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Research Article

Dynamic Modelling of a Wind/Fuel-Cell/Ultra-Capacitor-Based Hybrid Power Generation System

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Abstract: Recent research and development of alternative energy sources have shown excellent potential as a form of contribution to conventional power generation systems. In order to meet sustained load demands during varying natural conditions, different energy sources and converters need to be integrated with each other for extended usage of alternative energy. The paper focuses on the combination of wind, Fuel Cell (FC) and Ultra-Capacitor (UC) systems for sustained power generation. As the wind turbine output power varies with the wind speed: an FC system with a UC bank can be integrated with the wind turbine to ensure that the system performs under all conditions. A dynamic model, design and simulation of a wind/FC/UC hybrid power generation system with power flow controllers is proposed. In the proposed system, when the wind speed is sufficient, the wind turbine can meet the load demand. If the available power from the wind turbine cannot satisfy the load demand, the FC system can meet the excess power demand, while the UC can meet the load demand above the maximum power available from the FC system for short durations. Furthermore, this system can tolerate the rapid changes in wind speed and suppress the effects of these fluctuations on the equipment side voltage in a novel topology.

Keywords: Fuel cell, hybrid system, ultra-capacitor, wind speed

INTRODUCTION

Renewable Energy Sources are those energy sources which are not destroyed when their energy is harnessed. Human use of renewable energy requires technologies that harness natural phenomena, such as sunlight, wind, waves, water flow and biological processes such as anaerobic digestion, biological hydrogen production and geothermal heat. Amongst the above mentioned sources of energy there has been a lot of development in the technology for harnessing energy from the wind.

Wind is the motion of air masses produced by the irregular heating of the earth‘s surface by sun. These differences consequently create forces that push air masses around for balancing the global temperature or, on a much smaller scale, the temperature between land and sea or between mountains. Wind energy is not a constant source of energy. It varies continuously and gives energy in sudden bursts. About 50% of the entire energy is given out in just 15% of the operating time. Wind strengths vary and thus cannot guarantee continuous power. It is best used in the context of a system that has significant reserve capacity such as fuel cell and ultra capacitor.

Khan and Iqbal (2005) and Khan *et al*. (2005) have presented the model of a small wind-fuel cell hybrid energy system and analyzed life cycle of a wind-fuel cell integrated system. The system consists of a 400 W wind turbine, a Proton Exchange Membrane Fuel Cell (PEMFC), ultra capacitors and a power converter. The output fluctuation of the wind turbine due to wind speed variation is reduced using a fuel cell stack.

Delfino and Fornari (2003) have presented a grid integrated fuel cell-wind turbine system. The fuel cell-wind turbine hybrid power plant connected to a MV network has been studied, with particular reference to the control system.

De Battista *et al*. (2006) reported power conditioning for a wind hydrogen energy system. It basically consists in continuously shaping the power reference of a conventional maximum power point tracking algorithm.

Bechrakis *et al*. (2006) have presented a simulation and operational assessment for a small autonomous wind-hydrogen energy system.

Shakyaa *et al*. (2005) studied the feasibility of a stand-alone hybrid wind-Photovoltaic (PV) system incorporating compressed hydrogen gas storage for Cooma (Australia).

Williams *et al*. (2004) have developed high temperature fuel cells for distributed generation.

Dell and Rand (2001) have presented the current global use of energy in its various forms and consider projections for the year 2020 with particular attention to the harnessing of “clean” and renewable forms of

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energy for electricity generation and road transportation.

Burke (2000) has modelled ultra capacitor using micro porous carbons than with the other materials and most of the commercially available devices use carbon electrodes and an organic electrolyte. The energy density of these devices is 3-5 Wh/kg with a power density of 300-500 W/kg for high efficiency_90-95%. Charger discharges.

The main disadvantage of wind turbines is that naturally variable wind speed causes voltage and power fluctuation problems at the load side.

This problem can be solved by using appropriate power converters and control strategies. By Combination of wind, Fuel Cell (FC) and Ultra-Capacitor (UC) systems for sustained power generation. As the wind turbine output power varies with the wind speed: an FC system with a UC bank can be integrated with the wind turbine to ensure that the system performs under all conditions. A dynamic model, design and simulation of a wind/FC/UC hybrid power generation system with power flow controllers have been proposed. In the proposed system, when the wind speed is sufficient, the wind turbine can meet the load demand. If the available power from the wind turbine cannot satisfy the load demand, the FC system can meet the excess power demand, while the UC can meet the load demand above the maximum power available from the FC system for short durations.

MODELLING AND SIMULATION

Wind turbine model: The kinetic energy in a parcel of air of mass, m, flowing at speed, vw in the x direction is:

$$U = \frac{1}{2} m v_w^2 = \frac{1}{2}(\rho A x) v_w^2 \tag{1}$$

The power in the wind, Pw, is the time derivative of the kinetic energy:

$$P_w = \frac{du}{dt} = \frac{1}{2}\rho A v_w^2 \frac{dx}{dt} = \frac{1}{2}\rho A v_w^3 \tag{2}$$

where,

A = Turbine swept area [m^2]

Cp = Performance coefficient of the turbine

Cp = pu per unit (p.u.) value of the performance coefficient cp

Kp = Power gain for cp pu = 1 and υ wind pu = 1 p.u., kp≤1

Pm = Mechanical output power of the turbine [W]

Pm = pu power in p.u. of nominal power for particular values of ρ and A

β = Blade pitch angle [◦]

λ = Tip speed ratio of the rotor blade tip speed to wind speed

ρ = Air density [kg/ (m^3)]

υ wind = Wind speed [m/s]

υ wind_pu = p.u. value of the base wind speed. The based wind speed is the mean value of the expected wind speed in (m/s)

The actual mechanical power outputs are given by Eq. (3) to (7):

$$p_m = C_p(\frac{1}{2}\rho A v_w^{3)} = \frac{1}{2}\rho\pi R^2 v_w^3 C_p(\lambda, \beta) \tag{3}$$

$$c_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\left(c5/\lambda_i\right)} + c_6\lambda \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

$$\lambda = \frac{\omega_R R}{V_w} \tag{6}$$

$$\omega_R = \frac{2\pi n}{60} \tag{7}$$

Modelling of induction motor: The dynamic model of induction motor is shown in Fig. 1. A doubly fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications.

