Journal of Practical Auditing and Accounting

J. Practical Audit. , 13: 29-35, 2022

Research Paper

A Power Management in an Isolated Micro Grid with Reduce Voltage Deviation of Ultra-Capacitor

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Abstract— This paper deals with the important task of voltage control of the ultra-capacitor (UC) in an isolated grid-off wind turbine (WT), photovoltaic (PV) and fuel cell (FC) islanding. Renewable and distributed energy resources have recently been introduced as alternative energy source due to pollution-free operation and no fossil fuel consumption. Among various alternative sources, PV, WT, and FC are more desirable than the others. The frequency control of an isolated network is not exact as enough. Therefore, to improve the frequency control, using an UC bank is proposed. In this paper improved droop control is utilized for the electric power sharing between PV, FC, and UC. The output power of WT is controlled based on wind speed to capture the maximum energy from wind. If the frequency of grid is going to decrease, then the UC will boost the active power rapidly, to keep the power balance. Meanwhile, the PV, WT, and finally FC will increase the power generation, if possible, to preserve the UC charge. If the load demand is decreasing and extra energy source from wind, day-light, and hydrogen flue is available, then the electric power sources supply the load and generate exceed power to charge the UC. Supposing that the load is very light and the FC produces minimum power and the UC is fully charged. In this case, if WT and/or PV continue maximum power extraction then the UC starts to over change and an over-voltage will occur on the dc terminal voltage of the UC which may damage the insulation (di-electric) of the capacitor units. Therefore, a voltage control on UC terminal is unavoidable.

Keywords— Frequency Control, Wind Turbine (IGWT), Solid Oxide Fuel cell (SOFC), Ultra-Capacitor (UC), Photovoltaic (PV), Isolated Network, Fuzzy Controller

I. INTRODUCTION:

Due to the world wide increase of energy consumption, reduce of fossil fuel and global warming, the usage of renewable energies has become more important. Among renewable power generators, photovoltaic (PV) power generations play an important role as clean electric power supplies. PV systems depend on climate situation and geographic position and such factors may cause problems such as frequency deviations and voltage fluctuations in power system grid operation [1].

For high power PV generators, it is necessary to provide frequency regulation service in power systems [2]. Subsequently, a suitable algorithm for frequency control, as a duty of PV, seems to be a good solution. Wind energy is widely found in the universe and due to not using fuel and no environment cost, it is known as clean energy [3]. If wind turbine (WT), PV and fuel cell (FC) hybrid together, the undesirable effect of the network could be reduced and there would be a clean power system apart from the usage of fossil fuel. Due to the type of electrolyte and the fuel that is used in FC power systems, they are made of different types. The type of solid oxide fuel cell (SOFC), which produces high power, is used in high-power grids [4]. Because of long time delay of FC, it is not able to quick compensation of the variation of the load and, so Ultra Capacitor (UC) would be responsible for the compensation of the load and FC power system [5-7]. Previous researches show that the existence of UC is impressive in load frequency control [8-11]. It should be considered that the terminal voltage of UC has to be in a suitable range, so in addition to frequency control, there should be the UC voltage control too, so that at situations which PV, induction generator wind turbine (IGWT) and FC are not capable of supply the load power demand, with regard to the suitable range of UC voltage, the extra power got captured from UC. In this paper, the frequency of hybrid PV, IGWT, FC and UC is controlled using an improved droop control method. Detailed model of renewable resources are used in this simulation. Different controllers are purposed in [12] and [13] for frequency control. Because of advantages of fuzzy controllers [14], a fuzzy controller is used in this paper for UC bank voltage control with appropriate strategy. Suitable charge and discharge voltage of UC bank in nominal rang for the hybrid system can have many benefits, including suitable frequency control, UC bank performance improvement, and increased fuel cell life expectancy. Simulation results show good performance of fuzzy controller of the hybrid isolated network.

