expressed by a simple linear first order lag as:

$$\frac{P^*_{FC}}{P_{FC}} = \frac{1}{1+sT_{FC}} \tag{5}$$



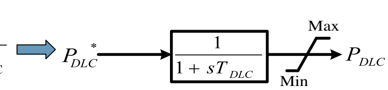
where T_{FC} is called time constant of FC system.

2.4. DLC bank storage subsystem

Recently, DLCs are being attracted as future replacements for the batteries in different applications due to high efficiency, fast load response, modularity, long life, no maintenance and environmental friendly.

The transfer function of DLC bank can be expressed by a simple

$$\frac{P^*_{DLC}}{P_{DLC}} = \frac{1}{1+sT_{DLC}} \tag{6}$$



linear first order lag as [18]:
where T_{DLC} is called time constant of DLC system.

2.5. Power deviation and system frequency variation

The total power generation must be effectively controlled and properly dispatched to maintain a stable operation of an autonomous system to satisfy power demand of isolated load by proper control of different power generation and components. The power balance is expressed as follow:

$$\Delta P = P_{Net} - P_{Load} \tag{7}$$

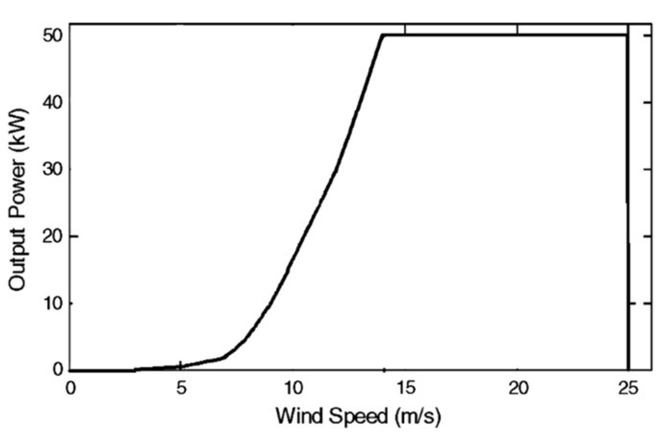


Fig. 3 Wind turbine output power characteristic curve.

Table 1
Parameters of the studied hybrid system.

$T_{WTG} = 1.5$ s	$T_{PV} = 1.8$ s
$T_{FC} = 0.26$ s	$T_{DLC} = 0.01$ s
$M = 0.4$ and $D = 0.03$	

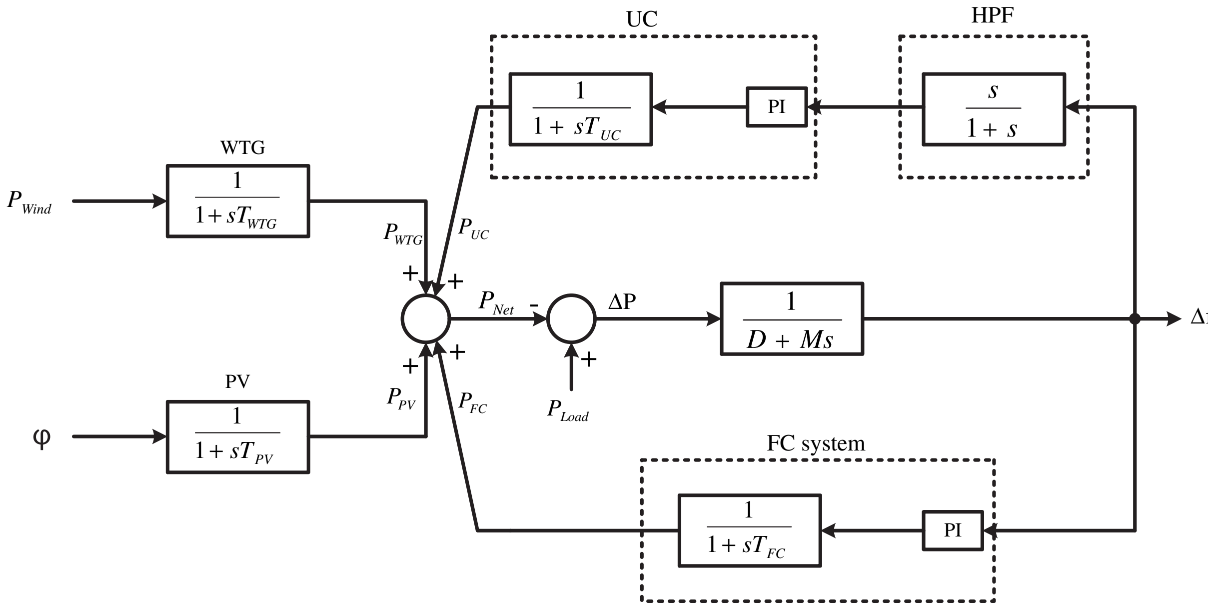


Fig. 4 Block diagram of proposed hybrid power generation/storage system and its control strategy.

