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Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems

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ABSTRACT

In this paper a hybrid energy system combining variable speed wind turbine, solar photovoltaic and fuel cell generation systems is presented to supply continuous power to residential power applications as stand-alone loads. The wind and photovoltaic systems are used as main energy sources while the fuel cell is used as secondary or back-up energy source. Three individual dc–dc boost converters are used to control the power flow to the load. A simple and cost effective control with dc–dc converters is used for maximum power point tracking and hence maximum power extracting from the wind turbine and the solar photovoltaic systems. The hybrid system is sized to power a typical 2 kW/150 V dc load as telecommunication power plants or ac residential power applications in isolated islands continuously throughout the year.

The results show that even when the sun and wind are not available; the system is reliable and available and it can supply high-quality power to the load. The simulation results which proved the accuracy of the proposed controllers are given to demonstrate the availability of the proposed system in this paper. Also, a complete description of the management and control system is presented.

1. Introduction

Everybody will agree on the fact that future progress of mankind will be impossible without a very substantial and continuing energy supply. Energy is necessary for mankind and always will be. There is a huge correlation between lack of energy and poverty [1].

Recently, pollutions in the air are progressing with increasing the consumption of energy. The ever-increasing demand for conventional energy sources like coal, natural gas and crude oil is driving society towards the research and development of alternative energy sources. In 2000, the domestic greenhouse gas emission in Japan was 1332 million tons of CO2, which increased by 8% in comparison with that of 1990. If the Kyoto protocol to the united nations framework convention on climate change; the conference of parties III (COP3); held in December, 1997 comes into effect, Japan will be obliged to reduce CO2 by 6%, compared with 1990. As a result, Japan is required to reduce by 14% (172 million tons) on average during the period between 2008 and 2012. Particularly the emission in the residential/commercial sector in 2000 was on the increase by 21.3%, compared with that of 1990. More efforts of emission control for housing and buildings are demanded [2,3].

Many such renewable energy sources like wind turbine (WT) and solar photovoltaic (PV), which are clean and abundantly available in nature, are now well developed, cost effective and are being widely used, while some others like fuel cells (FC) are in their advanced developmental stage [4–6]. Wind energy is the fastest growing energy technology in terms of percentage of yearly growth of installed capacity per technology source. The growth of wind energy, however, is not evenly distributed around the world. By the end of 2001, the total operational wind power capacity worldwide was 23,270 MW. Of this, 70.3% was installed in Europe, followed by 19.1% in North America, 9.3% in Asia and the Pacific, 0.9% in the Middle East and Africa and 0.4% in South and Central America [7]. Today's wind turbines are state-of-the-art-of modern technology-modular and very quick to install [8,9]. The applications PV systems have become more widespread in both developed and developing countries. The world's primary energetic consumption is only 1/10,000 of the one available on the surface of sunny countries. If adequately exploited, solar energy may become sufficiently powerful, providing enough energy for future mankind [1]. PV is scaleable from very small to very large and easy to integrate with existing power converters [10–14]. PV and WT have become two of the most promising sources of energy due to the fact that their energy sources are free and sustainable. Besides this, these energy sources are preferred for being environmental friendly.

For different regions and locations, climatic conditions, including solar irradiance, wind speed, temperature, and so forth, are always changing daily and seasonally. Thus, there exist instability

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shortcomings for electric power production from PV modules and WT system. One of the major issues confronting users and designers of wind PV energy systems is the random, fluctuating nature of the energy sources. This makes them unpredictable or even unreliable in the eyes of some compared to traditional supplies of electric energy [15]. Although many researches deal with maximization of output energy, the fluctuation of power has not been considered sufficiently. Reduction of the fluctuation is often realized by using much capacity of expensive energy storage or installing a dump load.

The integration of renewable energy sources to form a hybrid system is an excellent option for distributed energy production. In order to efficiently and economically utilize renewable energy resources of wind and PV applications, some form of back up is almost universally required. Storage energy systems (SES) as battery banks or super capacitors are very important for solar–wind power generation systems [16]. Solar and wind energy are stored during sunny and windy days and released later during cloudy days or at night, and to smooth power demands, electric energy is stored during off peak periods and later used during peak periods [15]. Rechargeable and disposable batteries use a chemical reaction to produce energy. The problem is that after many charges and discharges the battery loses capacity to the point where the user has to discard it. In addition, the optimum match design sizing is very important for solar–wind power generation systems with battery banks. The sizing optimization method can help to guarantee the lowest investment with a reasonable and full use of the PV system, wind system and storage system, so that the system can work at the optimum conditions with optimal configurations in terms of investment and reliability requirement of the demand load for residential and commercial applications [16–22]. The telecommunication systems are considered one of the most critical loads in the application of new energy systems, and should have absolute reliability. Loss of load for such systems may contribute a great problem or loss of data. For such reasons a complex hybrid systems are used to assure the required degree of reliability.

Integrating PV and wind energy sources with fuel cells, as a storage device replacing the conventional huge lead-acid batteries or super storage capacitors, leads to a non-polluting reliable energy source and reduces the total maintenance costs. The fuel cell generation system offers many advantages over other generation systems: low pollution, high efficiency, diversity of fuels, reusability of exhaust heat and on site installation. Many such hybrid systems comprising of WT, PV and FC have been discussed in literature [23–28]. A hybrid photovoltaic fuel-cell generation system employing an electrolyzer for hydrogen generation and battery for storage purpose is designed and simulated in [25]. The simulation results of a hybrid system using an electrolyzer, fuel cell, renewable energy and diesel generator are given in [26]. However, in these systems storage devices or back-up energy source as diesel generators are still used. El-Shatter et al. proposed a stand alone hybrid wind–PV–fuel cell energy system. Two dc–dc buck boost converters are employed for maximum power point tracking (MPPT) and dc output voltage regulation for each subsystem of PV and WT. Also, four complex fuzzy logic controllers (FLC) are designed to adjust the duty cycles of the two buck boost converters to achieve MPPT and output voltage regulation for wind and PV systems [27]. Proportional integrator (PI) type controller, which controls the duty cycle of the dc–dc converters using PWM switching, is introduced by Das et al. [28].