II. SYSTEM CONFIGURATION

Fig. 1 shows the block diagram of the proposed hybrid isolated network which consists of an IGWT, FC, PV, UC and Load. In this system, PV and IGWT have priority to produce power and for the detail study of proposed hybrid isolated network, high order mathematic model is employed.

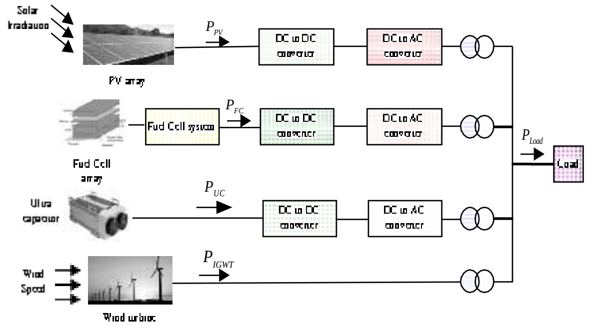

Fig.1.The block diagram of the proposed hybrid isolated network.

A. Wind Turbine Power System

Fig. 2 shows the diagram of an induction generator driven by a variable speed wind turbine. In this study, a squirrel-cage induction generator coupled with a variable speed WT is considered.

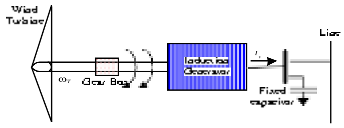

Fig. 2.The diagram of IGWT

1) *Induction generator model*

The mathematical model of the induction generator is described in ref [15]. Also the electrical output power of WT can be expressed in ref [16]. The power coefficient depends on wind speed, the rotational speed of the turbine, and the turbine blade parameters that can be expressed in ref [17].

B. Photovoltaic Power System

The simplified equivalent circuit of a PV cell involves series resistance R_S , light current I_L , saturation current resistance I_0 and a thermal voltage timing completion factor α Fig. 3 [18].

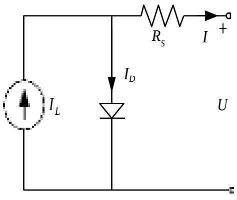

Fig. 3. Simplified-equivalent circuit PV

C. Fuel Cell Power System

A perfect model of SOFC described in [19] is used in this study. Fig. 4 shows the SOFC model which is used in combined with other element of power systems. The relationship between those parameters can be expressed as [19]. The power supplied by the SOFC is calculated as:

$$P_r = V_r\ I_r \qquad (1)$$

Where V_r and I_r are the output voltage and output current, respectively. Output voltage of FC which is calculated using the following equation is:

$$V_r = N_0\left[E_0 + \frac{R_0 T_0}{2F_0}\left(\ln \frac{PH_2\sqrt{PO_2}}{PH_2O}\right)\right] - rI_r \qquad (2)$$

Fuel utilization (U_f) is the ratio between the reacted and supplied hydrogen.

$$U_f = \frac{q_{H_2}^{T}}{q_{H_2}^{in}} \qquad (3)$$

Ratio between hydrogen and oxygen flow rate (RH_O) is defined as:

$$RH\_O = \frac{q_{H_2}^{in}}{q_{O_2}^{in}} \qquad (3\text{-}1)$$

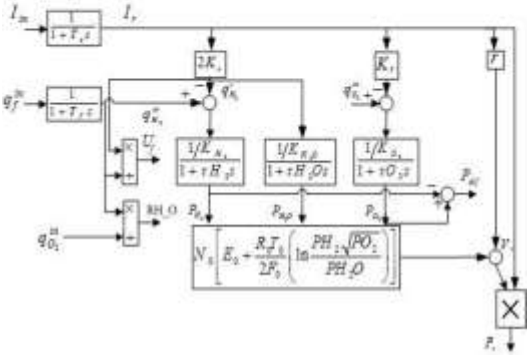

Fig.4. Dynamic model of SOFC

D. Ultra Capacitor Power System Model

The equivalent UC bank unit involves on equivalent series resistance (ESR) with the charging and discharging resistance, an equivalent parallel resistance (EPR) a capacitance and self-discharging losses following are the parameters used to mathematic model of the UC bank (Fig. 5) [20].

