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Dynamic Modeling and Simulation of a Wind/Fuel Cell/Ultra-Capacitor-Based Hybrid Power Generation System

P. Naresh
Assistant Professor
GITAM(Deemed to be University)
P.Maniraj
PG Scholar
GITAM (Deemed to be university)

ABSTRACT:*In recent days, Integration of conventional energy systems with non-conventional systems known as hybrid systems is the trending topic in research, as one system cannot deliver all the desired characteristics. In this thesis, we are interested in integration of wind system with a conventional system. When we try integrating, the main disadvantage of wind turbine system is that the input for the system is wind, available naturally but the 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.The fuel cell and ultra-capacitor systems combined so as to suppress these limitations, forming a hybrid wind power generation system. In this thesis, a dynamic modelling and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system is explained. The objective is to concentrate on the combination of wind/fuel/UC systems for sustained power generation. When the wind speed isn't ample to satisfy the load demand, the FC system will meet the surplus power demand whereas the UC will meet the load demand higher than maximum power available from the FC for a brief duration. The fuel cell suppresses the effects of fluctuations and harmonics that are occurred by the change in wind speed.*

KEYWORDS: Dynamic model, Wind power, Fuel cell, Ultra-capacitor, Renewable energy and hybrid power generation

INTRODUCTION:

Studies recommend that in next fifty years, a massive portion of the Non-Renewable fuel resources obtainable are depleting. Research concern has to shift towards rising the performance in the generation of electricity through renewable resources available extravagantly in nature. These Non-Renewable sources can be harvested from the nature resulting in generation of clean, eco-friendly and sustaining power which can be used as an alternative to the increasing demand. Of all the Non-Renewable sources available, the advanced research is carried out on wind energy, the world's fastest growing energy source expanding globally at a very good rate of 30-40% annually in last ten years. Wind is the element that is available in nature and is variable in nature, resulting in fluctuating speeds at the output of the turbine. At isolated areas also, where there is no inter-grid connection available, wind systems become a suitable choice and it is well known that to maintain the grid at its nominal values there should be no fluctuations in the parameters. These variable speeds became the root cause for variations in voltage and power fluctuation problems at load side. This drawback can be sorted out via power electronic converters and adapting different control strategies. By using power converters, we can limit the fluctuations in the system, there is still a problem with the storage of the energy generated by the turbine for future use when there is no source for required wind speed but there exists load demand.

One of the solutions for the storage is by using the converters, where by using proper conversion parameters the wind energy produced can be converted and stored in the form of hydrogen, which will be converted to electrical energy via fuel cell (FC). When compared to the conventional battery storage systems-

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these FC systems are significantly advantageous in terms of energy density and long-term storage [2,3]. The use of electrolyzer helps in synthesis of hydrogen there by allowing for both storage and transportation of large amounts of power at higher energy densities. Thus, by collaborating a hydrogen generation system to wind-based generation helps in reducing the dependency on the fossil fuels [4,5].According to Ref. [6,7], wind electrolysis is an innovative process for economically sustainable renewable-hydrogen production system. Furthermore, coupling wind turbines with electrolyzers has the potential to provide low-cost, environmentally friendly distributed generation of hydrogen in addition to electricity [4]. Thus, the stored hydrogen energy can be used by FC power plants during the low wind speed conditions.FC plants involve electro chemical reactions where oxygen and hydrogen are converted from chemical form to electrical energy. Of all the various types of FC systems available proton exchange membrane (PEM) FC power plants are found to be especially suitable for hybrid energy systems because of their higher power density and lower operating temperature.

Ultra Capacitor (UC) can be defined as a super capacitor or electric double layer capacitor, which is a large capacitance device. UC is more efficient than the battery due to the limitation on a life cycle, the prompt storage and stored energy consumption. By integrating UC to the FC system the overall performance of the hybrid power system model for variable loads is significantly increased there by making economic sense during peak power demands and transient events. The energy density for the UC is high and can be used as an alternative to FC by supporting the system during low wind speed conditions. With integration of FC and UC systems into hybrid power system there are considerable economic conditions like plant size and cost of the system.

