Voltage Control of PV-FC-Battery-Wind Turbine for Stand-Alone Hybrid System Based on Fuzzy Logic Controller

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Abstract

Most of power systems experience a transient mode. In a special case, the operation of solar panel and wind turbine is depended to solar irradiance and wind speed. In addition, maintenance dc-link voltage and output AC voltage regardless variations of wind speed and solar irradiation can be a challenging topic. In this paper, a new strategy based on the stability of dc-bus voltage for a hybrid power system is proposed. Firstly, the operation of dc-bus voltage for a stand-alone hybrid power system consists of solar panel and wind turbine is investigated. In this case, a PI controller is used to regulating at its reference value. Finally, the performance of dc-link voltage in a stand-alone hybrid system included a solar PV, wind turbine, battery, and the fuel cell is studied. Furthermore, the Fuzzy logic controller is used as a power management energy in this case. The MATLAB/Simulink and SimPowerSystems software packages are used to model a proposed stand-alone haybrid power system. Simulation results show that proposed strategy has better performance under fast variation of irradiance.

Keywords— Solar panel, Wind turbine, Fuel cell, Battery, Fuzzy logic, Power management

1. Introduction

Using of current energy sources like coal, natural gas and crude oil for producing electricity cause high costs and environmental pollution. Studying of new energies was highly regarded after the oil crisis of the 1970s [1, 2]. Renewable energies can also be a good alternative for thermal and nuclear power sources and these energies have not any pollution to the environment. Renewable energy sources such as solar, wind, and tides hydraulic widely used to generate electricity. The hybrid system contains the renewable energy systems that produce electricity previously mentioned. Ackermann et al. explained a new distribution of electricity that describes distributed generation. This system is based on renewable energy sources such as photovoltaic (PV) cells, wind turbines, fuel cells, and micro-turbines. These systems are tested to meet the needs of the world [3].

Chen et al. submitted simulation models which contain the wind and solar energy sources. In this model, details of solar cells, wind turbines, and fuel cells the simulated to produce energy in the form of a hybrid system. The researcher has used fuel cell to support the ultra-capacitor model.When the wind speed and solar radiation are not enough [4]. Hirose et al. presented a hybrid system that contains bank battery and diesel generator. When energy is needed more than the produced amount, the system uses the battery band and diesel generator. When the battery charged, the dump loads controlled, so the lifetime of the battery would be improved [5].

Guo et al. have presented a hybrid system in Simulink, which contains fuel cell and a wind turbine that is controlled by fuzzy PI Moderator. In this simulation, according to the international standards, harmonic distortion rate is lower than 5 % and load variations react rapidly [6]. Ray et al. presented a hybrid system which contains fuel cell and diesel generator with renewable energy sources like wind and photovoltaic. This system has elements that store energy. Variety of differences in wind speed and solar radiation causes different oscillation in output power and makes the frequency of the wind and photovoltaic systems far from the beach. In order to achieve better frequency deviation profiles, ultra-capacitor (UC) as an alternative energy storage element and proportional–integral (PI) controller added to the system [7].

Kabalci et al. have presented hybrid renewable energy sources including the wind, photovoltaic with solar panel and PMSG wind. Their generation system is designed by two parts, solar panel, and wind turbine model, and in Simulink, this model has three parts, solar energy plant, wind conversion system and DC–AC energy conversion. Three-phase AC voltages at the output of inverter which is controlling with sinusoidal pulse width modulation (SPWM) scheme, is generated by DC bus bar which is supplied to the full-bridge inverter. This output is developed with a signal which phase shifted carrier. Based on international standards, the total harmonic distortion (THD) has been obtained in different values [8].

In this paper, a fuzzy logic controller is used for a stand-alone haybrid power system with multiple sources.Simulation results confirm the better transient performance of the proposed strategy.

2. Stand-Alone Hybrid System

The proposed stand-alone hybrid power system consists of solar panel, wind turbine, buck converter with PI controller, rectifier, Fuel cell stack , the battery, full bridge inverter with SPWM Modulator and LC filter and the Fuzzy logic controller is shown in Fig. 1.