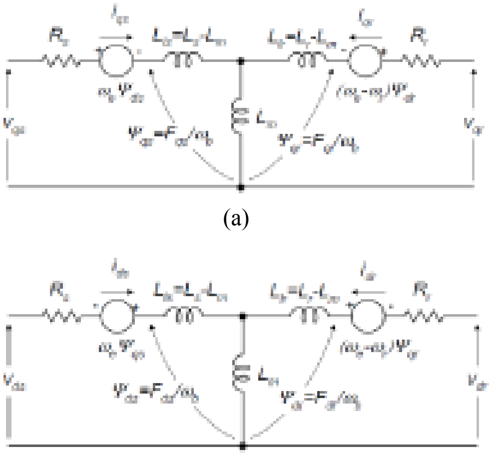
Firstly, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (Low Voltage Ride Through, LVRT). Secondly, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Thirdly, the cost of the converter is low when compared with other variable speed solutions because only fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason.

The equations related to Induction motor model is as follows:

$$n_s = \frac{60}{p} f_n \tag{8}$$

$$\omega_m = \frac{2\pi}{60} n_s \tag{9}$$

$$p_m = T_m \omega_m \tag{10}$$



(a)

(b)

Fig. 1: Dynamic model of induction motor

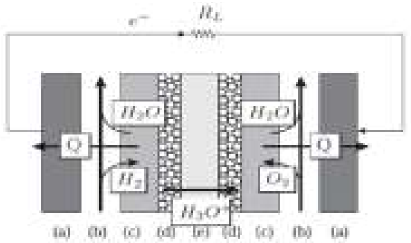


Fig. 2: Structure of a PEM fuel cell
a: Bipolar plate; b: Gas flow channel; c: Electrode layer; d: Catalyst layer; e: Polymer layer

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\,\omega_m - T_m) \tag{11}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{12}$$

$$V_s = E_s - (R_s' + j2\pi f\,L_s')\,I_s \tag{13}$$

Modelling of fuel cell: Gorgun (2006) presented the dynamic modeling of a Proton Exchange Membrane (PEM) electrolyser. Air is fed to the cathodic layer and hydrogen is fed to the anodic one. The central membrane works as a electrolyte that performs both the functions of transferring H+ from the anode to the cathode and reactant separation. Barbir (2005) discussed the electrochemical reactions involved and are summarized below (Fig. 2 and 3):

$$H_2 \rightarrow 2H^+ + 2e^- \tag{14}$$

$$2H^+ + \tfrac{1}{2}O_2 + 2e^- \rightarrow H_2O \tag{15}$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{16}$$

Ultra capacitor model: Each UC unit has a nominal voltage of 2.5 V corresponding to 2700 F. Assuming a 400 V dc output from the FC system, a string of 160 UCs in series (16.875 F/string) as in Fig. 4 is used to represent 400 V and the initial voltage of the UC bank is set to be 400 V. The energy is stored in a 16.875 F capacitance at 400 V. This size of the UC can be changed to suit various power capacities for different applications.

FC/UC hybrid system: The charge/discharge control of the UC bank to perform load sharing with the FC system when they simultaneously operate with the wind turbine is shown in Fig. 5. Although FC systems exhibit good power supply capability during steady state operation, the response of fuel cells during instantaneous and short-term peak power demand periods is relatively poor. In these periods, the UC bank can assist the FC system to achieve good performance whereas reducing the cost and size of the FC system.