In this thesis, a detailed analysis simulation and modeling of hybrid power system with integration of wind-FC-UC is developed by using a novel technique to complement and alleviate effects of wind speed variations. The dynamic modeling and simulation of wind/FC/UC hybrid power system is reported which is modified for this study, here the system is integrated with wind generator, electrolyzer and storage models. Modeling and simulation are performed in MATLAB 2010, the system specifications are, I3 processor with 6GB Ram and 1GB graphics. The modeling was done in Simulink and Sim-power-systems software packages to endorse the effectiveness of the hybrid system.

SYSTEM DESCRIPTION:

In this section, simulation of dynamic model for the FC/UC/wind hybrid power generation system is studied. The model consistsof a wind turbine system, an induction generator with capacitor for power factor correction, an AC/DC thyristor controllable double bridge rectifier whose firing angle is controlled through PI controller, an FC/UC system with a boost type DC/DC converter whose duty cycle is controlled by PI controller, two DC/AC IGBT inverters for gate signals, and a coupling transformer on the load side.Fig.1 shows the integrated system.

BLOCK DIAGRAM:

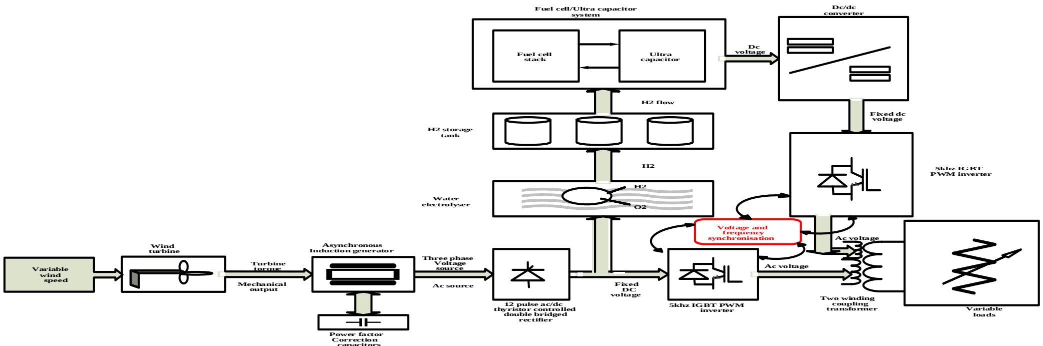

Fig. 1: Block diagram of the proposed system

DYNAMIC MODEL OF WIND TURBINE:

In this thesis, study of distinct models of wind turbines and wind power driven generators has beenexplained[1, 2].Proposed model exhibits the characteristics of wind speed versus turbine output power. The mathematical modeling of the proposed system is as follows.

A_t – turbine swept area (m^2)

μ - turbine's performance coefficient

μ_{pu} – per unit value of turbine's performance coefficient

G_p – power gain for the $\mu_{PU} = 1$ and $\omega_{pu}=1.,G_p \leq 1$

M_{out} – mechanical power output of turbine (WATTS)

M_{out-pu} – power in PU of nominal power of a particular value of ρ and A_t

θ –blade pitch angle (degrees)

Ψ- tip speed ratio of rotor blade tip speed to wind speed

ρ- air density ($Kg(m^3)^{-1}$)

ω – wind speed ($m\ s^{-1}$)

ω_{pu} – per unit wind speed

The mechanical output power of the turbine model is given as follows

$M_{out} = \mu(\Psi,\theta)\frac{\rho A_t}{2}\omega^3$ -------------- (1)

Eq. (1), can be simplified further for precise values of ρ and A_t. This new equation represents the per unit system of mechanical output power of the wind turbine system as

$M_{out-pu} = G_p \mu_{pu} \omega^3_{pu}$------------------ (2)

The modified simulation model of the proposed wind turbine system is depicted in the Fig. 2[2]. In this model the generator speed and wind speed are the inputs and the mechanical torque applied to the generator shaft is the output for the turbine model.