This paper is aimed at combining WT, PV and FC generating systems to maximizing the output energy and reducing the output power fluctuations. The paper presents a hybrid WT coupled permanent magnet (PM) generator, solar PV and proton exchange membrane (PEM) FC generating system. The WT and PV are used as primary energy sources, while the FC is used as secondary or back-up energy source. The FC is added to the system for the purpose of ensuring continuous load power flow. Each system is combined with its individual dc–dc boost converter to control each of the three sources independently. Only, one dc–dc converter is used for each energy source. The controller of WT and PV has the function of maximum power point tracking (MPPT) control while the controller of FC has the function of load power fluctuation compensator. A simple control method tracks the MPP of the WT is proposed without measuring the wind speed, which is very useful for actual small size wind turbines. The same control principle is applied to track MPP of the PV system without sensing the irradiance level and temperature. The FC is thus controlled to provide the deficit power when the primary combined PV and WT energy sources cannot meet the net load power demand. In the complete absence of power from the WT and PV sources, the FC will operate at its rated power capacity.

A simple MPPT controller is employed to achieve MPPT for both PV and wind energies and to deliver this maximum power to a fixed dc voltage bus. The fixed voltage bus supplies the dc load, while the ac loads are fed through a PWM inverter. The dc voltage bus can be regulated using a PWM voltage source inverter. The excess generated power can feed a water electrolyzer used to generate hydrogen for supplying the fuel cell. The dc power required for hydrogen generation can be supplied directly through the dc bus during surplus PV and wind power. The generated hydrogen can be stored in tanks to be utilized by the fuel cells when the PV and wind energy sources fail to supply the load demand. The water electrolyzer is not considered in this paper and the three dc–dc controllers are designed to manage the power flow between the system components in order to satisfy the load requirements at any conditions. The study defines the power generated by the wind and PV systems and the power generated by the fuel cells to supply the deficiency in the load demand. Simulation results proved the accuracy of the proposed system.

The results given in this paper prove the concept of individual control of the three energy sources. The effective control of PV output voltage to track its MPP, the control of the rectified voltage of PM generator to track the MPP of WT and the voltage control of FC to generate the deficit power to guarantee the continuous power flow has been accurately and efficiently achieved. Finally, constant load power has been obtained and the system is capable of providing a minimum power equals to the FC rating capacity even under worst environmental conditions, when there is no power output from WT and PV sources.

2. Hybrid energy system configuration

It is possible to achieve much higher generating capacity factors by combining solar photovoltaic and wind turbine generators with a storage technology to overcome the fluctuations in plant output. An efficient energy storage system is required, to get constant power and the electrical energy delivered by the wind turbine and photovoltaic has to be converted into capacitor or battery energy, which is easy to store. However, in such systems although the power fluctuations can be eliminated and the hybrid system operating well, continuous power flow to stand alone loads cannot be guaranteed due to the lack energy capacity of storage systems specially under worst climatic conditions, when the generated power from the hybrid system are completely absent or in the case of insufficient output power. The fuel cell as a promising alternative can be used as back up energy source for the hybrid generation systems.

The system studied in this paper comprises of a 1 kW wind turbine generator, 1 kW solar photovoltaic and 1.25 kW fuel cell stack. Individual dc–dc boost converter is used to control each of the three sources. The individual dc–dc converters in turn connected in parallel. All the energy sources are modeled using PSIM® software tool to analyze their dynamic behavior [29]. The complete hybrid system is simulated for different operating conditions of the energy source. The simulation results prove the operating principle, feasibility and reliability of this proposed system.

Fig. 1 illustrates the proposed hybrid energy system configuration composed of a PV, WT coupled to a PM generator with a three-phase diode bridge rectifier as primary energy sources and FC stack as back up energy source. All the three energy systems are connected in parallel to a common dc bus line through three individual dc–dc boost converters. The diodes D1, D2 and D3 play an important role in the system. The diodes allow only unidirectional current flow from the sources to the dc bus line, thus keeping each source from acting as a load on each other. Therefore in the event of malfunctioning of any of the sources, the respective diode will automatically disconnect that source from the overall system. The dc bus line output voltage from all converters is set to be fixed and the output voltage from each source is controlled independently.

2.1. Solar photovoltaic

Solar photovoltaic generation system are becoming increasingly important as renewable energy source since it offers many advantages such as incurring no fuel costs, not being polluting, requiring little maintenance, and emitting no noise, among others. The building block of PV arrays is the solar cell, which is basically a p–n semiconductor junction. The current–voltage (I–V) characteristic of a solar photovoltaic is given by Eq. (1) [11–14,21].

$$I_{PV} = n_p I_{SC} - n_p I_O \left\{ \exp\left[\frac{q(V_{PV} + R_s I_{PV})}{AkTn_s} \right] - 1 \right\} - n_p \frac{(V_{PV} + R_s I_{PV})}{n_s R_{sh}} \quad (1)$$

where V_{PV} and I_{PV} represent the output voltage and current of the solar cell, respectively; R_s and R_{sh} are the series and shunt resistance of the cell; q is the electron charge ($1.6e^{-19}$ C); I_{SC} is the light-generated current; I_O is the reverse saturation current; A is a dimensionless junction material factor; k is the Boltzmann constant ($1.38e^{-23}$ J/K); T is the temperature (K); n_p and n_s are the number of cells connected in parallel and in series, respectively.

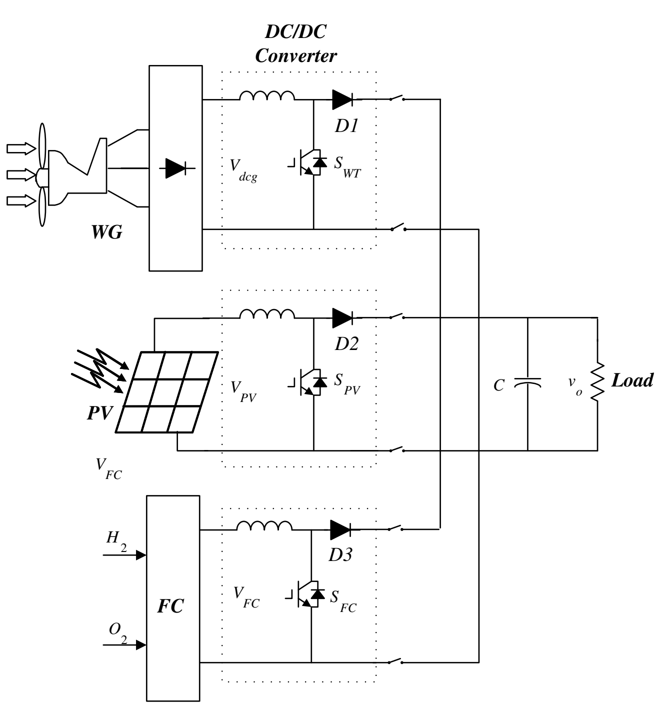


Fig. 1. Proposed hybrid generation system.