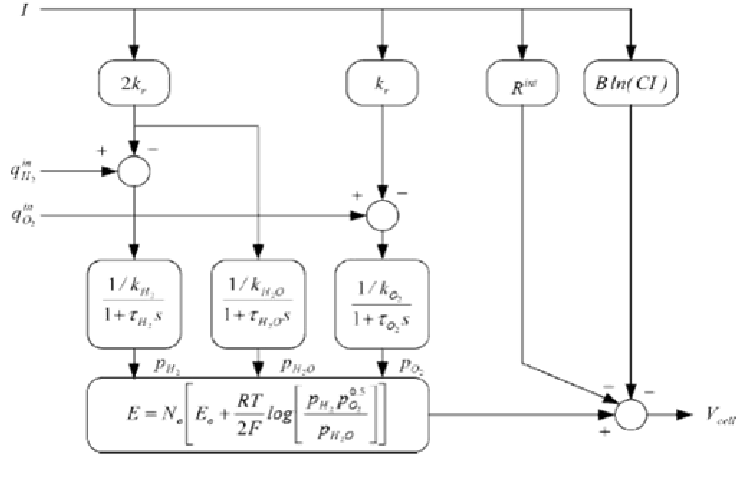


Fig. 3: The PEM fuel cell model

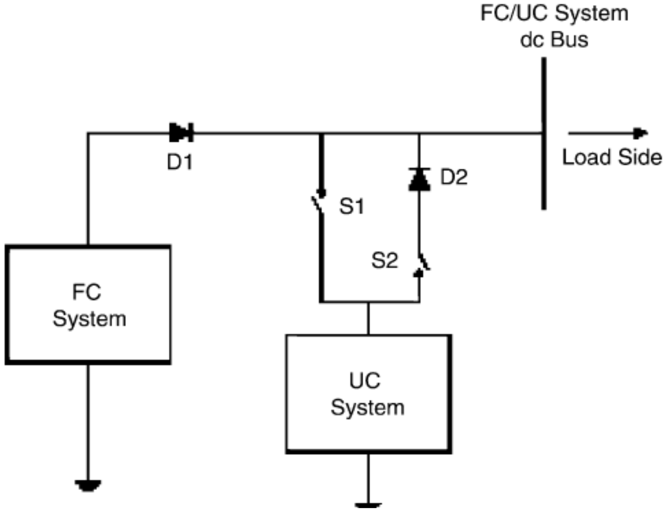


Fig. 4: The FC/UC hybrid system

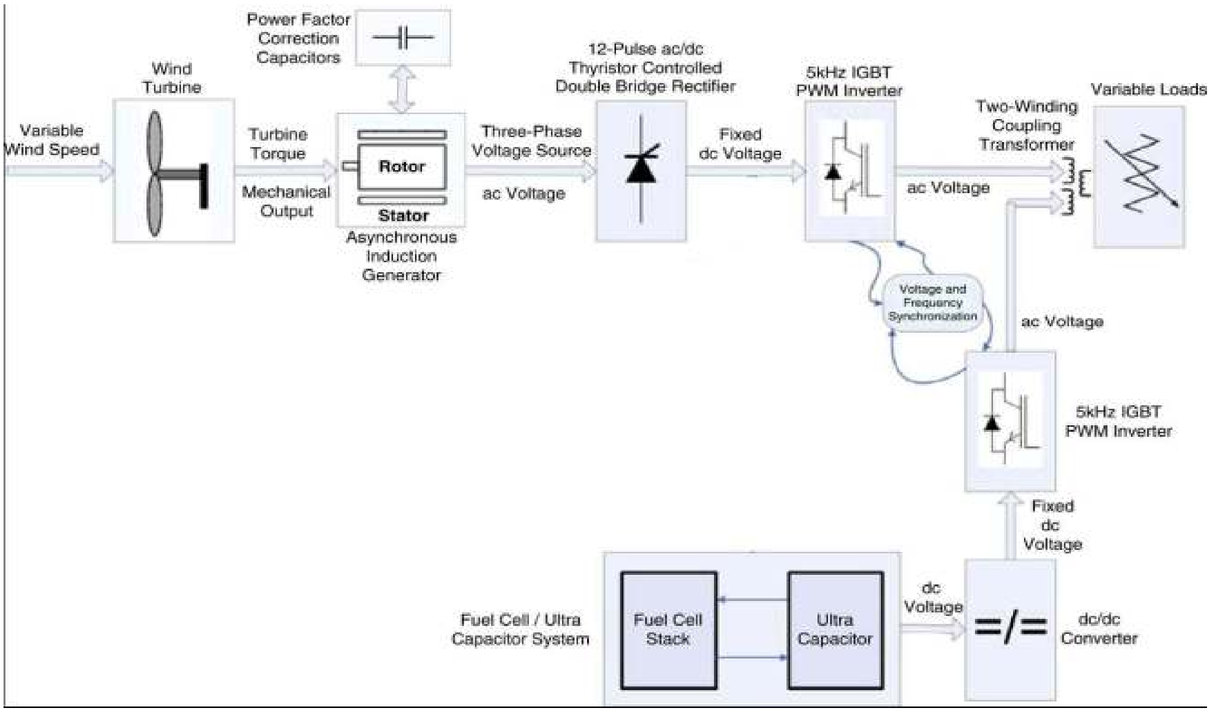


Fig. 5: Block diagram of proposed system

HYBRID POWER GENERATION SYSTEM

The dynamic simulation model is described for the wind/FC/UC hybrid generation system. The developed system consists of a wind turbine, an induction generator with power factor correction capacitor bank, an ac/dc thyristor controlled double-bridge rectifier with PI controlled firing angle, an FC/UC system with a boost type dc/dc converter with PI controlled duty cycle, two dc/ac IGBT inverters with 5 kHz carrier signal and a two-winding coupling transformer located at the load side. The block diagram of the integrated overall system is shown in Fig. 5.

RESULTS AND DISCUSSION

From the results it is evident, that the combination of wind turbine, Fuel Cell (FC) and Ultra-Capacitor (UC) systems result in sustained power generation. As the wind turbine output power varies with the wind speed: an FC system with a UC bank ensure that the system performs under all conditions. When the wind speed is sufficient, the wind turbine meet the load demand as shown in Fig. 6 to 12. If the available power from the wind turbine cannot satisfy the load demand, the FC system meet the excess power demand as shown in Fig. 13 to 20, while the UC can meet the load demand above the maximum power available from the FC system for short durations which is evident from Fig. 21 to 24.