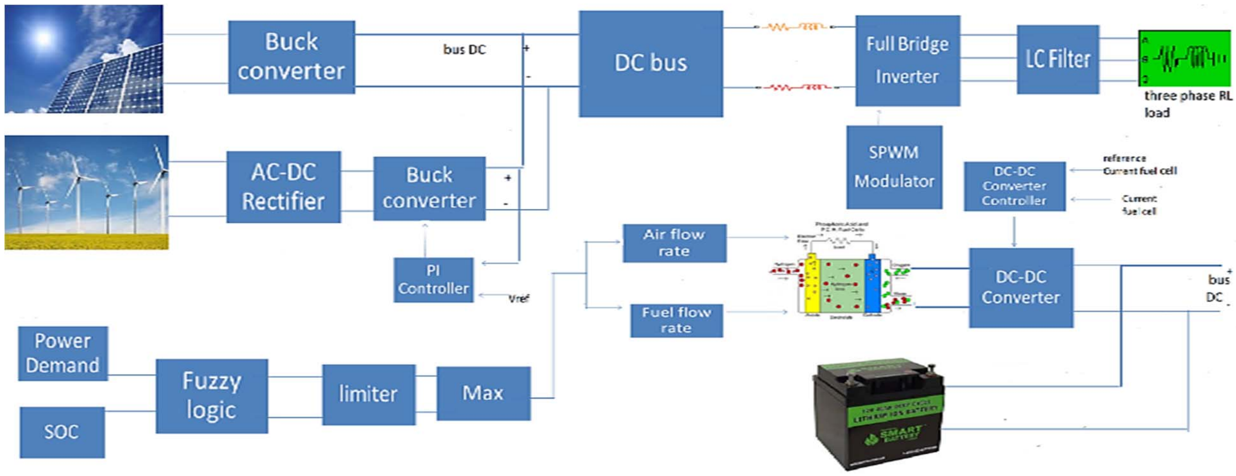

Fig. 1. Proposed System Schematic.

2.1. Photovoltaic panel

A Solar PV receives light and convert into electricity. The output of solar cell as a function of sun irradiance and temperature [5, 11]. The solar cell can be modeled as (1) [8],

$$I_{pv} = I_{ph} - I_p \left[e^{\frac{q(Vpv+IpvRs)}{\eta KT}}\right] - \frac{V_{pv}+I_{pv}.R_s}{R_{sh}} \quad (1)$$

According to the Formula I_{pv} is cell current, V_{pv} is cell voltage, I_{ph} is photocurrent, I_p is the output current of series resistors, R_s and R_{sh} are the series and shunt resistors, q is the electron charge, η is the quality factor of n–p junction, k is the Boltzman constant which is 1.38×10^{-23} J/ K and T is the ambient temperature.

2.2. Wind Turbine

The Wind Energy Conversion System (WECS) changes to wind energy into electricity by an electromechanical energy conversion. Wind turbine powers are obtained from the following equation [8].

$$P_m = \frac{1}{2} Cp\,(\lambda, \beta)\,.\,\rho\,.\,A\,.\,V^3 \quad (2)$$

P_m is the mechanical output power of wind turbine, Cp is the coefficient of performance, λ is pitch angle (degree), β is the peak velocity ratio, ρ is the air density (kg/m^3), A is the rotor swept area (m^2), υ is the velocity of wind (m/s) .

2.3. Fuel cell

A fuel cell is a device that converts chemical potential energy into electrical energy. The voltage of the fuel cell varies according to the load [10].

$$V_{fc} = N_{cell}.\ V_{cell} \quad (4)$$

Pressure, temperature, flow rates and composition of fuel and air during the operation of the fuel cell are modeled. The output fuel cell voltage V_{fc} is calculated by multiplying the numbers of cells N_{cell} and the cell voltage output V_{cell}. The air and hydrogen flow rates are calculated by Eqs. (5) and (6) as follows [13].

$$U_{O_2} = \frac{60000RTNi_{fc}}{ZFP_{air}\,V_{lpm(air)}O_2\%} \quad (5)$$

$$U_{H_2} = \frac{60000RTNi_{fc}}{ZFP_{fuel}\,V_{lpm(fuel)}H_2\%} \quad (6)$$

where R is 8.3145 j/ (mol k), F is 96485 an s/mol, O_2% is the percentage of oxygen in the oxidant (%), T is temperature, P_{air} is absolute supply pressure of air (atm), $V_{lpm\ (air)}$ is air flow rate (1/min), $V_{lpm\ (fuel)}$ is fuel flow rate (1/min) , H_2% is the percentage of hydrogen in the fuel (%), P_{fuel} is absolute supply pressure of fuel (atm) and Z is number of moving electrons.