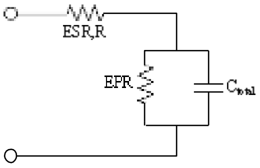

Fig.5. Equivalent circuit of UC.

The following expression can explain how much energy would drown from the ultra-capacitor bank unit [20]:

$$E_{UC} = \frac{1}{2}C\left(V_i^2 - V_f^2\right) \qquad (4)$$

Fundamentally, the UC bank unit has the duty of supplying a prearranged amount of energy. The terminal voltage of UC decreases when the UC bank unit release energy and when it absorbs energy, the terminal voltage increases. A number of UC units can be arranged to build a UC bank, which capable to provide the load demand [21].

III. POWER MANAGEMENT IN ISOLATED NETWORK

A suitable control strategy is used to control the frequency deviation and so obviously satisfy the load demand during 1800 (Sec.) using PV/IGWT/UC/FC hybrid isolated network. The duty of main controller is determining the reference power of each unit by gathering the voltage and current data of network lines. Solar energy and wind turbine are clean power, therefore, they have priority to satisfy load power demand and control the frequency deviation over that power produced from other generators. If the terminal voltage of UC be out of valid range of UC's factory datasheet, may it cause damage on UC. If the power produce from PV and IGWT be more than demand power, the extra power would be captured by UC. So, It's voltage will be increased. The terminal voltage of ultra-capacitor could be decreased with decrease the power produced from IGWT, PV and SOFC. At first, the power produced from SOFC will be regulated at minimum power reference and the power produced from IGWT and PV will be decreased based on the terminal voltage of UC. The power produced from IGWT and PV will so decreased that the terminal voltage of UC kept in the valid range. In another extreme case, if the terminal voltage of UC be less than a minimum valid voltage, the reference power of SOFC will be switched at maximum power and both of IGWT and PV will produced the related maximum power of themselves, until the terminal voltage of UC place at the valid range. In addition to supply the excess power demand, UC bank unit compensate the tracking mismatches and delays of IGWT, PV and SOFC which have slower response time than UC to control the load frequency deviation. Based on the factory datasheet of UC, the maximum terminal voltage of it set to be 550 volt and the minimum voltage of it set to be 75 volt to avoid damaging, over charging, deep charging and for appropriately operation of the dc-dc converter and inverter connected to the AC line, respectively.

A. Frequency Controller design

In this hybrid isolated network, power produced from IGWT, PV and SOFC with power of UC aggregate to satisfy the load demand. The total power P_{total} of all units can be written as;

$$P_{total} = P_{IGWT} + P_{PV} + P_{FC} \pm P_{UC} \tag{5}$$

The total power production has to be controlled and appropriately dispatched to assure the load power demand. The power balance can be expressed as:

$$\Delta P = P_{total} - P_{Load} \tag{6}$$

The frequency deviation Δf would be expressed as:

$$\Delta f = \frac{\Delta P}{K_{sys}} \tag{7}$$

Which K_{sys} is the system frequency characteristic constant of the isolated network. The transfer function of the system changes to per-unit deviation in power can be written as:

$$G_{sys} = \frac{\Delta f}{\Delta P} = \frac{1}{K\left(1+sT_{sys}\right)} = \frac{1}{D+Ms} \tag{8}$$

Where M and D are the equivalent inertia and damping constants of the hybrid isolated network, respectively [22].

B. Design of the improved droop controller

This part explains the control system that enables for parallel operated FC/PV/IGWT systems which operate independently to gain the active load sharing [23]. The droop control has been applied to control of the parallel FC/PV/IGWT to achieve the active load sharing between each system in proportion with the capacity of each unit. The droop characteristic of each unit is shown in Fig. 6. Proper load sharing between each unit could be achieved by suitably considering the droop coefficients m_{PV} and m_{FC} .