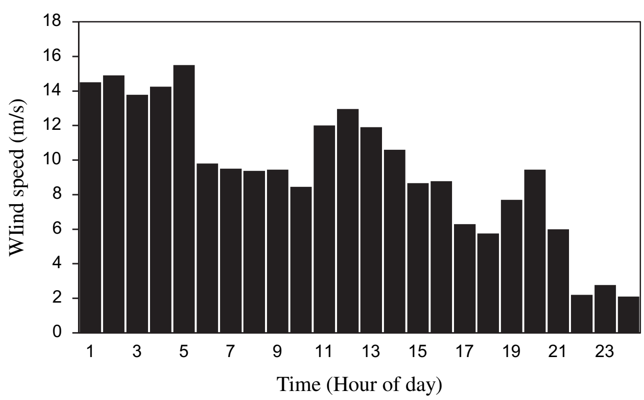


Fig. 5 Real wind speed data used for proposed system simulation.

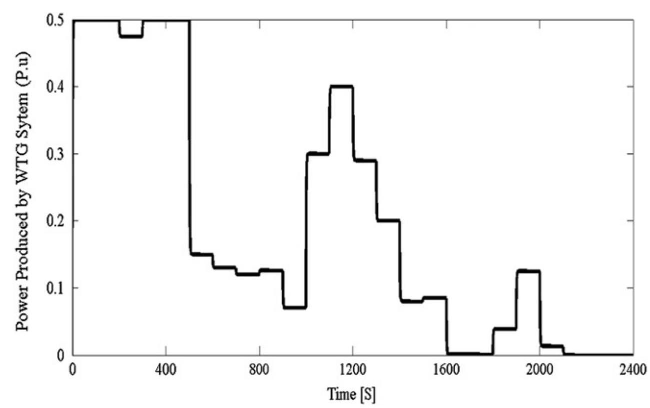


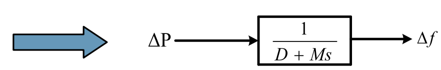
Fig. 7 Power produced by wind turbine generator.

The fluctuation in the frequency profile Δf is expressed by the equation

$$\Delta f = \frac{\Delta P}{K_{sys}} \tag{8}$$

where K_{sys} is called system frequency characteristic constant of the hybrid power system. The transfer function for system frequency variation to per unit power deviation can be expressed by

$$\frac{\Delta P}{\Delta f} = \frac{1}{D + sM} \tag{9}$$



where M and D are the equivalent inertia constant and damping constant of the hybrid power system, respectively [19].

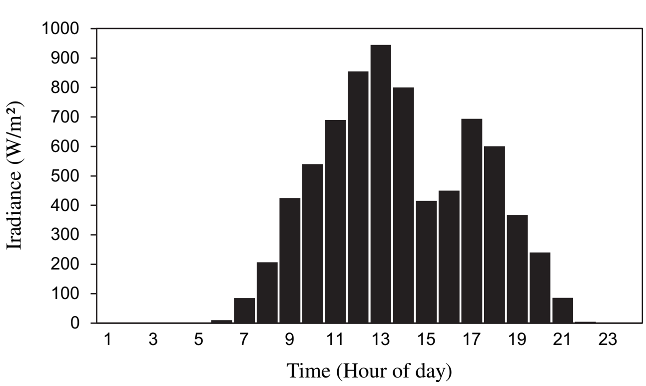


Fig. 6 Real irradiance data used for proposed system simulation.

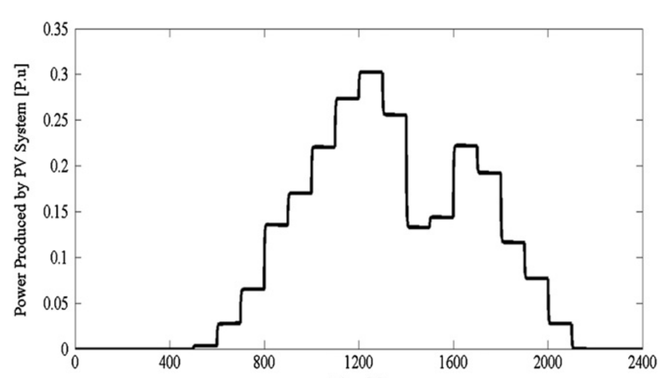


Fig. 8 PV power generated for whole day.

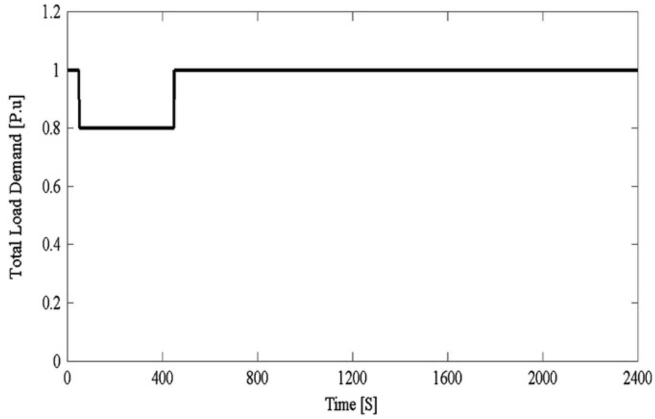


Fig. 9 Variation of load demand.