2.4. Battery model

A battery is an electrochemical cell that transforms chemical energy into electrical energy. The equivalent circuit of the battery is composed of an internal resistance and the fixed voltage V_{Batt} .The parameter V_{Batt} can be calculated by two different equations [13,14]. If the current of the low frequency dynamic is positive, then the battery is in discharge mode, $V_{Batt} = V_{discharge}$, as shown in Eq. (3) and if the current low frequency dynamic is negative, then the battery is in the charge mode, $V_{Batt} = V_{Charge}$,as calculated in Eqs. (7) and (8).

$$V_{discharge} = V_0 - \frac{KQ_{max}}{Q_{max} - q} i^* - \frac{KQ_{max}}{Q_{max} - q} q + A * exp(-B.q) \quad (7)$$

$$V_{charge} = V_0 - \frac{KQ_{max}}{0.1 * Q_{max} - q} i^* - \frac{KQ_{max}}{Q_{max} - q} i.t + A * exp(-B.q) \quad (8)$$

Where Q_{max} is the maximum capacity (Ah), V_0 is the constant voltage (v), A is the exponential voltage and B is the exponential capacity $(Ah)^{-1}$,q=it is the available capacity (Ah), and k is the polarization constant $(Ah)^{-1}$. The SOC is calculated as:

$$SOC_{Batt} = 100\left(1 - \frac{\int i(t)dt}{Q}\right) \quad (9)$$

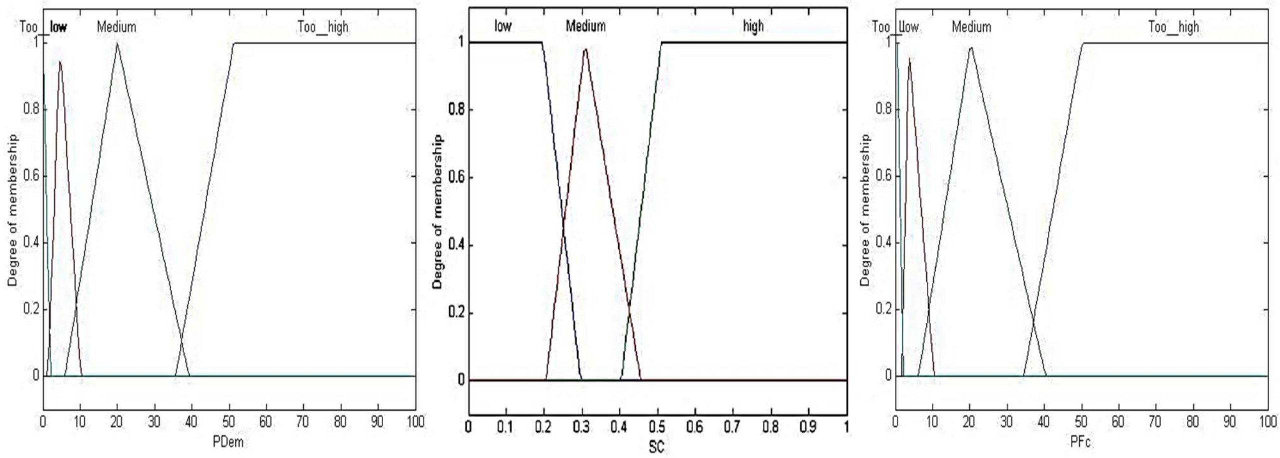

Fig. 2. Membership functions of input and output variables.

2.5. Full bridge inverter

All the DC bus voltages are converted to three-phase AC voltage owing to sinusoidal pulse width modulation (SPWM) controlled switching by a full bridge inverter. The model of full bridge inverter is commutated at 5kHZ switching frequency acquired by a unique carrier triangular signal.The modulation index value (m_i) is the peak value of modulating signal (V_{ref}) to the carrier (V_{tri}) which is less than 1 or more than 1 at the operating region according to equation (10). In SPWM control technique, the line voltages in linear modulation range and the over-modulation range are defined as given in Eqs. (11) and (12) in linear modulation [11].

$$m_i = \frac{V_{ref}}{V_{tri}} \tag{10}$$

$$V_{AB} = V_{AC} = V_{BC} = m_i \frac{\sqrt{3}V_d}{2} \qquad 0 < m_i \leq 1 \tag{11}$$

$$\frac{\sqrt{3}V_d}{2} < V_{AB} = V_{AC} = V_{BC} < \frac{4}{3}\frac{\sqrt{3}}{2}V_d \quad m_i \geq 1 \tag{12}$$

Also, produced high frequency harmonics can be eliminated using simple passive LC filter [12].