Eq. (1) was used in the simulations to obtain the output characteristics of a solar array as that shown in the experimental measurements of Fig. 2. The I–V and P–V curves clearly show that the output characteristics of a solar PV are non-linear and are crucially influenced by the solar radiation, temperature and load condition. Each curve has a MPP, at which the solar array operates most efficiently. The energy conversion efficiency of the PV systems is low and its initial installation cost is high, therefore, it must be ensured that it operates at all time to provide maximum power output. The power output P_{PV} of the PV is given by

$$P_{PV} = I_{PV} V_{PV} \quad (2)$$

Several techniques for tracking MPP of PV systems have been proposed as the hill climbing, P&O, IncCond and adaptive hysterisis-band algorithms [11–14]. In this paper the voltage-based MPPT technique have been used to track the MPPT of the PV array used [21].

2.2. Wind turbine generator

The fundamental equation governing the mechanical power capture of the wind turbine rotor blades, which drives the electrical PM generator, is given by [9,21]

$$P = \frac{1}{2}\rho A C_p V^3 \quad (3)$$

where ρ is the air density (kg/m^3), A is the area swept by the rotor blades, V is the air velocity (m/s), C_p represents the power coefficient of the wind turbine. Therefore, if the air density, swept area and wind speed are assumed constant the output power of the wind turbine will be a function of the power coefficient. The wind turbine is normally characterized by its C_p–TSR characteristic, where the TSR is the tip-speed ratio and is given by

$$\mathrm{TSR} = \frac{\omega_m R}{V} \quad (4)$$

In Eq. (4), R and ω_m are the turbine radius and the mechanical angular speed, respectively and V is the wind speed. The power coefficient has its maximum value at the optimal value of the tip-speed ratio ($\mathrm{TSR_{opt}}$) which results in optimum efficiency of the wind turbine and capture of maximum available wind power by the turbine.

In this paper the MPPT of WT is achieved by controlling the voltage at the output of a diode bridge rectifier attached to the PM generator, while allowing a constant dc bus line voltage. In low wind speed conditions, the voltage may be lowered to prevent the dc link from reverse biasing the diode rectifier. Under high wind speed conditions, the voltage may be increased, reducing losses. In addition, adjusting the voltage on the dc rectifier will change the generator terminal voltage and thereby provide control over the current flowing out of the generator. Since the current is proportional to torque, the dc–dc converter will provide control over the speed of the turbine. Control of the dc–dc converter may be achieved by means of a predetermined relationship between turbine rotational speed and the diode rectifier voltage. Detailed analysis of this technique can be found in [21].

2.3. Fuel cell system

The fuel cell is an electrochemical device that generates electricity by a chemical reaction that does not alter the electrodes and the electrolyte materials. Thus, the fuel cell is a static device that converts the chemical energy of fuel directly into electric

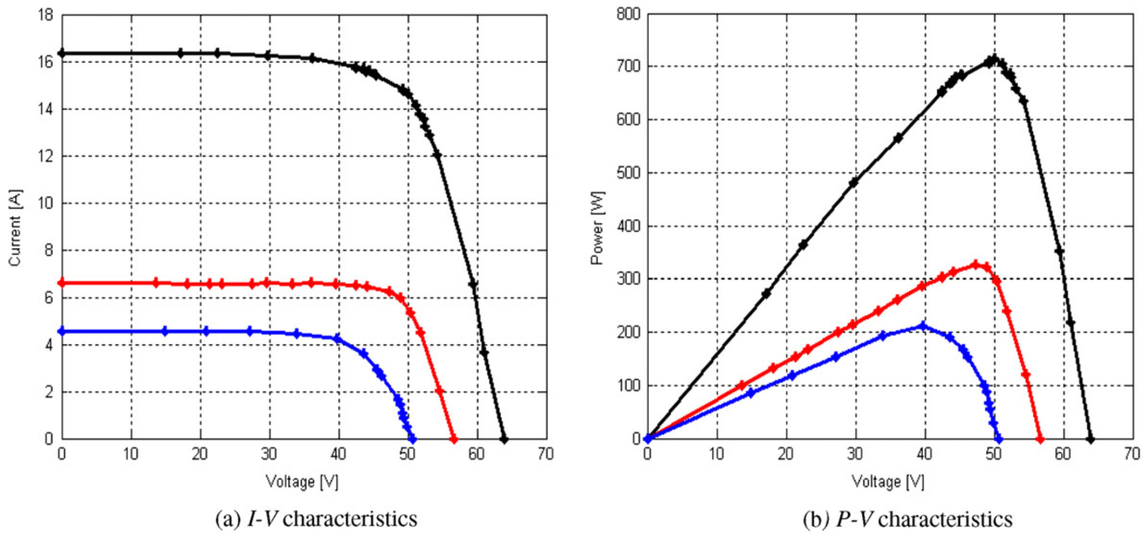


Fig. 2. Measured characteristics of PV array.

energy. Water and heat are only the byproducts of the fuel cell if the fuel is pure hydrogen. The superior reliability, with no moving parts, is the additional benefit of the fuel cell as compared to the diesel generator. A typical FC consists of an electrolyte and two catalyst coated electrodes. The electrodes are a porous cathode and anode located on either side of the electrolytic layer. Gaseous fuel; usually hydrogen; is fed continuously to the anode and oxidant; oxygen from air; is fed to the cathode. When hydrogen is passed across anode, and a catalyst, it is possible to separate hydrogen into protons and electrons. The electrons will pass through an external circuit as a current while the protons will go through the electrolyte. The electrons come back from the external circuit and combine with protons and oxygen to produce water and heat. It can say that the hydrogen fuel is combined with oxygen to produce electricity.