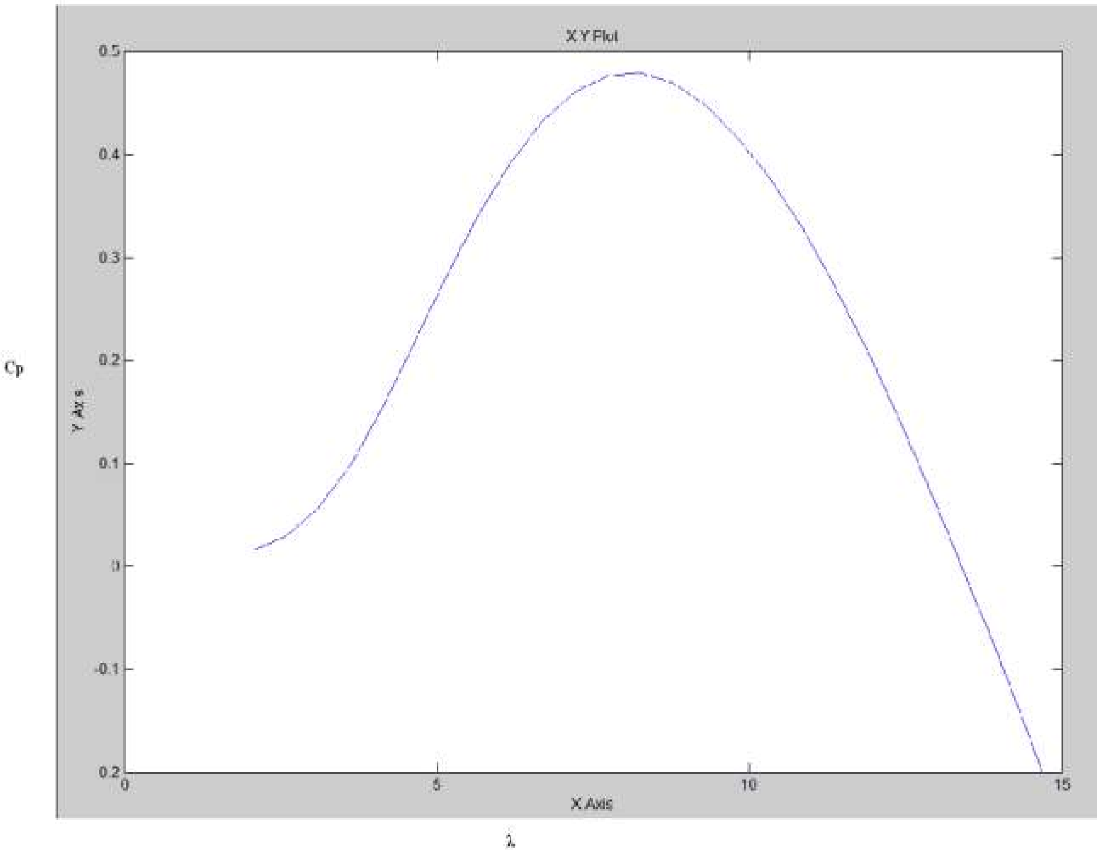


Fig. 6: Cp-λ graph

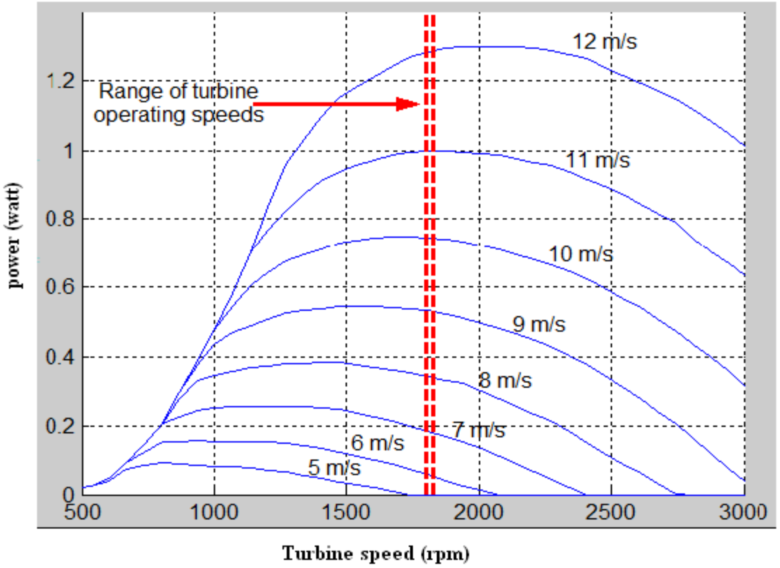


Fig. 7: Wind turbine characteristic

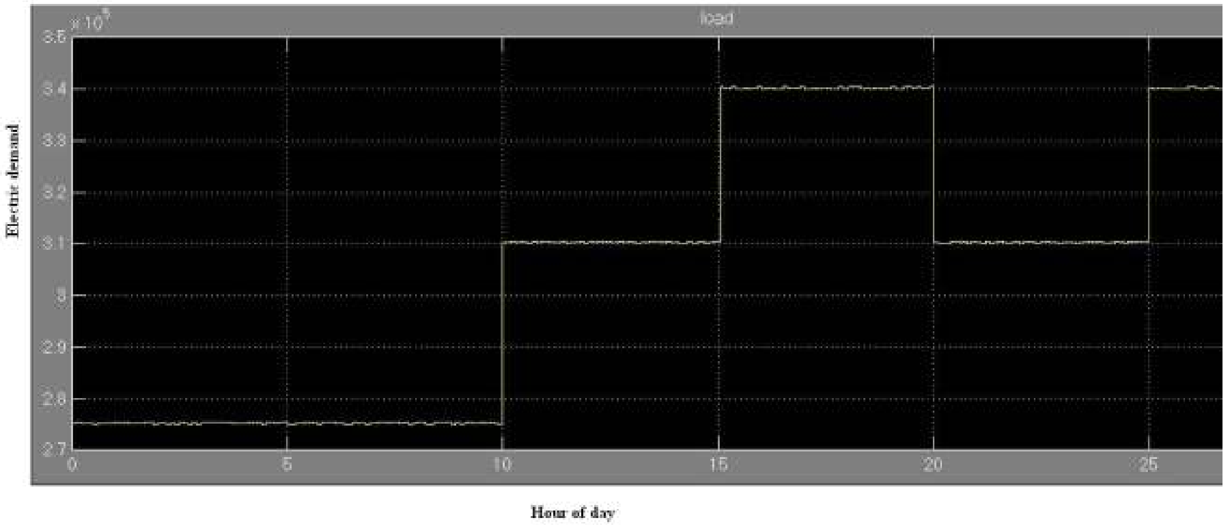


Fig. 8: Load demand

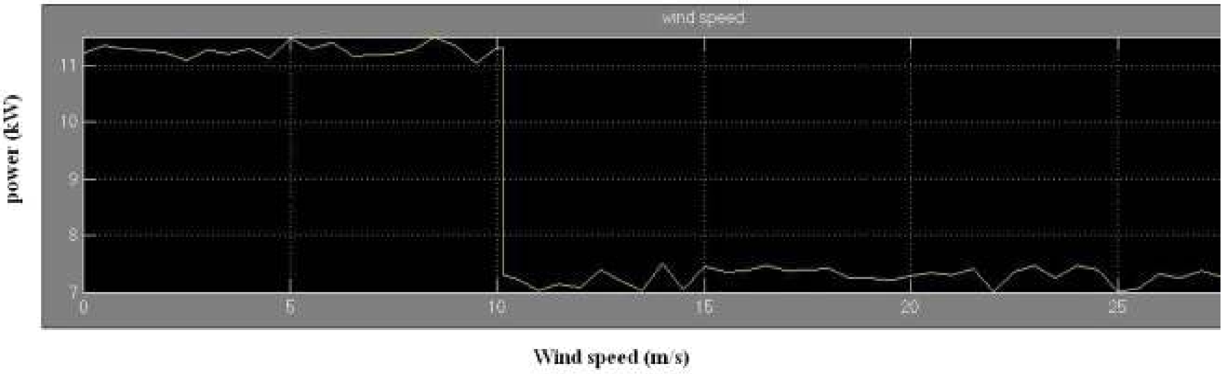