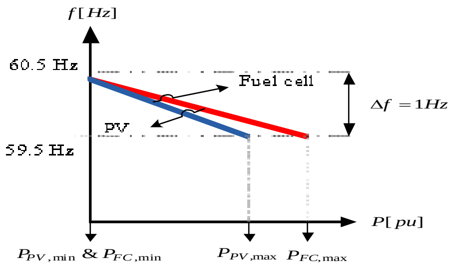

Fig. 6.The droop characteristics of each unit

The following improved droop control is designed to improve the transient response of the conventional droop [23]:

$$P_{FC} = \frac{1}{m_{FC}}(\Delta f) + k_{dFC}\frac{d(\Delta f)}{dt} \tag{9}$$

$$P_{PV} = \frac{1}{m_{PV}}(\Delta f) + k_{dPV}\frac{d(\Delta f)}{dt} \tag{10}$$

Where K_{dFC} and K_{dPV} are the gains of the derivative term. In Fig. 7, in order to depict the derivative behavior, the time constant of the filter, T_d is set to be small. The low-pass filters LPF$_1$ and 2 are installed to reduce the system noise. The slopes $(1/m_{PV})$, $(1/m_{FC})$ decide the reference output power of each system that are the base values. For the improved droop controller, the transitional outputs U_{PV_P} and U_{FC_P} of PV and FC are added to the base output of each system. The block diagram of the suggested system is shown in Fig. 7. Fig. 7 shows the detail structure of frequency control of the proposed hybrid power system.

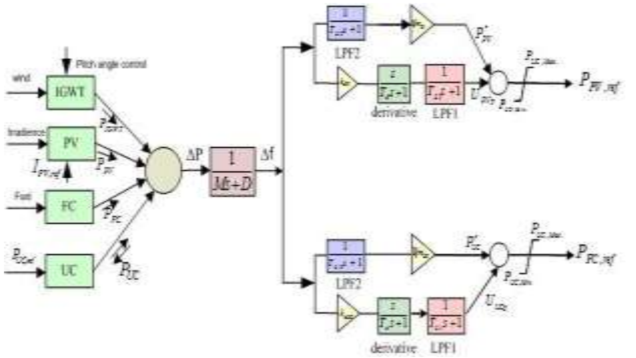

Fig.7.The configuration of improved droop control.

In this islanding mode, when the sum power produced of IGWT and PV is greater than the load demand, the active power flows to the UC bank unit. The UC's inverter operates in two modes at the same time: inverter mode ac, frequency deviation control and active-rectifier mode charging the UC bank unit. Obviously, in this case, the power generated from PV and IGWT is injected into the UC bank unit.

C. Fuzzy controller strategy

It's known that use different systems like (WT, PV, UC, FC), produce varieties power by PV and WT and load variations during a day leads to imbalances between production and consumption power; that all of them induce change in system frequency. So a suitable controller is needed for the aim of frequency stabilization. The fuzzy logic controller (FLC) is widely used due to its flexibility and needless to system mathematical equation. In this paper, FLC is used to exploit the maximum power of (WT, PV, UC, FC) with considering the UC voltage, after that, the frequency deviation control will be performed. In the first stage, the FLC controls UC voltage by producing reference current input to FC. In the second stage, pitch angle of wind turbine blades is controlled and in final stage, PV generated power is controlled. After that a relatively constant frequency is achieved.

1) UC Voltage Control

In this paper, UC is used in order to control the system frequency. Due to load variations in a day, UC voltage is charged and discharged. Therefore, the UC voltage is changed in a wide range. UC voltage control in nominal values causes UC to have its maximum performance. UC voltage control is performed by controlling the generated power in FC which infused to the system. A controller is put between UC and FC which its inputs are UC voltage and generated power of FC and the output is FC reference current. The first fuzzy controller includes some membership functions (MFs) in input and output. In Table 1 the rule bases are designed based on system condition and designer's experience to control the UC voltage. The MFs of input and output are shown in Fig 8. It is better to consider that all of input MFs for all controllers are the same.