2.6. Fuzzy logic

The fuzzy logic controller for stand-alone hybrid power system has two input variables and one ouput variable. The fuzzy subset of P_{dem} is divided into {Too low, Low, Medium, Too high}, the fuzzy subset of SOC is divided into{low, Medium, Too high} and the fuzzy subset of P_{Fc} is divided into {Too low, Low, Medium, Too high }. These classes of linguistic labels are characterized by membership function are show in Fig. 2. The fuzzy reasoning ruless with 12 items are established for mainpulated variables as Table.1 show. Defuzzification is a process that converts the linguistic labels into crasp solution variables [10].

Table 1. Fuzzy reasoning rules

P_{dem}/SOC	Low	Medium	High
Too low	Too high	Too low	Too low
Low	Too high	Low	Too low
Medium	Too high	Medium	Too low
Too high	Too high	Too high	Too low

3. Results and Discussion

This paper simulates two configurations of the stand-alone hybrid power system and evaluates the transient behavior under changing of insolation conditions. The fuel cell is a 68 cells, 2.4kw, 48v Alkaline fuel cell according to Ref [13]. The battery is a 60 v, 10.9 Ah, %60 state of charge and lithium-ion battery. The main parameters of the PV panel are set according to NE-170UC1 solar panel of Sharp which has maximum power out about 170W [9].

3.1. Case 1: Operation a stand-alone hybrid system consists of solar panel and wind turbine

The curves related to wind turbine system are shown in fig. 5, fig. 6, fig. 7 and fig. 8. The speed of wind turbine is considered in the constant amount of 8.7m/s. The output voltage of PMSG is three-phase AC voltage. For this reason, a DC voltage without fluctuation is obtained through an uncontrolled full bridge rectifier. The Fig. 5 shows the output voltage of the rectifier with an overshoot more than the normal amount which system is intended to be unstable. So, a buck converter within a PI controller is required to decrease the fluctuation of the DC output voltage as shown in fig. 7. Also, the DC current is not changed before and after the converter. The current and voltage of solar panel are depicted in fig. 3 and fig. 4. The input of solar panel is an irradiation solar with sequence repeating waveform and temperature with ramp waveform. According to fig. 3 and fig. 4, the voltage and current of solar panel stabilized in 0.1s. Moreover, the steady-state error of voltage and current is almost zero. Ultimately, the solar panel and wind turbine is connected to DC-bus. The DC-bus voltage is shown in fig. 9 with the settling time of 0.3 s.

3.2. Case 2: Operation of a stand-alone hybrid system with a solar panel, wind turbine, fuel cell, and battery

In this case, fuel Cell and battery are added with a fuzzy logic controller.All of the sources are connected to DC bus according to fig. 1. The DC bus voltage is shown in fig. 10 with the settling time of almost 0.01s and the steady state error of almost zero. Also, the DC bus voltage is converted to a three-phase voltage through inverter and LC filter.The output phase A voltage of the inverter is seen in fig. 11. The total harmonic distortion ratio of any phase voltage (THD) is measured at %1.35 at the load side.

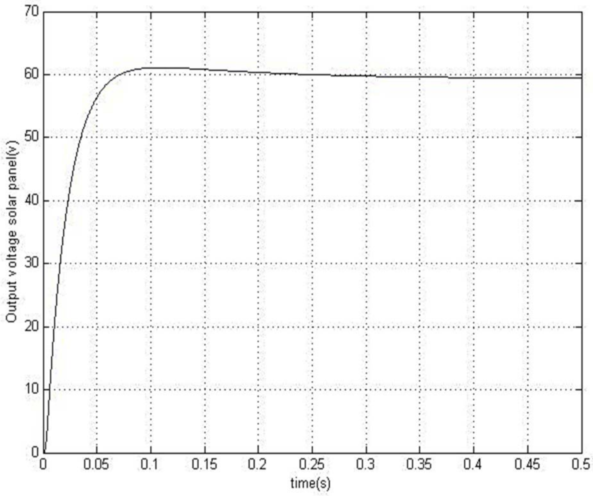

Fig. 3. solar plant current for the first case configuration.