Fig. 9: Wind turbine speed

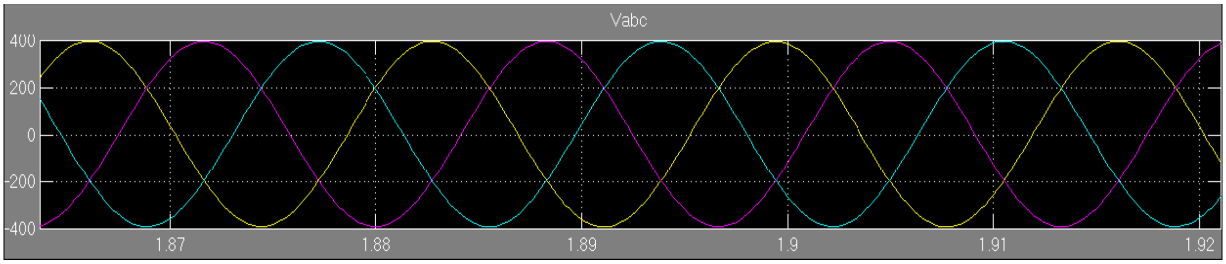


Fig. 10: Wind turbine output voltage

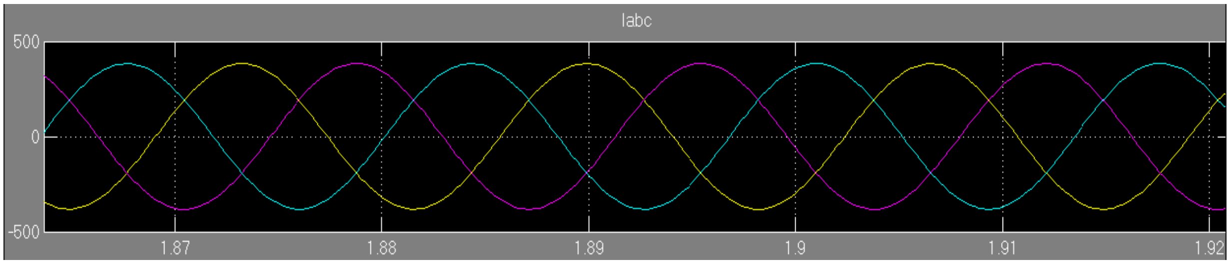


Fig. 11: Wind turbine output current

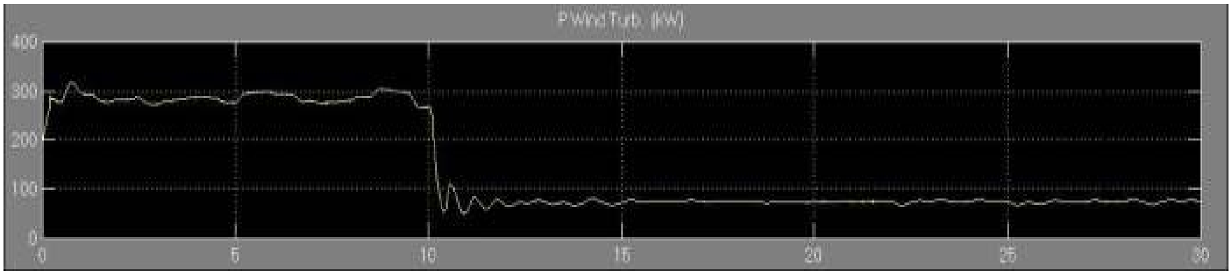


Fig. 12: Wind turbine output load