DYNAMIC MODELLING OF FUEL CELL:

The PEMFC also known as polymer electrolyte membrane fuel cell model is described in Ref [7,9] and Ref [10,12].is further studied and modified in Simulink for this model. This model works based on the relationship between the partial pressure of hydrogen, oxygen,water and the output voltage. Fig 3 illustrates detailed model of PEMFC, this model is embedded in the MATLAB model of Sim-Power Systems as a controlled voltage source integrating overall system model.

In MATLAB, "log 10" and "log" are used as logarithmic commands within the Simulink blocks as shown in Fig. 3. Here the use of base-10 logarithm in the Nernst equation and base-e logarithm in the activation voltage equation. Also, in the Simulink model of the FC system, for better understanding the input variables of the function blocks must be denoted with lowercase 'u' as shown in Fcn1, Fcn2 and Fcn3 blocks.

In the FC system the amount of hydrogen consumed depends directly on the load demand. The hydrogen required is obtained from storage tank. The rate of flow of hydrogen is controlled to regulate the FC power output. This control strategy is a feedback-based control where the FC current output is feed back to the input.

DYNAMIC MODELLING OF ULTRA-CAPACITOR:

The mathematical modelling of the system is as follows and the parameters are stated below

C – Capacitance (F)

C_{uc} – total capacitance of ultra - capacitor system (F)

E_{PR} – equivalent parallel resistance (Ω)

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E_{SR} – equivalent series resistance (Ω)

ε_{uc} -Energy released or captured by UC bank

n_s – Number of capacitors connected in series

n_p – number of capacitors connected in parallel

R_{uc} – total resistance of ultra - capacitor system

$V_{uc\text{-}i}$ – initial voltage of capacitor before discharging starts

$V_{uc\text{-}f}$ – final voltage of capacitor after discharging ends

The equivalent circuit of ultra-capacitor bank is illustrated in Fig.4. This circuit consists of C(capacitance), E_{SR} equivalent resistance in series and E_{PR} equivalent resistance inparallel represents the self-discharging losses.

The energy drawn by the UC bank is directly proportional to capacitance and change in initial and final voltages which can be expressed as

$\varepsilon_{uc} = \frac{1}{2}C\,(V_{u}^{2}{}_{-i} - V_{u}^{2}{}_{-f})$ - - -- - - - - - - - - - - (3)

When the UC bank is supplied with sufficient amount of energy, the terminal voltage of the UC bank decreases. Eq.11 represents the relationship between the energy drawn or released by ultra-capacitor bank and voltage variation. The energy value of an UC bank is positive, when the UC bank releases the energy to the load side and it is negative if the energy is absorbed by the UC bank.

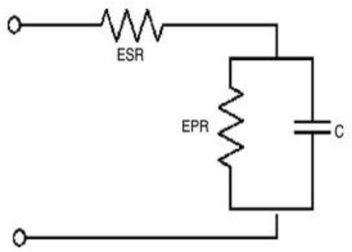

Fig.4 Equivalent circuit

Depending upon the load specifications, the effective energy required for the load can be supplied through different configurations of UC bank. In general, the practical model consists of a number of units of UCs connected in series and parallel which supplies the required terminal voltage and energy or capacitance to the UC storage system effectively. The series and parallel capacitors of the UC system determines the terminal voltage and the total capacitance. The total resistance and capacitance of the system can be calculated as,

$R_{uc} = n_s \frac{E_s}{n_p}$-------------------------------------- (4)

$C_{uc} = n_p \frac{C}{n_s}$-- (5)

During a short-term peak load demand the UC units arranged in the UC bank are sufficiently capable to satisfy the load demand [9, 10]. The UC bank model required is implemented in the Sim-Power Systems of MATLAB.