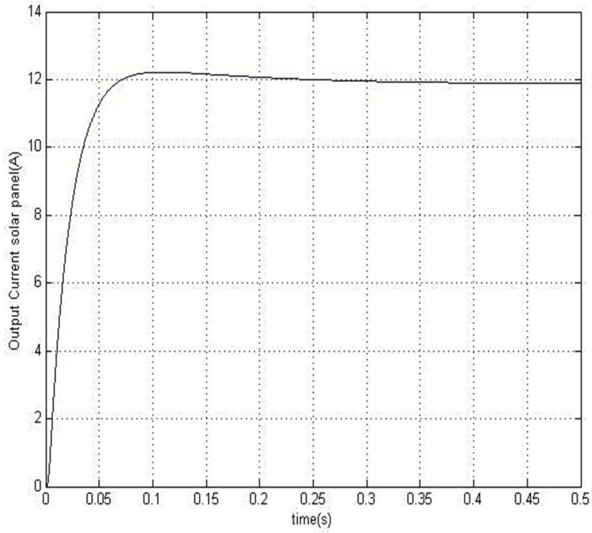

Fig. 4. solar plant voltage for the first case configuration.

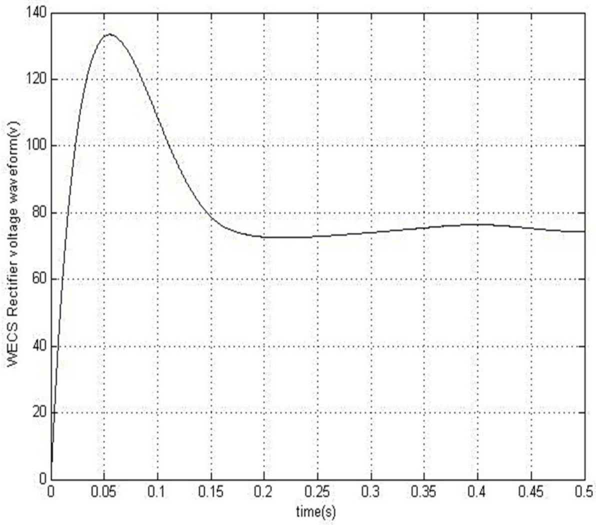

Fig. 5. WECS rectifier voltage for the first case configuration.

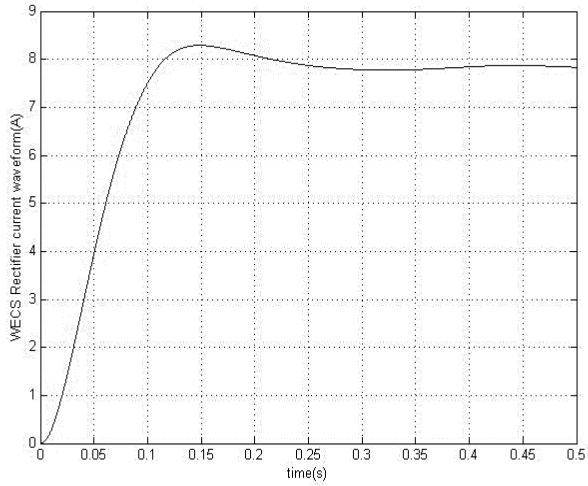

Fig. 6. WECS rectifier current for the first case configuration.

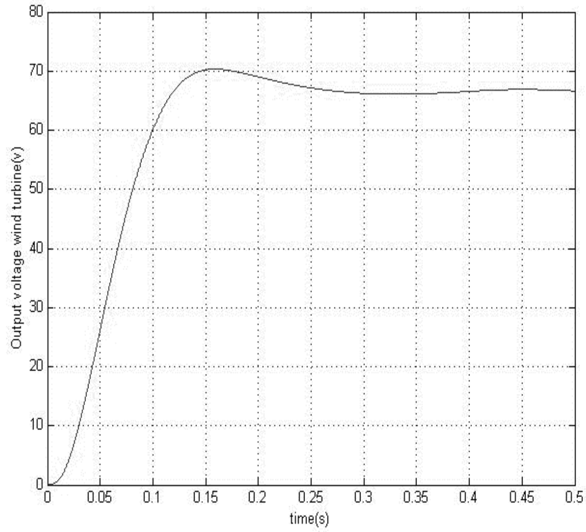

Fig. 7. Regulated output voltage of wind turbine for the first case configuration.