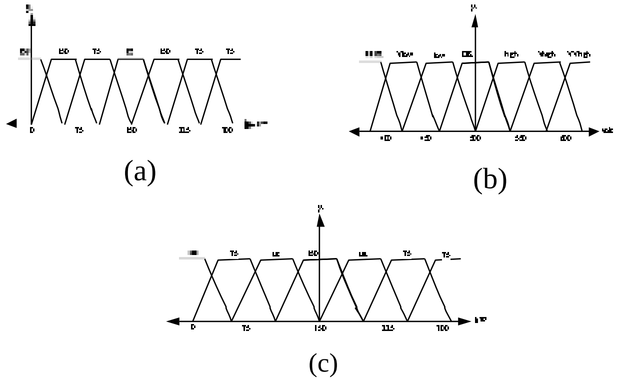

Fig.8. The MFs for first proposed fuzzy controller of (a) output power of FC (b) UC voltage (c) input current of FC.

TABLE 1
INPUT AND OUTPUT OF THE FIRST FUZZY CONTROLLER

FC power UC voltage	Ua	Ub	Uc	Ud	Ue	Uf	Ug
VVlow	ue	ue	ue	ue	ue	ue	ue
Vlow	ud	ud	ud	ud	ud	ud	ud
low	uc	uc	uc	uc	uc	uc	uc
OK	uc	uc	uc	uc	uc	uc	uc
high	uc	uc	uc	uc	uc	uc	uc
Vhigh	ub	ub	ub	ub	ub	ub	ub
VVhigh	ua	ua	ua	ua	ua	ua	ua

2) Wind Turbine Blades Pitch Angel Control

In normal conditions, maximum generated power of WT is utilized in the system where as sometimes control the wind turbine pitch angle is done in order to regulate UC voltage and frequency. Here, the second fuzzy controller includes some MFs in input and output (Fig 9). The input is UC voltage and output is setting pitch angel. Also the input MFs are the similar to previous section. Rule bases can be seen in Table 2.

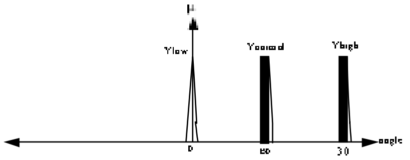

Fig.9. MFs for the output signal fuzzy controller

TABLE 2.
INPUT AND OUTPUT OF THE FUZZY CONTROLLER TWO

input	UC voltage	VV low	V low	low	OK	high	V high	VV high
output	pitch angel	Y low	Y normal	Y high	----	-----	-----	-----
rule base	If (input)	VV low	V low	low	OK	high	V high	VV high
	Then (output)	Y high	Y high	Y high	Y low	Y low	Y low	Y low

3) PV power control

In final stage, PV power is controlled. In this step, normal conditions give maximum PV power production. if the voltage of UC excesses the maximum permissible voltage, to prevent the over-voltage of UC, PV power has to decrease, which is performed by third fuzzy controller. Therefore, UC voltage will be remained in its nominal valid voltage range. In third fuzzy controller the UC voltage is input and the output is the reference power of PV. A rule base is written in Table 3. MFs of this section are shown in Fig 10.

TABLE 3.
INPUT AND OUTPUT OF THE THIRD FUZZY CONTROLLER

input	UC voltage	VV low	V low	low	OK	high	V high	VV high
output	decreases PV power	OK	Y	-----	-----	-----	-----	-----
rule base	If (input)	VV low	V low	low	OK	high	V high	VV high
	Then (output)	OK	OK	OK	Y	Y	Y	Y

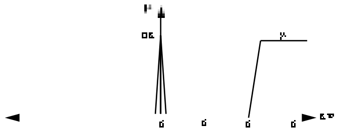

Fig.10. MFs for the output signal of fuzzy controller

Fig. 11 shows the detail structure of the main improved droop controller to decide the reference power of each unit.