ELECTROLYZER MODEL:

In general, when electric current is passed between two electrodes separated by an aqueous electrolyte there by resulting in decomposition to its basic elements. This process is known as electrolysis. When such electrochemical reaction of water results in formation of hydrogen and oxygen molecules through decomposition and is given by

H_2O + electrical energy $\quad H_2 + \frac{1}{2}O_2 \longrightarrow$ - - - - - - (6)

The model involves following parameters

F – Faradays constant

I_e – electrolyzer current

n_e – number of electrolyzer cells in series

η_f – faradays efficiency

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N_H – produced hydrogen moles per sec

According to faraday's law, rate of hydrogen produced in an electrolyzer is directly proportional to the amount of electric current induced in the equivalent electrolyzer circuit [11].

$$N_H = \frac{\eta_f \; n_e I_e}{2F} \text{-- -} (7)$$

The ratio between the theoretical and actual amount of maximum hydrogen produced in the electrolyzer system is defined as Faraday's Efficiency. Here the working temperature is assumed to be 40 and is expressed as

$$\eta_f = 96.5e^{(0.0 \quad /I_e - 7 \quad .5/I_e^2)} \text{----------------} (8)$$

The voltage current characteristic of the electrolyzer (Von Hoerner) model is represented by the input resistance of the electrolyzer temperatures ranging between 39 and 52 .The operating point of the model performs sufficiently at 45 Amps and 50 Volts.Therefore, the DC bus Voltage of the electrolyzer is fixed at 400V using power electronic controller bridge (Two level thyristor), to producesufficient amount of Hydrogen it requires eight suchElectrolyzer units used in series (45A-400V).

POWER CONDITIONING UNIT OF THE SYSTEM BUS:

In the proposed model, the strategy used for the power control is based on the load demand if the output of the wind system alone can provide sufficient power for load and electrolyzer unit. When wind speed is reduced, the deficit power is provided by the hydrogen produced in the electrolyzer which is used in the FC system to provide the power required by the model. Under normal circumstances, if the total demand of the system exceeds the produced power by the FC unit the deficit power is supplied by the UC units to satisfy the load demand. To implement the prior mentioned strategy for power management, suitable power controllers are used at pertinent points by integrating all the system components. In the model shown in Fig. 7 depicts the control mechanism based on two fixed DC buses integrated with power electronic equipment into the system.

POWER CONDITIONING OF WIND TURBINE OUTPUT:

It is a known fact that the speed of the wind is volatile in nature, this variation in speed results in fluctuations in frequency and amplitude of the output voltage produced by the generator coupled to turbine. To regulate the fluctuations in the conditioning model instead of a normal voltage and frequency regulator we use a power electronic double bridge converter on the ac bus. This bridge circuit has a fixed voltage level thus by converting this voltage to ac we can stabilize the fluctuations.

The double bridge rectifier causes less harmonic distortions on the source side due to low commutation time, also has a controllable DC output voltage with a 12-pulse power electronic ac/dc converter with a firing angle α which is controlled by a PI controller.

UC CHARGE – DISCHARGE CONTROL SYSTEM:

In this section, we present the control mechanism of the UC bank during load sharing with FC system when operated simultaneously with wind turbine system. FC system has poor reliability during instantaneous and short-term peak load demand, by using UC banks we can assist the FC systems to achieve good performance and also reduce in size and cost of FC system.

The integration of the FC system with UC can be done not only by using power electronic circuits but also can be done using series or parallel connections. In the study, we integrated the UC bank and FC system using semiconductor switches S1 and S2 which are used to control the power sharing between both the systems. Under normal functioning S1 is closed and provides a path for excess power to flow to UC and S2 is open. During high power demand condition, the FC system generates the rated powerthe deficit power is supplied by the UC system, at this period both the FC and UC system starts discharging, S1 is open and S2 is closed providing path for UC to discharge along D2 satisfying the load demand. FC system discharges over

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Diode D1. During this scenario the over loading of the FC by the UC system is blocked by the D1 as it doesn't allow flow of reverse current from UC system.