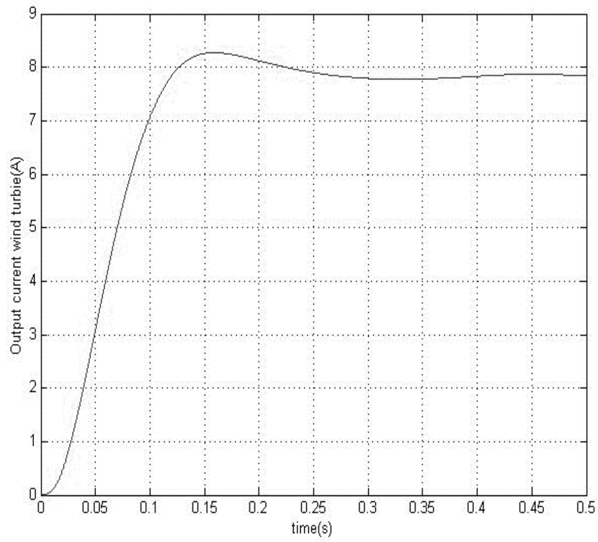

Fig. 8. Output current of wind turbine for the first case configuration.

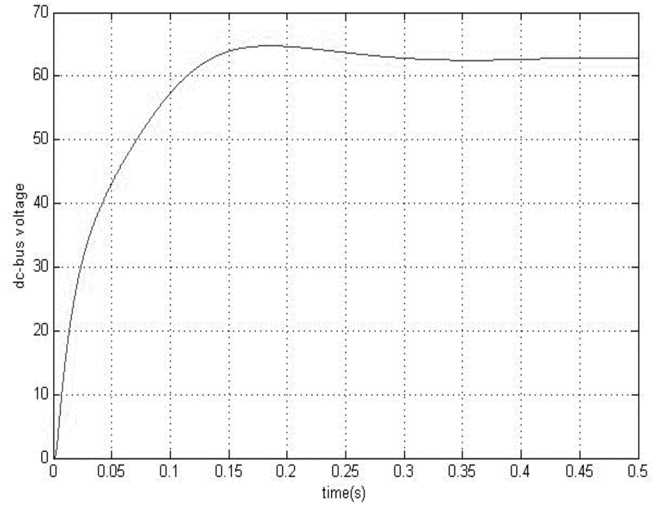

Fig. 9. DC-Bus voltage for the first case configuration.

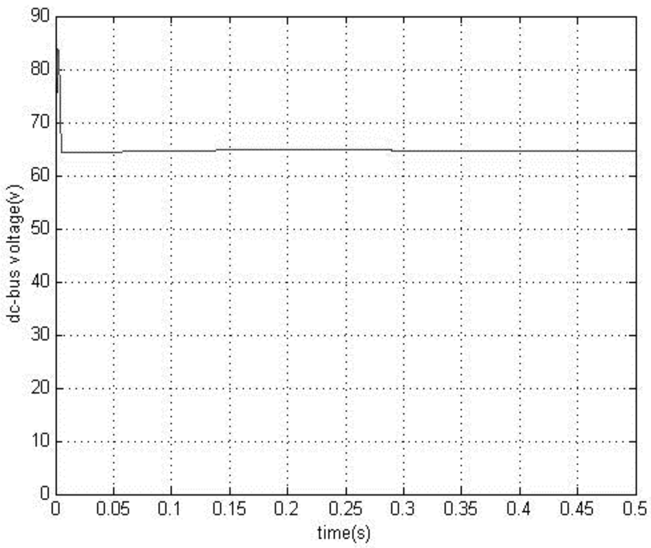

Fig. 10. DC-Bus voltage for the second case configuration.