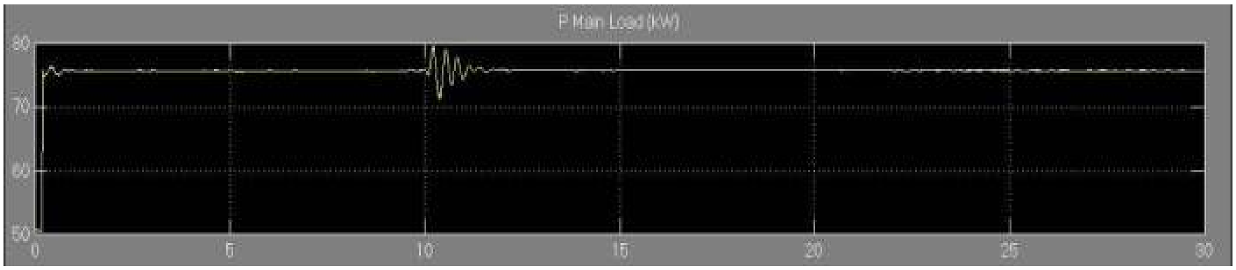


Fig. 13: Constant load supplied by wind turbine

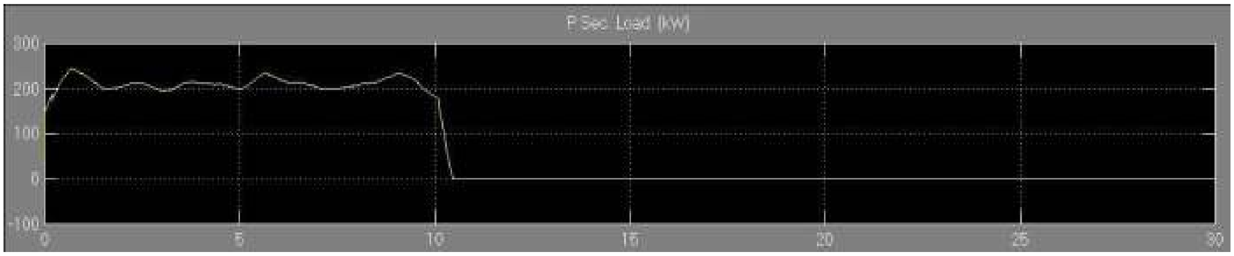


Fig. 14: Variable load supplied by wind turbine

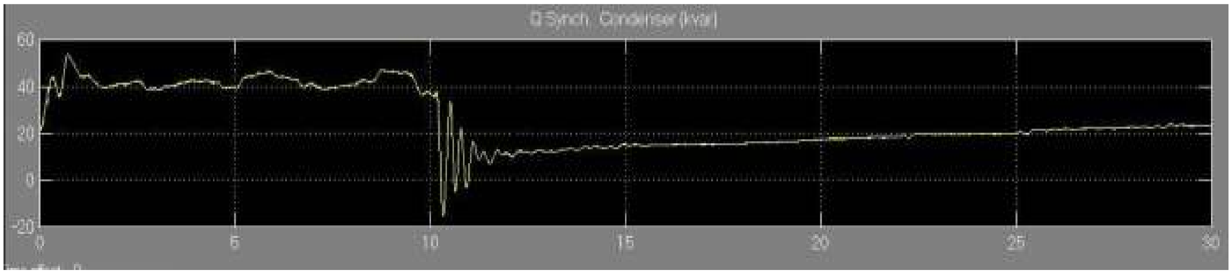


Fig. 15: Q synchronous condenser (Kvar)