Proton exchange membrane fuel cell (PEMFC) is the most promising fuel cell for small-scale applications. The PEM uses a polymer membrane as its electrolyte [30,31]. In the proposed system, air is used as the oxidant and hydrogen from a hydrogen tank as a fuel; the cell pressure is atmospheric and the cell temperature is 70 °C. PEMFCs are gaining importance in many applications as distribution systems because of their low operating temperature, higher power density, specific power, longevity, efficiency, relatively high durability and the ability to rapidly adjust to changes in power demand. Furthermore, PEM fuel cells have the advantage that they can be placed at any site in a distribution system, without geographic limitations, to achieve the best performance. However, a PEMFC requires pure hydrogen as the fuel, thus complicating the design of the reformer system. Platinum metal is required to coat the electrodes to enhance the reactions. Because of the higher cost of platinum, the PEM system is relatively expensive. Any other type of FC as high-temperature solid oxide (SO) fuel cells can alternatively be used in the proposed system. The net reaction in a typical FC is given by

$$H_2 + 1/2O_2 \rightarrow H_2O \tag{5}$$

The output voltage of the fuel cell [31] is given by

$$V_{cell} = E - \Delta V_{act} - \Delta V_{ohm} - \Delta V_{trans} \tag{6}$$

where E is the open circuit voltage, ΔV_{act} is the voltage drop due to the activation of the anode and cathode, ΔV_{ohm} is the ohmic voltage drop resulting from the resistance of the electrodes and the resistance of the electrolyte, ΔV_{trans} is the voltage drop resulting from the reduction of concentration of reactants gases. Detailed description of fuel cell modeling and polarization characteristics can be found in [31]. Assuming that each cell has equivalent output voltage, the current for the complete stack can be found using the following overall equation for the electrical terminals:

$$V_{FC} = N_{cell}\left[E - \ln\left(\frac{I_{FC} + A_{cell}i_n}{A_{cell}i_o}\right) - r\left(\frac{I_{FC}}{A_{cell}}\right) - m\exp\left(n\frac{I_{FC}}{A_{cell}}\right)\right] \tag{7}$$

where N_{cell} is the number of cells connected in series, A_{cell} is the electrode area. The V–I and P–I characteristics of the fuel system under study are shown in Fig. 3 [31]. The total power contribution to the system from the fuel cell stack can be given as

$$P_{FC} = N_{cell} \cdot V_{cell} \cdot I_{FC} \tag{8}$$

3. System control

As shown in Fig. 1, the dc–dc boost converter divides the system voltage into two levels, variable voltage at the output terminal of the energy source V_i and fixed dc voltage at the dc bus line (load terminal) V_o.

The state equations of the dc–dc boost converter can be given by (9), where S is the switch state that takes the value 1 or 0, V_i is the input voltage to the dc–dc converter (output from each energy source) and V_o is the dc link output voltage.

$$\begin{bmatrix} \frac{dV_o}{dt} \\ \frac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1-S}{C} & \frac{-1}{RC} \\ 0 & \frac{1-S}{L} \end{bmatrix} \begin{bmatrix} V_o \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} V_i \tag{9}$$

In PV and WT systems, the terminal voltage is controlled based on the voltage error signal. For the PV system, the PV voltage and current are sensed to determine the reference voltage at which MPP occurs. The error signal which is the difference between the reference voltage and the actual voltage of the PV is fed to the voltage controller to control the duty cycle of the PV boost converter. For the WT the error signal is the difference between the reference rectified voltage of the PMG for MPPT and measured rectified voltage. This error signal is fed to the voltage controller, which controls the duty cycle of the WT boost converter.

The total supply generated power must be controlled so as to meet the required load demand since the output power of photovoltaic and wind turbine generators fluctuate with irradiation and wind speed. The FC output power is controlled based on the difference power command ΔP, which is the load power (command

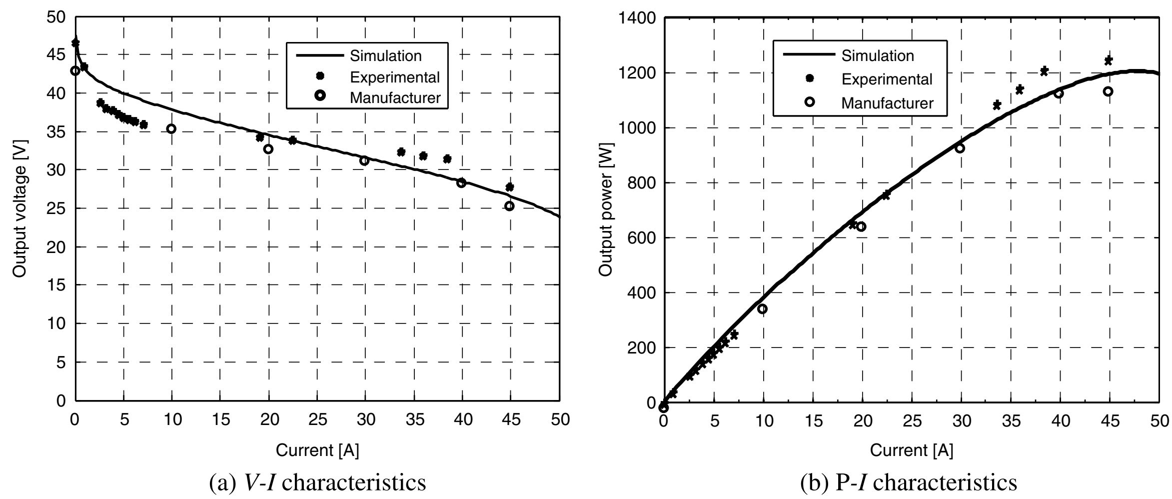


Fig. 3. Voltage–current and net output power characteristics of FC stack.

value) P_s minus the summation of the power generated from the PV and WT P_{PV} and P_{WT}, respectively,

$$P_{FC} = \Delta P = P_S - P_{PV} - P_{WT} \tag{10}$$

The FC terminal voltage is calculated according the desired FC power using a look-up table containing the experimental results of Fig. 3. The input of this look-up table is the difference power command ΔP, which means the FC reference or required power. Fig. 4 shows the configuration of the control topology of the three individual dc–dc converters. Since this system cannot allow reverse power flow, because of the configuration of dc boost converter, many generating units can be connected in parallel.

4. Simulation results

To prove the performance of the proposed hybrid system with its individual controllers, the complete system is simulated using PSIM® software [29]. All the three energy sources are accurately and effectively controlled. The size of the system components are estimated as shown in the following data:

The PV array is ELR615 160Z, 750 W, Fuji Electric solar panel consists of 15 modules three connected in series and five connected in parallel to produce maximum power of 0.75 kW at irradiation conditions of 1.0 kW/m^2. The wind turbine is a Wind Seeker 503 series coupled to PM generator and has a rated output of 1.0 kW at wind speed of 16 m/s. A PEM Nexa Ballard 310-0027