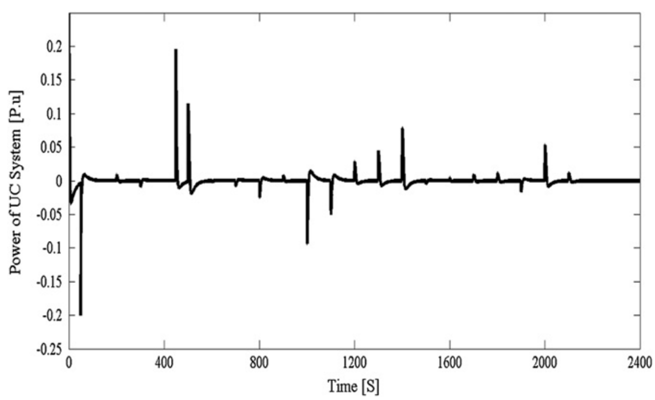


Fig. 10 DLC output power.

3. Proposed control strategy and modeling

Modeling and control strategy of proposed system are explained in this section. In the proposed system PV and WTG systems are used as main and primary power sources to produce power. But the power generated by integration of them highly depends on weather condition.

The power generated by WTG and PV are combined with FC to supply required power demand of connected load. The residual power of studied hybrid system due to slow dynamic of systems is properly satisfy by DLC system. The employed parameters for modeling of system are listed in Table 1. The net power generation is comprised by power of WTG, PV, FC and DLC system. The expression for P_{Net} given by

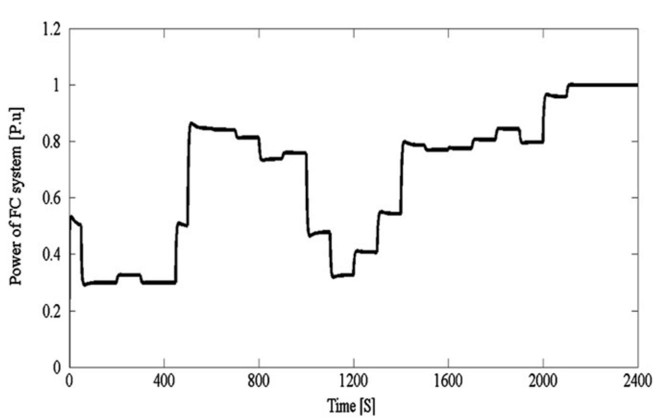


Fig. 11 Power supplied by the FC stack for whole day.

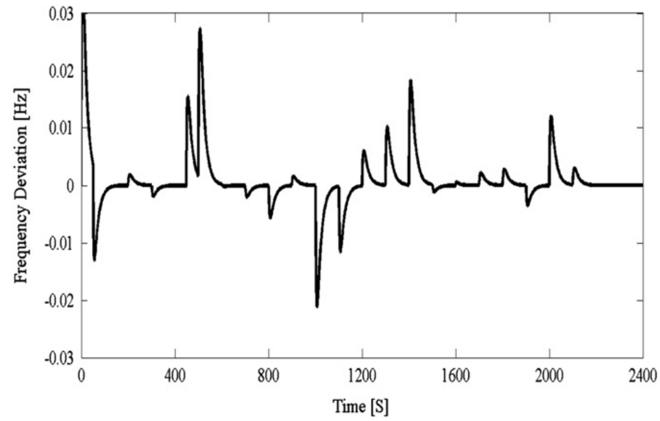


Fig. 12 Frequency deviation.

$$P_{Net} = P_{WTG} + P_{PV} + P_{FC} \pm P_{DLC} \tag{10}$$

To solve this problem the integration of DLC and FC system are used as back-up system. In the proposed system, a high-pass filter (HPF) is used to reduce charging and discharging of DLC bank in long-term. The frequency deviation of overall system divided in two parts with the aim of HPF. DLC bank compensates high frequency deviation due to its fast respond and FC system compensates low frequency deviation. The block diagram of proposed system is shown in Fig. 4.

4. Simulation results

The real wind speed and solar irradiation for the proposed method is shown in Fig. 5 and Fig. 6 respectively. Simulation results are shown in Figs. 7–12. Fig. 7 and Fig. 8 are the output power of WTG and PV systems. Steps load demands are applied to this system to show the effectiveness of proposed control strategy as shown in Fig. 9. Fig. 8 and Fig. 9 are the output power of FC and DLC systems.

The Fig. 12 shows that the frequency deviation can be control appropriately by coordination between FC and DLC to compensate the shortage and to complement whole hybrid power generation with considering the effects of system frequency variation.

5. Conclusion

This paper presented the frequency regulation of hybrid renewable power generation system by coordination control of WTG and the DLC system. In the proposed method, the load variation is reduced by FC in low frequency domain and the DLC bank in high frequency domain. By using the proposed method, the capacity of DLC can be reduced without charge and discharge in long-term. Simulation studies have been carried out to verify the system performance under different condition using the real weather data.

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