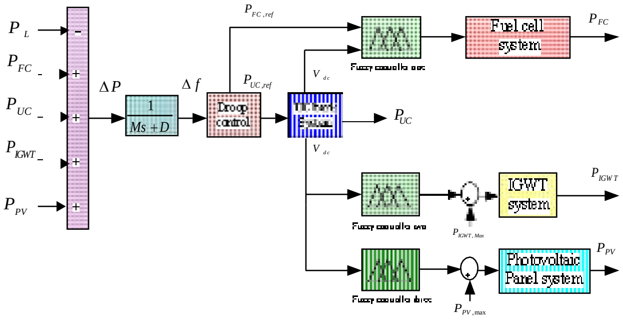

Fig. 11.The detail structure of main fuzzy controller

IV. SIMULATION RESULTS

In this study, the aim is to analyze the proposed frequency control method over a long period of time that includes day and night. The load power demand, solar radiation and IGWT profiles all used to test the performance of the proposed system. The solar radiation data is shown in Fig. 12.The wind speed during this simulation process is illustrated in Fig. 13

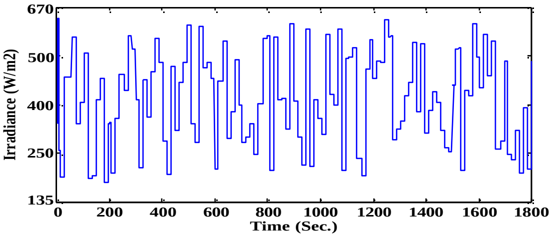

Fig.12. The irradiance of sun.

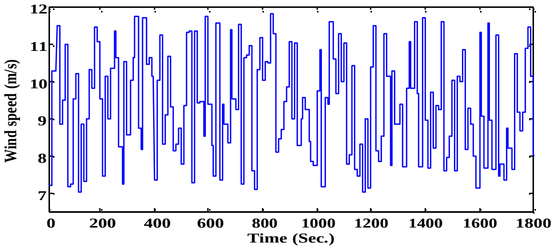

Fig.13. Wind speed curve.

The load demand power is shown in Fig. 14. In some situations, that the terminal voltage of UC units is more than $V_{UC,\max}$, the power that is drowned from IGWT and PV should be decreased. Fig. 15 and 16, shows the power generated from PV and IGWT with this control method and without that, respectively. The SOFC system power command is achieved according to the UC terminal voltage. The power produced by SOFC system is shown in Fig. 17. Because of cold start-up problems and slow response characteristic of SOFC, the minimum power generated of SOFC is 10% of nominal SOFC's power. Because of hysteresis control, the fast variations of SOFC's output power are not observed. Fig. 18 shows the power applied by UC bank units, which consists of the exceeded power of load demand and the tracking mismatch of frequency deviation. This figure shows the important task of UC in this hybrid power system for controlling the frequency deviation. The terminal voltage of UC bank corresponds to the charging and discharging power with the proposed method is shown in Fig. 19.