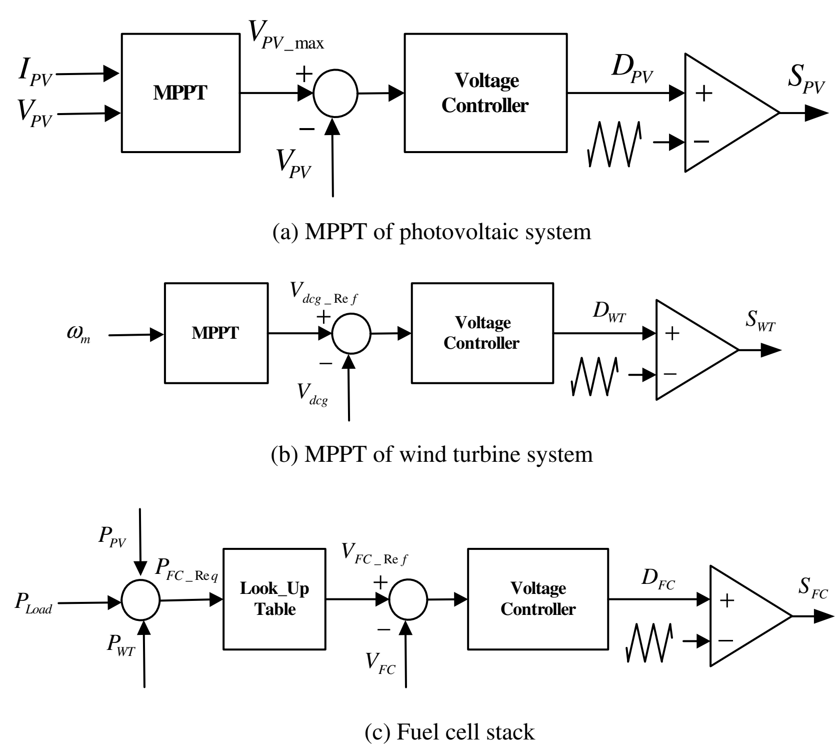


Fig. 4. Control principles of dc–dc boost converters.

power module fuel cell stack consists of 50 cells connected in series to produce rated output power of 1.25 kW. The hybrid system is sized to power a typical 2 kW/150 V dc telecommunication load or an ac residential power application continuously through the year in remote locations or isolated islands. The load is simulated as a constant resistive load connected to a fixed dc bus line voltage, since it can simulate the ac load with its connected inverter as a current source at a high power factor.

Fig. 5 shows the variation of the power output of the three energy sources and the total generated power. Fig. 5a shows the PV system is assumed to be 0.5 kW initially and then increases to 0.75 kW due to a sudden increase of irradiance level from 0.7 to 1.0 kW/m^2 at 0.5 s. Fig. 5b indicates that the WT output is generating 1.0 kW initially and then decreases to 0.5 kW due to a sudden decrease in wind speed from 15.6 to 2.5 m/s at 0.2 s. It is clear in both cases of Fig. 5a and b that the curves of maximum available PV and wind power coincide with the generated output power, which proves that the controller forces the system to extract the maximum power and deliver it as useful electric energy to the dc-link bus. Detailed description of the proposed controller of the PV and WT systems is found in [21].

The reference power command of FC is determined as the difference between the load power 2.0 kW and the generated power of PV and WT. This reference power serves as an input to a look-up table which calculates the reference voltage of the boost converter connecting the FC to the dc bus line voltage. The output

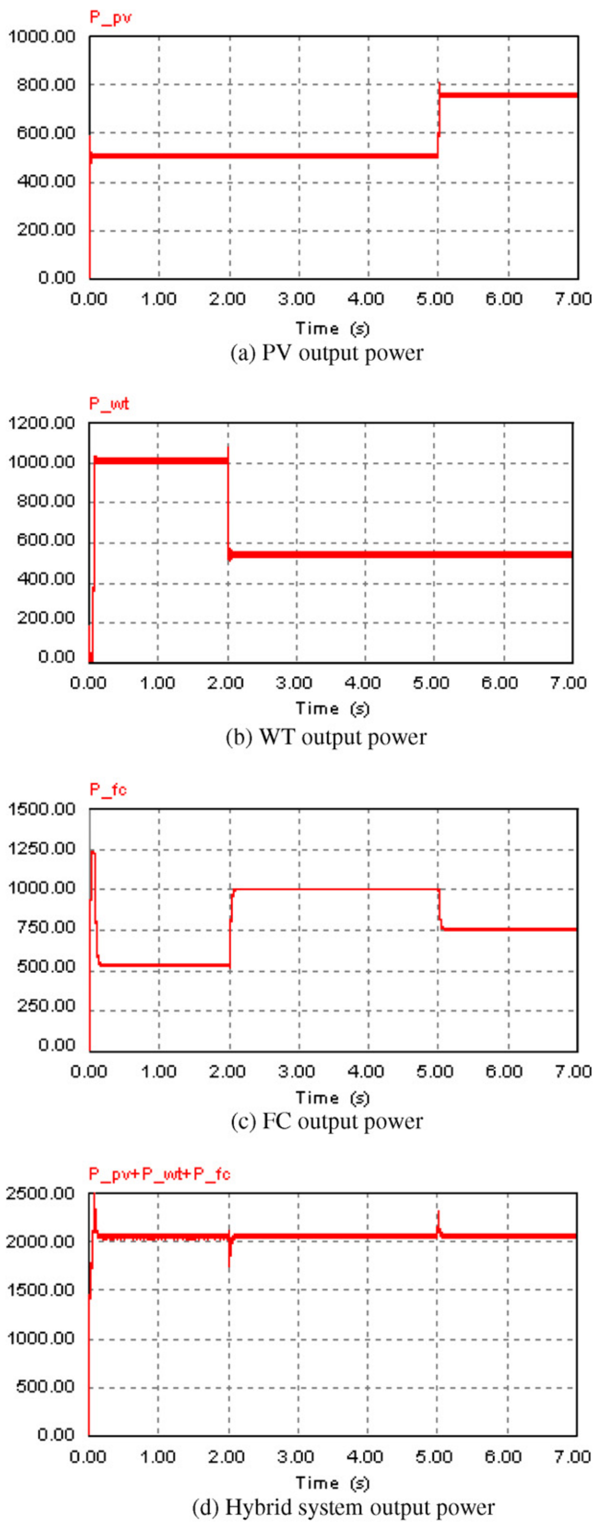


Fig. 5. Generated power by PV, WT and FC and total output power.