FC/UC OUTPUT POWER CONTROLLER:

Based on the model dynamics, the output voltage of FC system is decreased due to increased load demand. Thus, a boost type DC/DC converter is used to maintain the voltage value t o 400V at the output. A MOSFET type semiconductor switch is used as gate in the converter, the generated gate pulse is given to a PI controller-based system for determining the duty cycle to the load side voltage.

DC/AC CONVERTER TO LOAD SIDE:

In the system, earlier we have generated two fixed DC voltages are now converted to AC voltages using IGBT and PWM inverters as shown in Fig. 7. These inverters have a fixed DC input thus a three-phase ac output voltage of same amplitude and frequency is generated using a PWM generator, providing a gate signal to the inverter elements by controlling both the inverters.

The voltage equations and parameters required for the Inverter are illustrated below

$V_{L\text{-}L} = \frac{\sqrt{3}}{2\sqrt{2}} m V_{Dc}$ -------------------- (9)

Where,

m – Modulation index

V_{Dc} – inverter's DC input voltage

$V_{L\text{-}L}$ – inverter line to line output voltage

SIMULATION RESULTS:

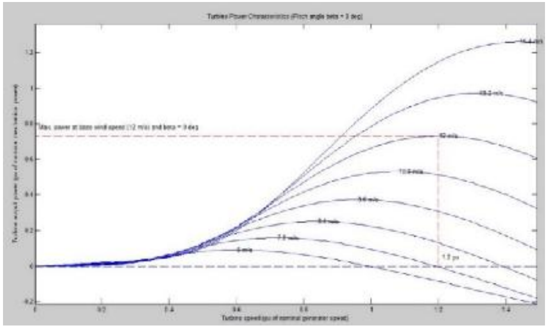

Fig.17 Power satisfied by the UC system

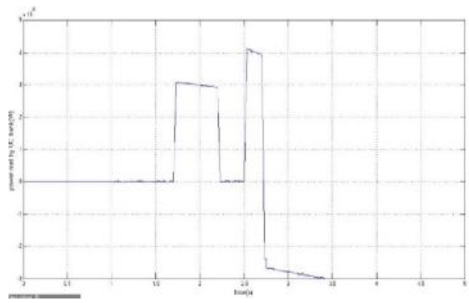

Fig.10 Wind turbine characteristics

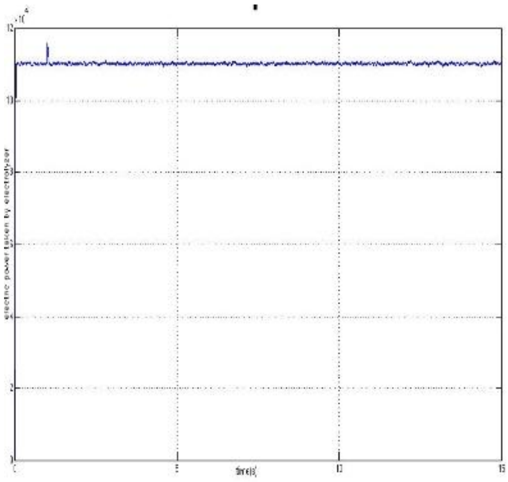

Fig.12 Electric power taken by electrolyzer

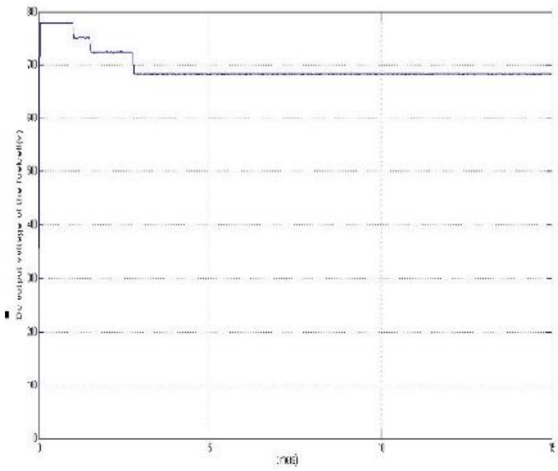

Fig.13 Output dc voltage of fuel cell

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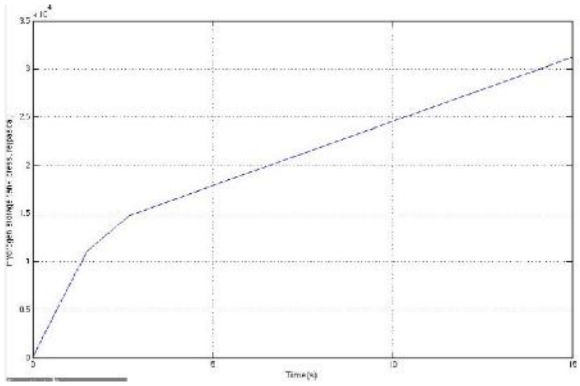


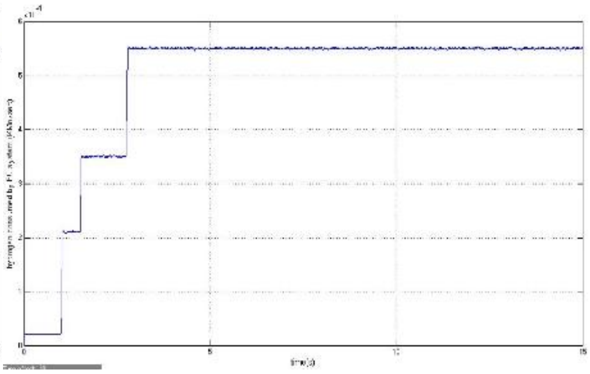
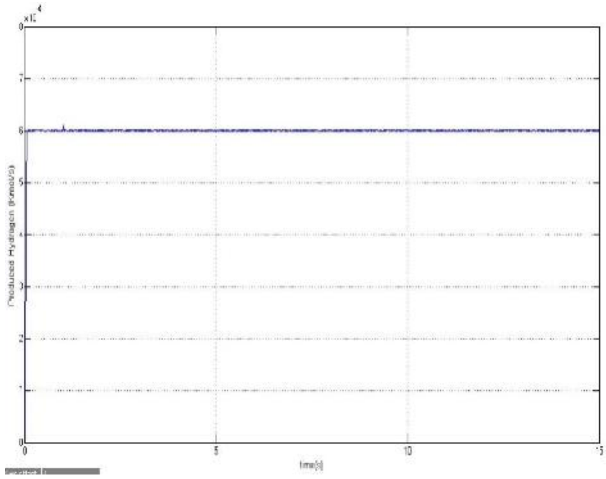


Fig.14 Hydrogen storage tank pressure

Fig.15 Hydrogen consumed by FC system



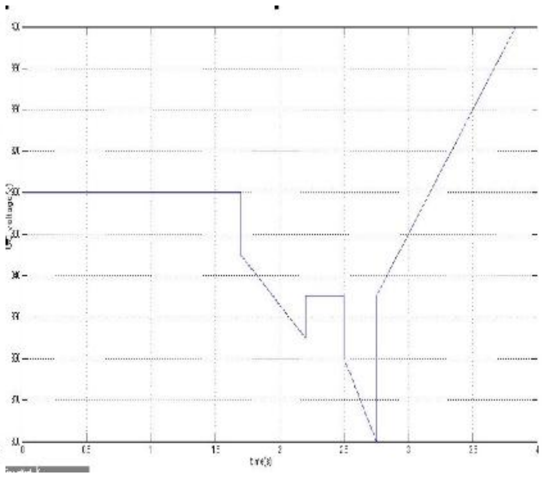
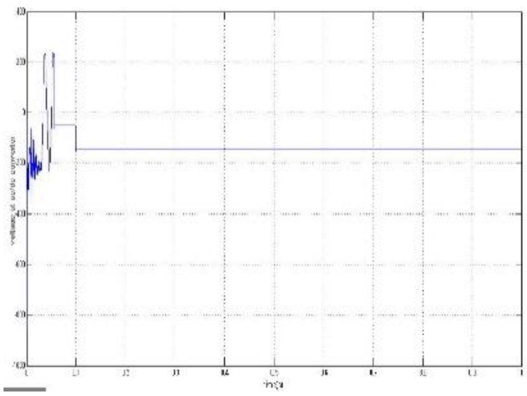