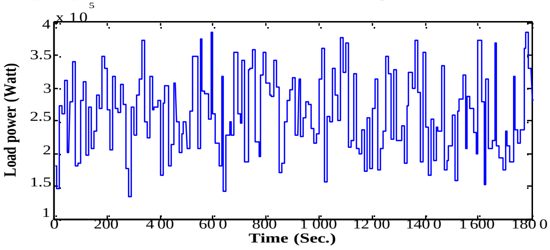

Fig. 14.The load power demand

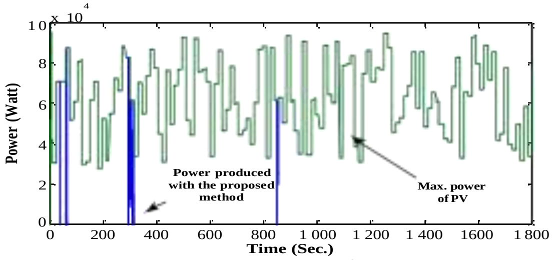

Fig.15. Output power of PV

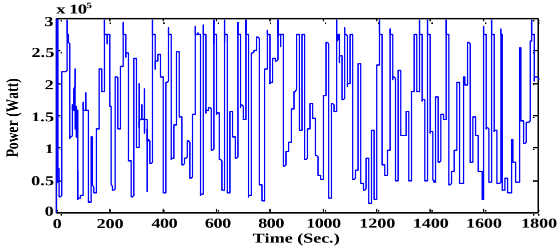

Fig.16. Output power of IGWT

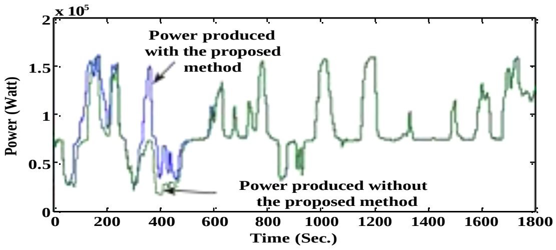

Fig.17. Output power of SOFC using the proposed method

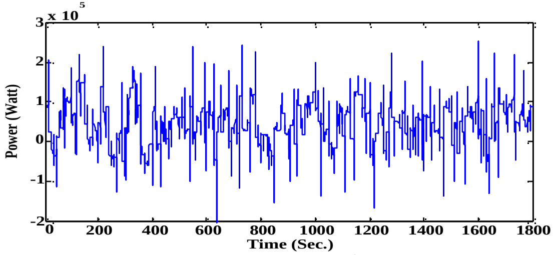

Fig. 18.The applied power of UC unit

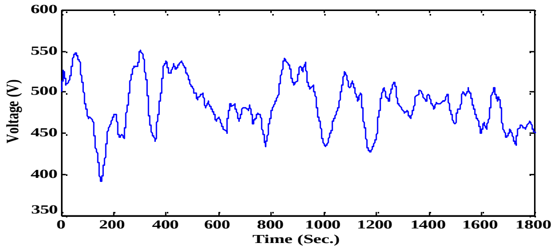

Fig. 19.The terminal voltage of UC unit.

The difference power between the demand power and power produced by IGWT/FC/PV/UC, causes the frequency deviation. Fig. 20 shows the power difference between load and generators. The frequency deviation is shown in Fig. 21 This figure shows that frequency deviation can be controlled by coordination between FC, PV and UC to compensate the shortage of load power demand. The appropriate range of frequency deviation shows the good performance of the improved droop control.

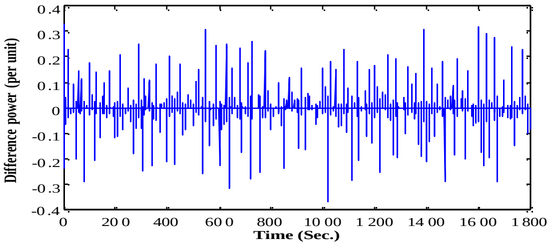

Fig. 20.The power difference between load and generators

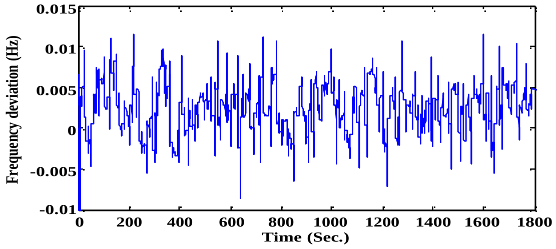

Fig. 21.The frequency deviation

V. CONCLUSIONS

In this paper, a PV/WT/FC/UC hybrid power system is designed and modeled for a stand-alone isolated network with well-designed fuzzy controllers. The available power from the PV and WT energy source is highly dependent on environmental conditions. To overcome this deficiency, we integrated PV and WT system with the FC/UC system using a new topology. A detailed simulation model has been developed which allows designing and analyzing any PV/WT/FC/UC hybrid system with various power levels and parameters. The dynamic behavior of the hybrid system is tested under variation of solar radiation, changed wind speed and load demand conditions. The proposed hybrid isolated network combined with the new fuzzy logic control algorithm reduces the FC system size while satisfying the peak power demand via the UC bank. The FLC by means of its control algorithm automatically performs UC voltage and frequency controlling.

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