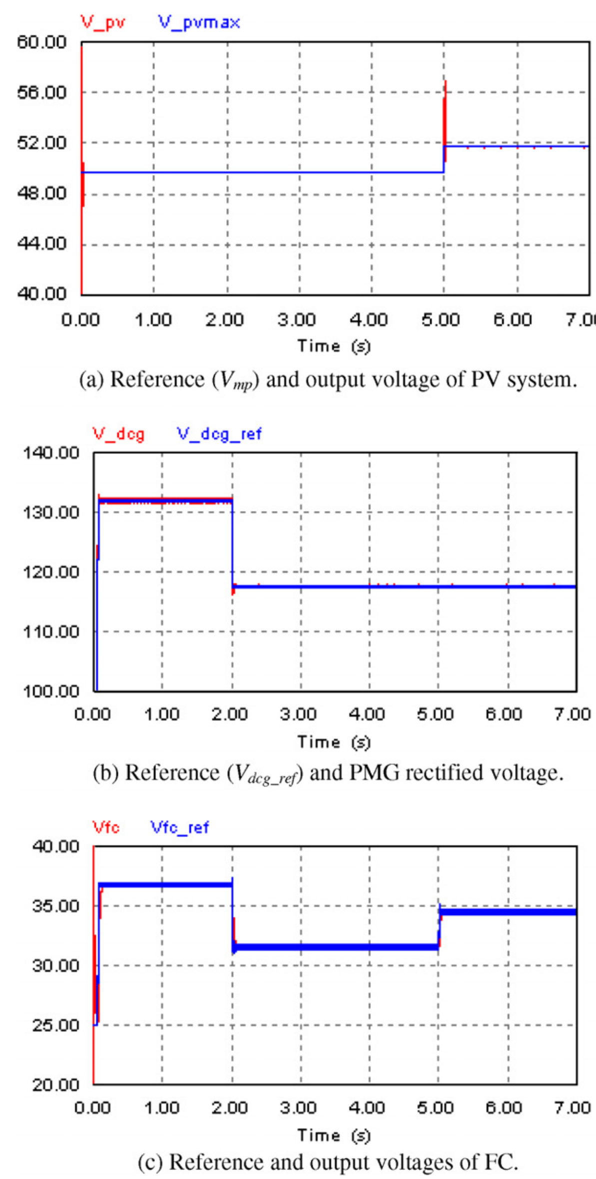


Fig. 6. Control of PV, WT and FC systems.

power of the FC system is shown in Fig. 5c, which varies with the changes in the PV and WT output power. The FC output power changes from 0.5 kW to 1.0 kW and then to 0.75 kW at a time of 0.2 and 0.5 s, respectively. Fig. 5d indicates the total generated power of the hybrid system. From Fig. 5d, it is clear to note that the hybrid system output power is always maintained constant at the load power demand in spite of the fluctuations in the PV and WT output power.

The dynamic response of the proposed system and the presented results are coincided well with the expected performance and it is completely agreed with the response and the results of the previously reported and related research [28].

Fig. 6 proves the concept of individual control of dc–dc converters of the three sources. From Fig. 6a, it is clear that the PV output voltage follows well the reference voltage of the maximum power point to extract the maximum power of the PV system. Fig. 6b shows the effective control of the PM generator rectified voltage follows the reference value to track the maximum power of WT. Detailed results of both PV and WT systems as the controller duty cycles for MPPT and output voltages can be found in [21]. Finally, Fig. 6c shows the out voltage control of the FC, which coincides well with the reference voltage from the controller (FC required power), to generate the deficit power between the load demand and the generated power from the PV and WT systems.

After examining the performance of the proposed hybrid system with a step change in the PV and WT output powers and in order to evaluate the dynamic performance of the system under investigation, another case study is simulated for continuous variations of the PV and WT output power. The results of simulations of the dynamic performance are presented. Figs. 7 and 8 present the results of the simulations carried out using PSIM®. Fig. 7a plots the variation in PV output power as the insulation changes rapidly and continuously. Fig. 7b shows the output power variation of WT as the wind speed changes rapidly and continuously. Detailed change in the insulation and wind speed changes are listed in [21]. Summation of PV and WT outputs is shown in Fig. 7c. Fig. 7d illustrates the difference power command and the FC output power, it can be clear to note that the FC is efficiently controlled to response instantaneously for sudden and continuous changes in the difference power command. Fig. 7e and f shows the load

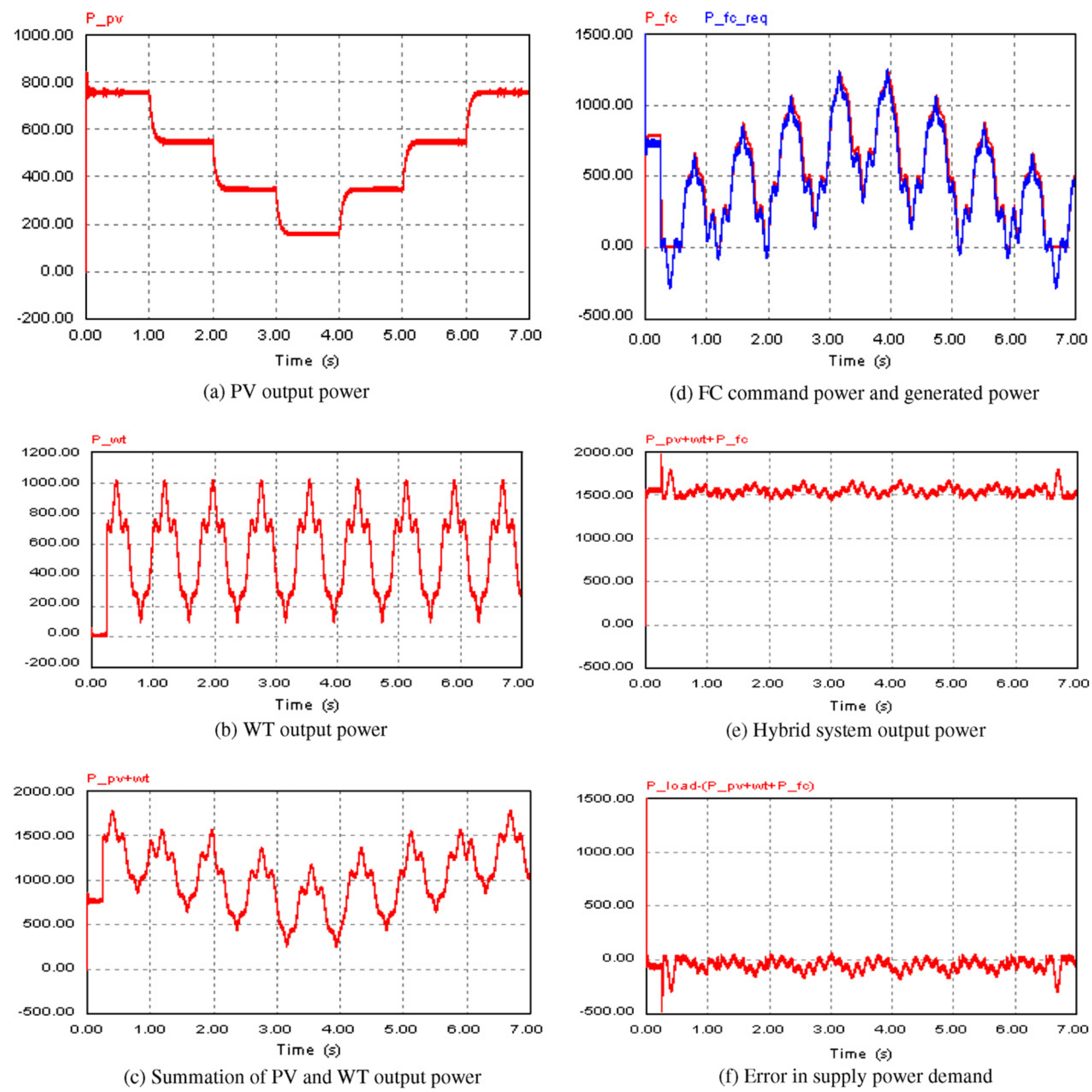
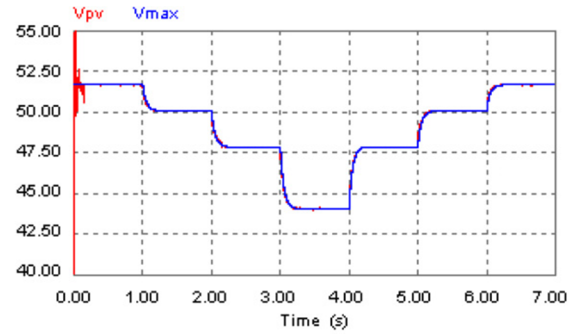
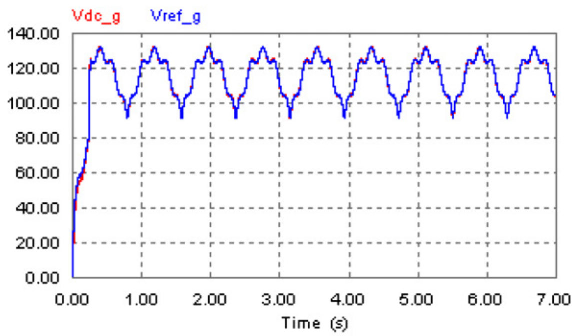