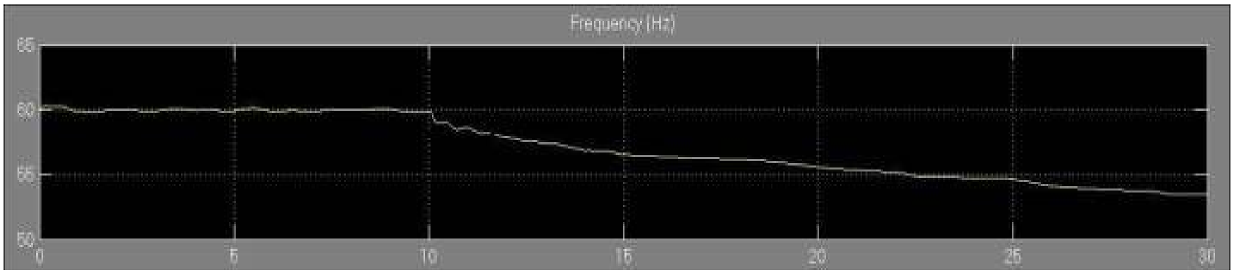


Fig. 16: Output frequency

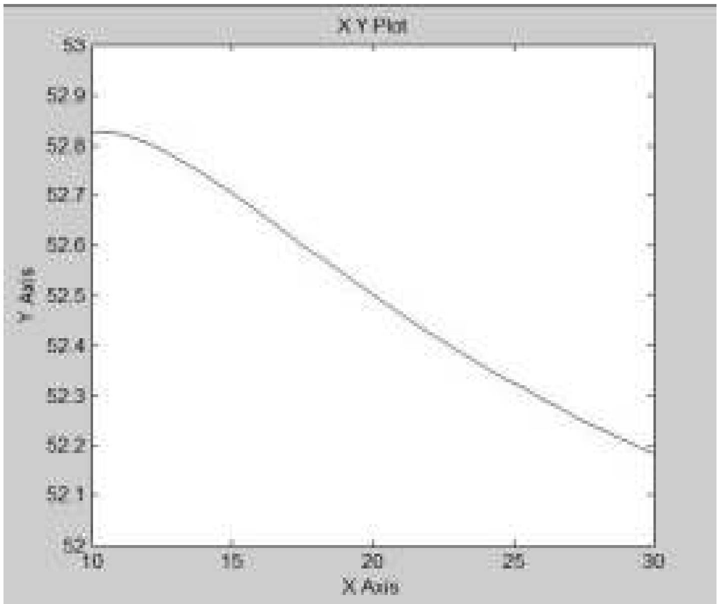


Fig. 17: V-I curve

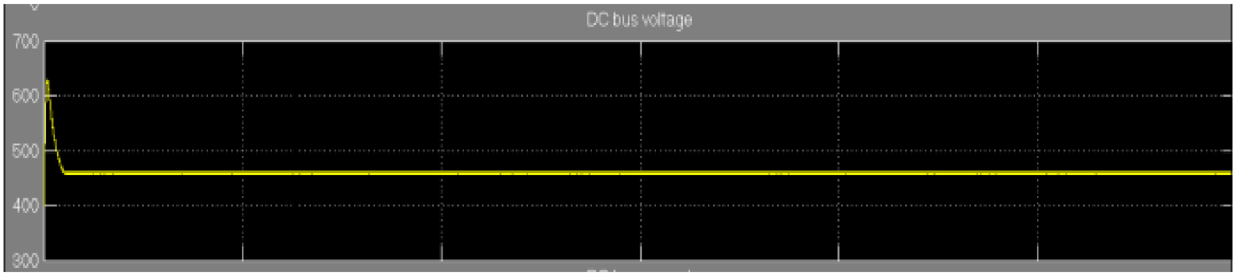


Fig. 18: Fuel cell DC output voltage

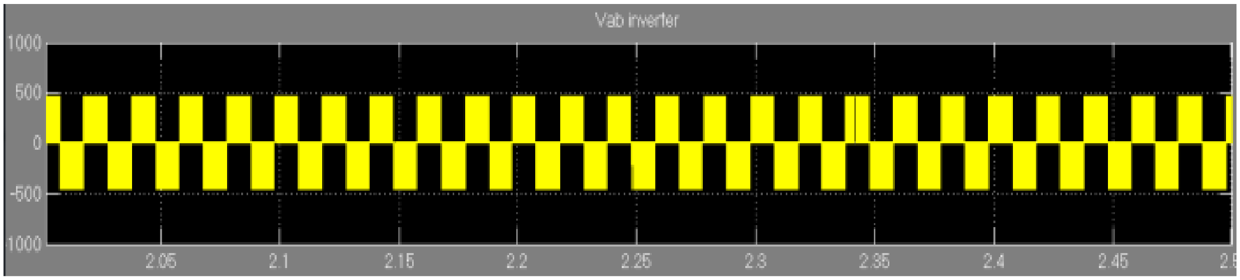


Fig. 19: Fuel cell output voltage after PWM

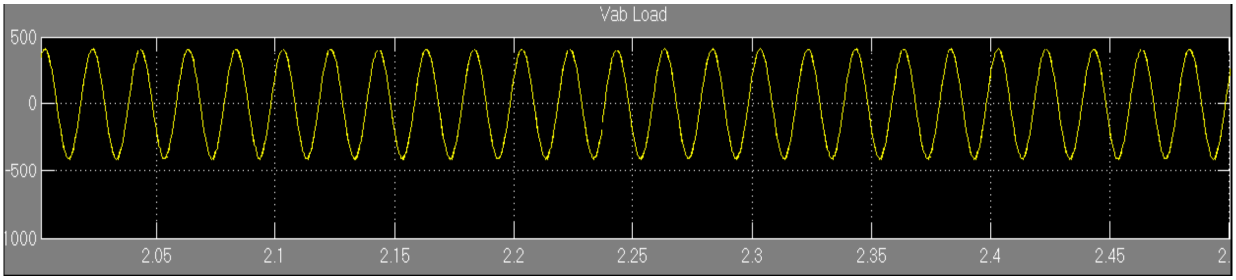


Fig. 20: Fuel cell output voltage after filter

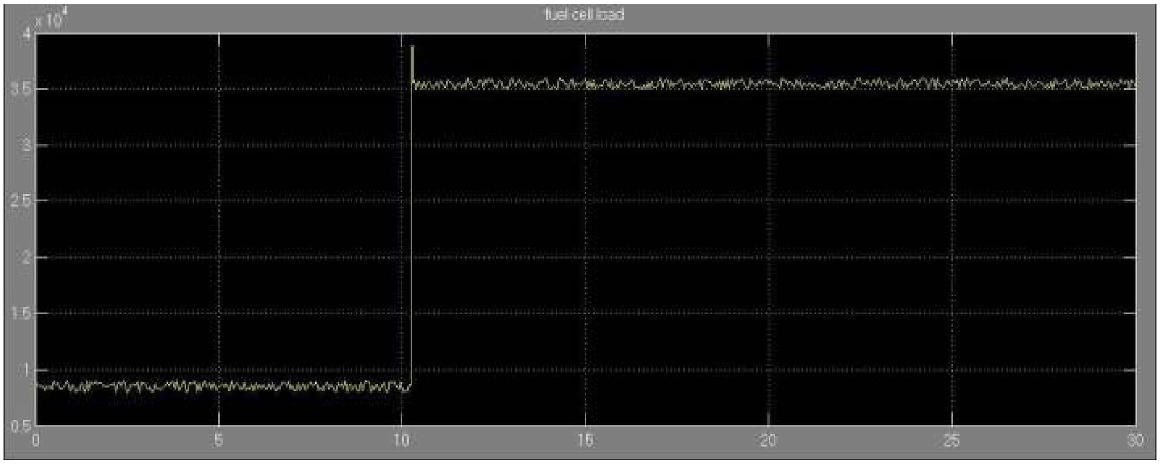


Fig. 21: Fuel cell load profile

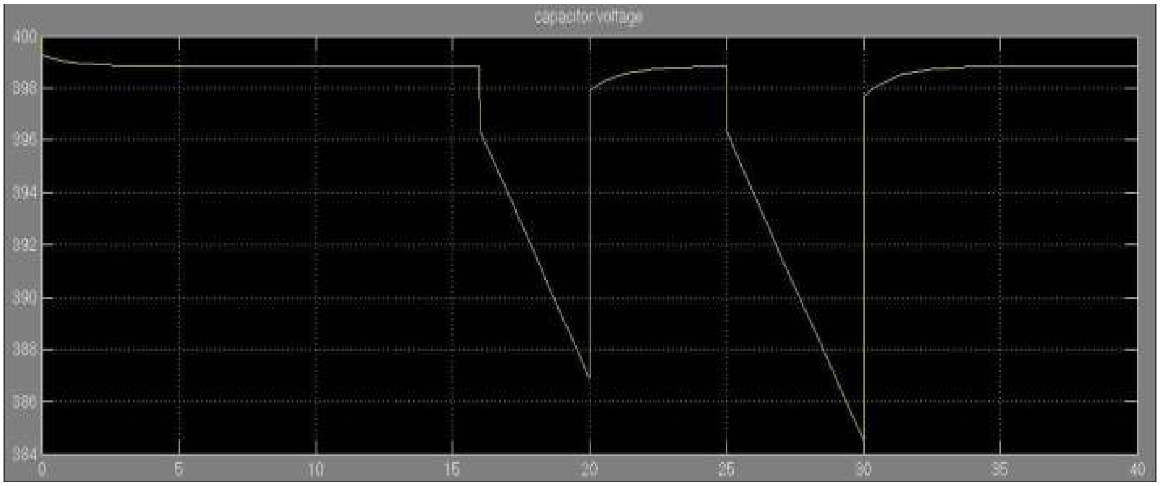


Fig. 22: Ultra capacitor voltage

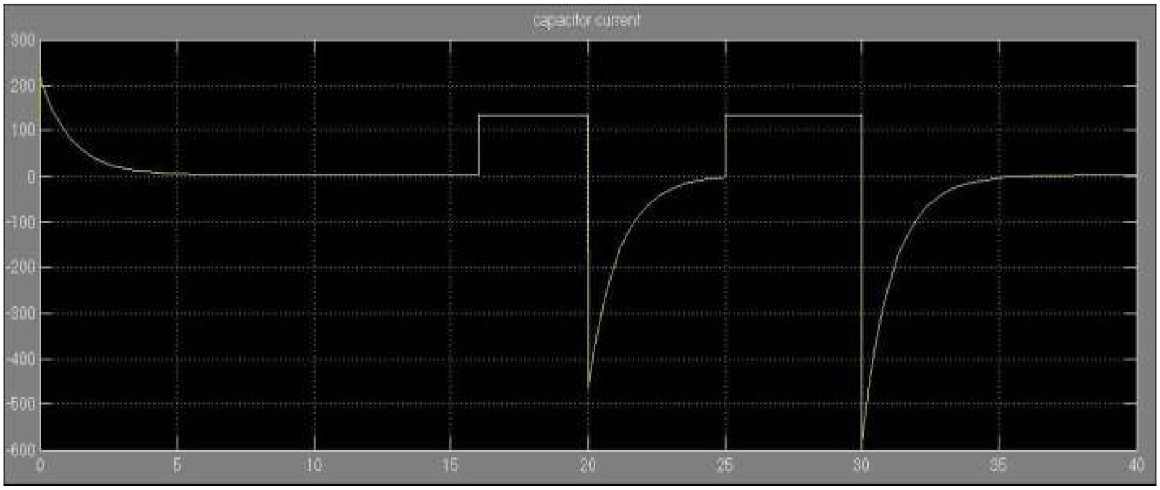


Fig. 23: Ultra capacitor current with respect to power demand

- Cp-λ characteristics
- Wind turbine characteristics
- Load profile
- Wind turbine output

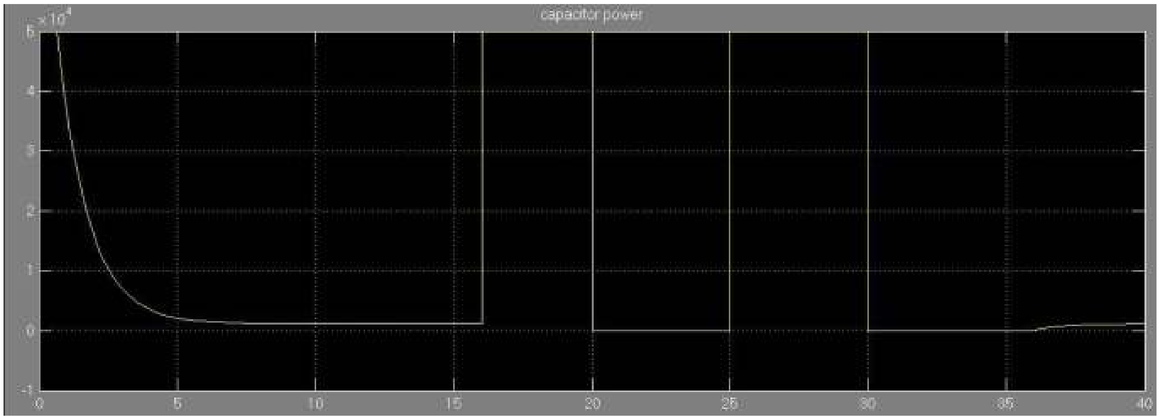


Fig. 24: Power satisfied by ultra capacitor

- Fuel cell characteristic
- Fuel cell output
- Ultra capacitor output

CONCLUSION

In this study, a novel wind/FC/UC hybrid power system is designed and modelled for a grid-independent user with appropriate power flow controllers. The available power from the renewable energy sources is highly dependent on environmental conditions such as wind speed. To overcome this deficiency of the wind system, we integrated wind turbine with the FC/UC system using a novel topology. This hybrid topology exhibits excellent performance under variable wind speed and load power requirements. The proposed system can be used for non-interconnected remote areas or isolated cogeneration power systems with non-ideal wind speed characteristics.

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