Fig.18 Produced amount of Hydrogen

Fig.19 UC bank voltage variation as a function of time



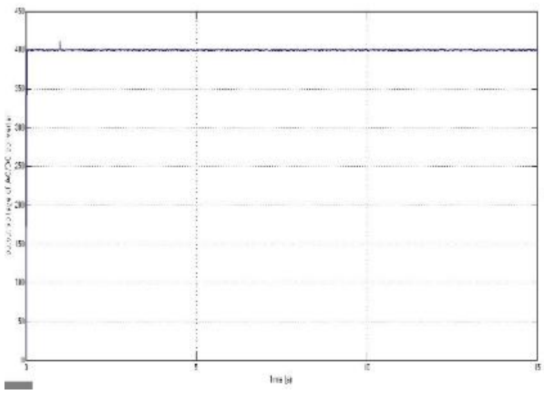


Fig.20 voltage at ac/dc converter system

Fig.21 Output voltage of ac/dc converter

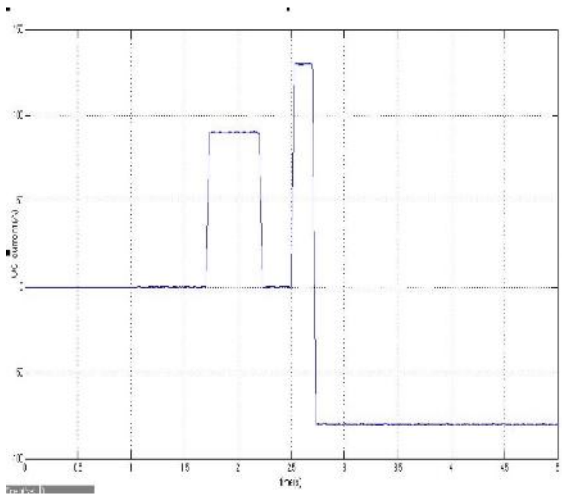


Fig.22 UC current change with respect to power demand

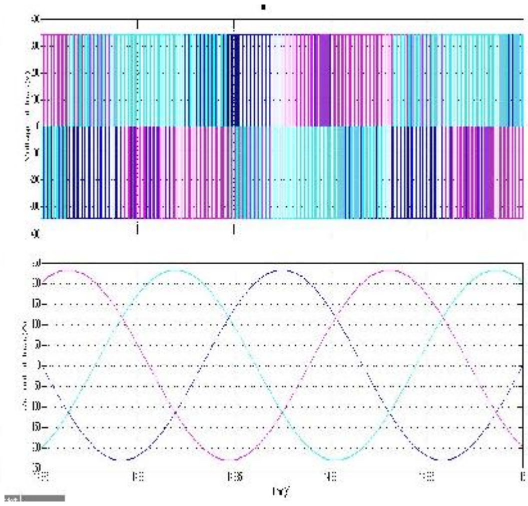


Fig.23 Voltage and current met by load

CONCLUSION:

In this paper -A hybrid power generation system is suggested for obtaining the capability to individually generate a reliable power source at isolated areas where there is no inter-grid connection available. Since, the standard renewable energy available at most of the areas is wind, we tend to harvest this energy in to electricity. The disadvantages like variable wind speed and voltage level fluctuations are surpassed by inclusion of fuel cell and ultra- capacitor technologies in this generation system. A dynamic modelling and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system is carried out. The simulation results have showcased a good reliable rate of implementable hybrid system in real life situations.

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