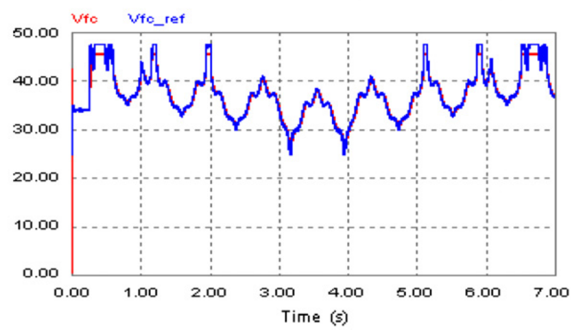
Fig. 7. Generated power by PV, WT and FC and total output power.



(a) Reference (V_{mp}) and output voltage of PV system



(b) Reference (V_{dcg_ref}) and PMG rectified voltage



(c) Reference and output voltages of FC

Fig. 8. Control of PV, WT and FC systems.

power and the deviation between the load power and the hybrid system generated power, respectively. Observing these figures, the load power level remains reasonably constant around 1500 W (power command) and the error in supply demand power is almost zero. These simulation results indicate that the proposed hybrid generation system can supply almost high-quality power to the load when the output power of the PV and WT changes suddenly and rapidly.

Fig. 8 shows the efficient control of the three dc–dc converters to control the reference output voltage of the three systems to track its reference value even under sudden and continuous change in the irradiance level and wind speed.

Fig. 9 illustrates the changes in output voltage, stack current and airflow that accompany a step change in load for Nexa Barrad FC. At idle, the oxidant airflow rate closely tracks the requested flow. After a load step to full power, the air pump rapidly speeds up. There is a brief (about 0.5 s) undershoot (2.5 V) in stack voltage during this transient, before the output voltage stabilises at 26 V. Stack current also increases slightly during this transient interval, due to increased parasitic power draw from the air compressor. A similar transient interval occurs after a load step from full power to idle. Airflow is gradually reduced, due to inertia in the air pump.

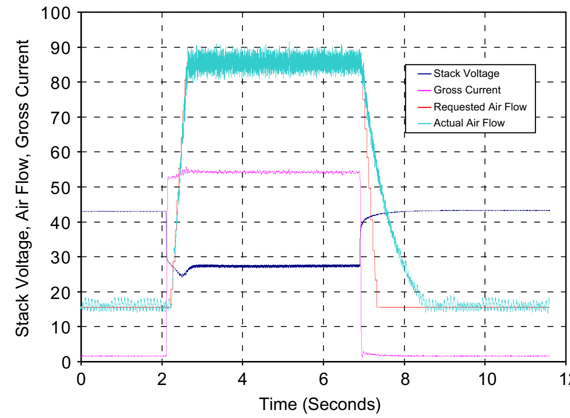


Fig. 9. Nexa Barrad PEMFC transient response characteristics.

Output voltage gradually recovers and stabilises to 43 V over a 0.5 s interval. Therefore, the Nexa Ballard FC has a fast dynamic response; it takes only 0.5 s to accelerate from no load to its rated output power. Also, it can reduce its output from rated power to idle at 0.5 s. Therefore, it is able to suppress most of the fluctuations in the output power of PV and WT hybrid system up to 2 Hz. High frequency fluctuations can be suppressed using storage devices as electrolytic double layer capacitor (EDLC), which is the subject of future work. Such device is necessary to suppress the high frequency fluctuations for very critical loads and to absorb the excessive generated power. Therefore, the system can supply very high-quality power to load demand.

5. Conclusions

The output power of wind turbine and solar photovoltaic generators mostly fluctuates and has an effect on system frequency. One of the existing methods to solve these issues is to install batteries which absorb power from wind turbine generators. The other method is to install dump loads which dissipates fluctuating power. However, such methods are costly and not effective and cannot guarantee continuous power flow to the load. Therefore, this paper presents a solar photovoltaic, wind turbine and fuel cell hybrid generation system to supply a continuous output power. The fuel cell is used to suppress the fluctuations of the photovoltaic and wind turbine output power. The photovoltaic and wind turbines are controlled to track the maximum power point at all operating conditions. The fuel cell is controlled to supply the deficit power between the load power demand and the generated power of the combined photovoltaic and wind turbine sources. Therefore, the proposed hybrid generation system can supply high-quality power.