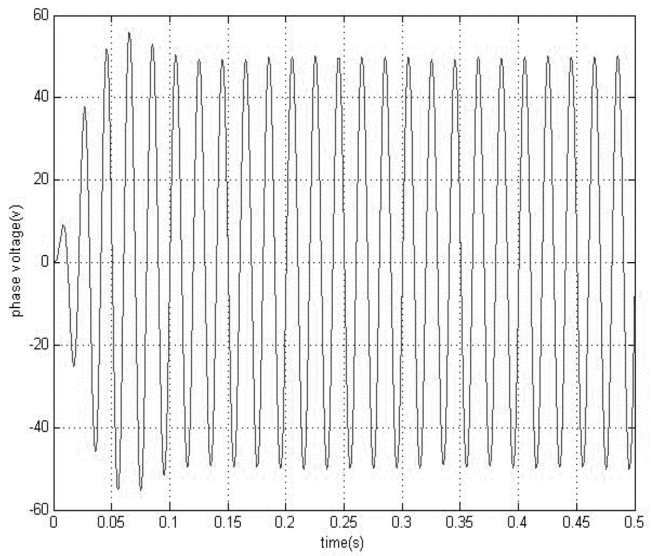

Fig. 11. Load phase voltage for the second case configuration.

4. Conclusions

In this paper, a new stand-alone hybrid power system based on the stability of dc-link voltage and load voltage is suggested. First of all, the behavior of a stand-alone hybrid power system consists of solar panel and wind turbine controlled by PI controller under fast variation of irradiance is studied. Simulation results are shown the response of DC-link voltage is slow under transient insolation conditions. For this reason, a new stand-alone hybrid power system is introduced. Fuzzy-logic controller is used for generating a reference signal for fuel-cell and battery based on demand power and SOC.In this case, DC-bus voltage stabilizes at 0.015 seconds under transient insolation conditions. Moreover, the generated phase voltages with a total harmonic ratio of voltage (THD) of 1.35% verify a good quality of voltage for a customer.

5. References

[1] Figueiredo, J. and J. Martins (2010). "Energy production system management–renewable energy power supply integration with building automation system." Energy Conversion and Management 51(6): 1120-1126.

[2] Ozgener, O. (2006). "A small wind turbine system (SWTS) application and its performance analysis." Energy Conversion and Management 47(11): 1326-1337.

[3] Ackermann, T., et al. (2000). Electricity market regulations and their impact on distributed generation. Electric Utility Deregulation and Restructuring and Power Technologies, 2000. Proceedings. DRPT 2000. International Conference on, IEEE.

[4] Chen, H.-C., et al. (2008). Dynamic modeling and simulation of renewable energy based hybrid power systems. Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on, IEEE.

[5] Hirose, T. and H. Matsuo (2012). "Standalone hybrid wind-solar power generation system applying dump power control without dump load." Industrial Electronics, IEEE Transactions on 59(2): 988-997.

[6] Guo, Z. and K. Y. Lee (2011). A self-adaptive fuzzy PI controller of power conditioning system for hybrid fuel-cell/turbine power plant. North American Power Symposium (NAPS), 2011, IEEE.

[7] Ray, P. K., et al. (2011). "Proportional–integral controller based small-signal analysis of hybrid distributed generation systems." Energy Conversion and Management 52(4): 1943-1954.

[8] Kabalci, E. (2013). "Design and analysis of a hybrid renewable energy plant with solar and wind power." Energy Conversion and Management 72: 51-59.

[9] Sharp NE-170UC1 multipurpose module. Sharp: USA; 2008.<http://files.sharpusa.com/Downloads/Solar/Products/sol_dow_NE170U1.pdf> [04.06.12].

[10] Hemi, H., et al. (2014). "A real time fuzzy logic power management strategy for a fuel cell vehicle." Energy Conversion and Management 80: 63-70.

[11] Kabalci, E. (2013). "Design and analysis of a hybrid renewable energy plant with solar and wind power." Energy Conversion and Management 72: 51-59.

[12] Bhende, C., et al. (2011). "Permanent magnet synchronous generator-based standalone wind energy supply system." Sustainable Energy, IEEE Transactions on 2(4): 361-373.

[13] MathWorks. http://www.mathworks.com.

[14] Garca P, Torreglosa JP, Fernndez LM, et al. Viability study of a FC-battery-SC tramway controlled by equivalent consumption minimization strategy. Int J Hydrogen Energy 2012;37:9368–82.