The proposed system has been simulated using PSIM® software with two case studies. The simulation results are coincided well with the theoretically expected results and the results of the previously reported and related research, which prove the operating principle, feasibility and reliability of the proposed system.

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References

[1] Rubbia Carlo. Today the world of tomorrow—the energy challenge. J Energy Convers Manage 2006;47(17):2695–7.
[2] Hamada Y, Goto R, Nakamura M, Kubota H, Ochifuji K. Operating results and simulations on a fuel cell for residential energy systems. J Energy Convers Manage 2006;47(20):3562–71.

[3] Hamada Y, Nakamura M, Kubota H, Ochifuji K, Murase M, Goto R. Field performance of a polymer electrolyte fuel cell for a residential energy system. Renew Sust Energy Rev 2005;9(4):345–62.
[4] Kim YH, Kim SS. An electrical modeling and fuzzy logic control of a fuel cell generation system. IEEE Trans Energy Convers 1999;14(2):239–44.
[5] Dokopoulos PS, Saramourtsis AC, Bakirtzis AG. Prediction and evaluation of the performance of wind-diesel energy systems. IEEE Trans Energy Convers 1996;11(2):385–93.
[6] Zahran Mohamed BA. Photovoltaic hybrid systems reliability and availability. Int J Power Electron 2003;3(3):145–50.
[7] Ackermann T, Soder L. An overview of wind energy—status 2002. Renew Sust Energy Rev 2002;6(1–1):67–128.
[8] Ozgener Onder. A small wind turbine system (SWTS) application and its performance analysis. J Energy Convers Manage 2006;47(11–12):1326–37.
[9] Wang P, Billinton R. Reliability benefit analysis of adding WTG to a distribution system. IEEE Trans Energy Convers 2001;16(2):134–9.
[10] Tian W, Wang Y, Ren J, Zhu L. Effect of urban climate on building integrated photovoltaics performance. J Energy Convers Manage 2007;48(1):1–8.
[11] Bose BK, Szczeny PM, Steigerwald RL. Microcomputer control of a residential photovoltaic power conditioning system. IEEE Trans Ind Electron 1985;IA-21(September/October):1182–91.
[12] Jiang JA, Huang TL, Hsiao YT, Chen CH. Maximum power tracking for photovoltaic power systems. Tamkang J Sci Eng 2005;8(2):147–53.
[13] Hussion KH, Zhao G. Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. Proc IEE 1995;142(1):59–64.
[14] Hua C, Lin J, Shen C. Implementation of a DSP controlled photovoltaic system with peak power tracking. IEEE Trans Ind Electron 1998;45(1):99–107.
[15] Mitchell K, Nagria M, Rizk J. Simulation and optimization of renewable energy systems. J Elect Power Energy Syst 2005;27(3):177–88.
[16] Yang Hongxing, Lu Lin, Zhou Wei. A novel optimization sizing model for hybrid solar–wind power generation system. J Sol Energy 2007;81(1):76–84.
[17] Hoff Thomas E, Perez Richard, Margolis Robert M. Maximizing the value of customer-sited PV systems using storage and controls. J Sol Energy 2007;81(7):940–5.
[18] Ayad Mohamed-Yacine, Pierfederici Serge, Rael Stephane, Davat Bernard. Voltage regulated hybrid DC power source using supercapacitors as energy storage device. J Energy Convers Manage 2007;48(7):2196–202.
[19] Billinton Roy, Karki Rajesh. Capacity expansion of small isolated power systems using PV and wind energy. IEEE Trans Power Syst 2001;6(4):892–7.
[20] Karki RajeshRajesh, Billinton Roy. Reliability/cost implications of PV and wind energy utilization in small isolated power systems. IEEE Trans Energy Convers 2001;16(4):368–73.
[21] Ahmed Nabil A, Miyatake Masafumi. A stand-alone hybrid generation system combining solar photovoltaic and wind turbine with simple maximum power point tracking control. In: Proc of CES/IEEE 5thinternational power electronics and motion control conference, IPEMC'06, Shanghai, China, 13–16 August; 2006.
[22] Celik Ali Naci. Techno-economic analysis of autonomous PV–wind hybrid energy systems using different sizing methods. J Energy Convers Manage 2003;44(12):1951–68.
[23] Rajashekara Kaushik. Hybrid fuel-cell strategies for clean power generation. IEEE Trans Ind Appl 2005;41(3):682–9.
[24] Sekiguchi N, Tani T. Fundamental study onphotovoltaic/fuel cell power hybrid system (characteristic of system utilized hydrogen absorbing alloys). Trans Inst Elect Eng IEEJ 1997;117-B(3):402–8.
[25] Islam Saiful, Belmans Ronnie. Grid independent photovoltaic fuel-cell hybrid system: design and control strategy. KIEEInt Trans Elect Mach Energy Convers Syst 2005;5-B(4):399–404.
[26] Senjyu Tomonobu, Nakaji Toshiaki, Uezato Katsumi, Funabashi Toshihisa. A hybrid power system using alternative energy facilities in isolated island. IEEE Trans Energy Convers 2005;20(2):406–14.
[27] El-Shatter Thanaa F, Eskander Mona N, El-Hagry Mohsen T. Energy flow and management of a hybrid wind/PV/fuel cell generation system. J Energy Convers Manage 2006;47(9–10):264–1280.
[28] Das Debosmita, Esmaili Reza, Xu Longya, Nichols Dave. An optimal design of a grid connected hybrid wind/photovoltaic/fuel cell system for distributed energy production. In: Proceedings of the 31st annual conference of the IEEE industry electronics society, IECON'05, Raliegh, North Carolina, USA, 6–10 November; 2005. p. 1223–8.
[29] Powersim Technologies. PSIM version 7.1, for power electronics simulations. User manual. Powersim Technologies, Vancouver, Canada. http://www.powersimtech.com.
[30] Uzunoglu M, Alam MS. Dynamic Modeling, Design and simulation of a PEM fuel cell/ultra-capacitor hybrid system for vehicular applications. J Energy Convers Manage 2007;48(5):1544–53.
[31] Ahmed Nabil A. Computational modeling and polarization characteristics of proton exchange membrane fuel cell with evaluation of the interface systems. Eur Power Electron J, EPE 2008;18(1): in press.