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

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ABSTRACT: *Studies suggest that in next 50 years, large portion of the Non-Renewable fuel resources available are depleting. Research concern has to shift towards improving the performance in generation of electricity through renewable resources available abundantly in nature. In recent days, combination of various systems is a trending research topic because a single system may not be delivering all the desired characteristics. In wind generation systems, few cons like variable wind speed and voltage level fluctuations are considered to be undesirable. So, fuel cell and ultra-capacitor systems are combined in order to suppress these limitations, forming a hybrid wind power generation system. In this paper, A dynamic modelling and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system is carried out. The objective is to focus on the combination of wind/fuel/UC systems for sustained power generation. When the wind speed is not sufficient to meet the load demand, the FC system can meet the excess power demand while the UC can meet the load demand above maximum power available from the FC for short duration. The fuel cell suppresses the effects of fluctuations and harmonics which are occurred by the change in wind speed.*

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

INTRODUCTION:

Energy is the primary requirement for any system to work in this world. For generation of electricity, rotation of the shaft in the generator plays an important role. So, the energy required for this rotation in the generator is obtained to a large extent from the steam evaporated from burning of fuels that are available in the nature. These fuels are Non-Renewable resources which are being depleted continuously due to their extreme usage. Since, they are a dependable standard source of energy, these fuels are also being used in other mechanical systems as well. Scientists have predicted that in next 50 years all the Non-Renewable resources available in the planets will become extinct. So, in order to keep on continuing the same amounts generation of electricity and to meet the extra demand in the future, Researches are being advanced towards developing generation systems having their source of energy from freely available Renewable resources such as wind, water (hydro), solar, geo-thermal etc. Wind is an unlimited source of energy and requires very less area for installation, So, can be easily installed at very densely populated areas also in the coming years unlike thermal plants. At isolated areas also, where there is no inter-grid connection available, wind systems become a suitable choice. But one of the few cons for the wind generation system is that the wind is variable parameter, i.e. it is not always constant. So, the need for proper storage of the excess power generated during high winds is very necessary. So, in order to rectify this problem a good storage and supply system is required, which is capable of meeting the requisite demand during low wind speed periods.

For any wind generation system, a proper turbine system is very important, [1] have presented a model for wind turbine system at different variable wind conditions and the related analysis were carried out on the factors effecting the overall system. pitch control and generator load control strategies were studied. A 3D FEM model of a generation system is with MPPT-based FOC control strategy is modelled and the various performance statistics were shown in-detail [2]. An induction generator coupled to the wind turbine in required energy conversion is studied along with a voltage regulation strategy based on a VAR compensating

equipment [3]. Different hybrid models consisting of Wind -Solar- collaborations were taken as case-studies for a better understanding of the differences in improvement strategies employed in terms of their respective performances [4-6]. The need for the technology to supply high voltages from a fuel cell is presented in [7]. The abilities to swap high voltages is clearly illustrated here. Various optimization techniques involved in implementation of fuel cell and ultra-capacitor technologies are analyzed which included Ant-colony technique and particle swarm optimization techniques [8-9]. A comprehensive literature has been provided in terms of designing the wind generations system with the implementation of fuel cell and ultra-capacitor technologies [10-11]. The problems like voltage fluctuations, wind speed variations, sudden transients, power demand maintenance etc were completely surpassed. [12] has proposed a pragmatic procedure for connecting the generation system designed so far to a working power grid in math lab/sim link environment. The convertor-based technique involved in enhancing the power required for supply into the existing power system is analyzed [13]. An illustrative example having 18650 lithium-ion cells and two 100-F ultracapacitors is studied. [14-15] proposed various equivalent circuit configuration models for placing the capacitors into the system. These literature work on- wind generation systems, fuel cell and ultra- capacitor systems has given a concrete understanding in order to go forward to implement the proposed hybrid power generation system in this particular field of study.
In this paper, the wind turbine is coupled with a fuel cell and parallelly to ultra- capacitor system forming a hybrid generation system altogether, which is solved in a Simulink/math lab platform at varying conditions based on the pragmatic natural environment situations. The simulation results obtained are showcased for analyzing the performance of the proposed hybrid system.

SYSTEM DESCRIPTION:
In this section, simulation of dynamic model for the FC/UC/wind hybrid power generation system are 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:

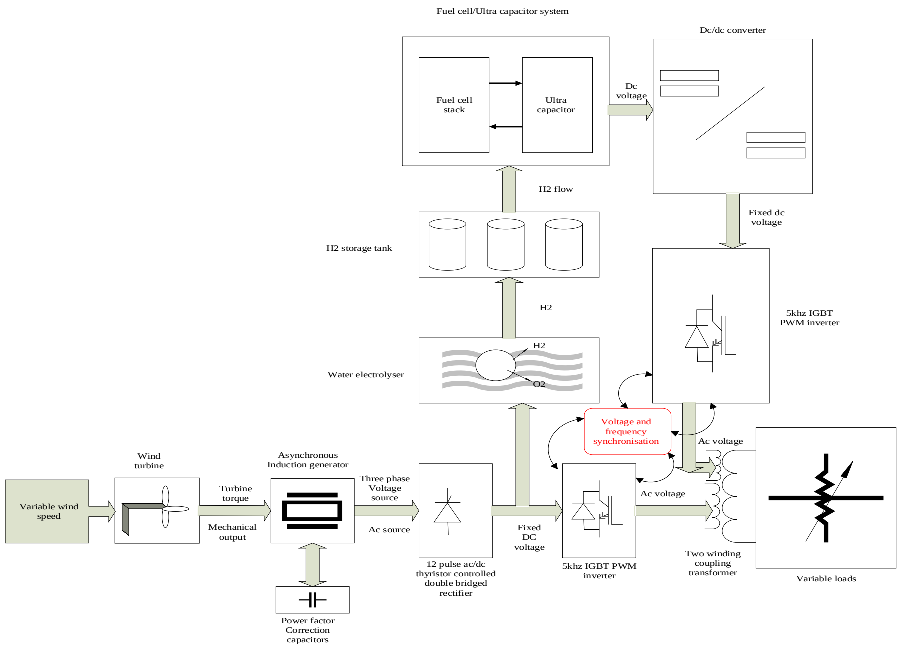


Fig. 1: Block diagram of the proposed system

Dynamic model of wind turbine:

In this thesis, study of distinct models of wind turbines and wind power driven generators have beenexplained[1,2].Proposed model exhibits the characteristics of wind speed versus turbine output power. The mathematical modelling 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 ω_{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.

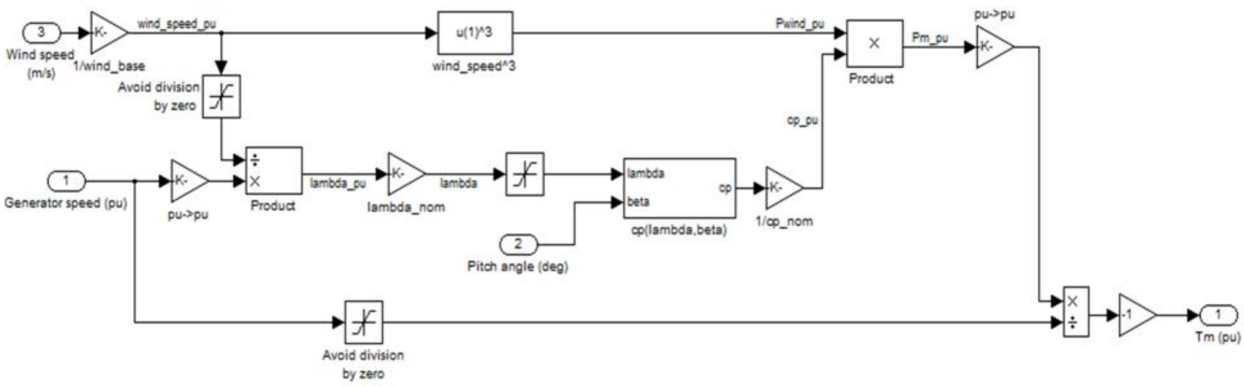


Fig. 2: Simulink model of wind turbine

Dynamic model of asynchronous induction generator:

In this study, the asynchronous induction machine used is a built-in Sim-Power System block which represents as a power generator driven by the turbine model [2,3]. The electrical and mechanical parts described in this model are assembled based on the procedure illustrated in Ref. [3].

Below are the parameters required for modelling of the asynchronous induction generator model.

V_s – stator induced voltage

F_r – Viscous Friction coefficient for rotor and load

f_n – Nominal frequency
I – Inertia constant of rotor and load
i_s – stator current
N_s – synchronous speed in rpm
p – number of pole pairs
E_{out} – electrical power output
M_{in} – mechanical input power
R_c – combined rotor and stator resistance & inductance
L_s – referred to stator
S_n – apparent power output
τ_e – electromagnetic torque
τ_m – mechanical torque of shaft
V_t – terminal voltage of stator
Δ- power angle
β – rotor angular position
ω_v – angular velocity

The asynchronous speed and the angular velocity of the rotor in an asynchronous machine can be articulated as

$N_s = \frac{6}{p} f_n$ -------- (3)

$\omega_v = \frac{2\pi}{6} N_s$ - ------(4)

The mechanical torque whichruns the rotor shaft of the system yields the mechanical input power as

$M_{in} = \tau_m \omega_v$ -----(5)

The derivative of the angular velocity and angular position of the rotor is expressed as

$\frac{d}{d}\omega_v = \frac{1}{2I}(\tau_e - F_r\omega_v - \tau_m)$ --------(6)

&

$\frac{d}{d}\beta = \omega_v$ -------- (7)

The induced and terminal voltages of the stator are related as

$V_t = V_s - (R_c + j2\pi f L_s)\, i_S$ ------- (8)

The real and reactive power together termed as apparent power is the output power for the induction machine model and is defined as

$S_n = 3V_t\, i_s^*$ ------------------- (9)

The active power termed as electrical power output of the induction machine model and is defined as

$E_{out} = 3\frac{V_S V_t}{\sqrt{R_C^2 + (2\pi f l\ s)^2}}$ ----------(10)

In this model, the induction machine rotor windings are short circuited (squirrel cage induction machine) and the required mechanical torque is produced by the wind turbine which is interconnected to the rotor shaft of the machine which depends on the wind and generator speed values. Thus, the load is connected to the electrical power output of the model, i.e., the stator windings of the machine.

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. The parameters used to explain the FC model are as follows,

B, C constants to simulate the activation over voltage in PEMFC system [A−1] and [V]

E_0 standard no load voltage [V]

F Faraday's constant [C kmol−1]

K_{H2} hydrogen valve molar constant [kmol (atm s)$^{-1}$]

K_{H2O} water valve molar constant [kmol (atm s)$^{-1}$]

K_{O2} oxygen valve molar constant [kmol (atm s)$^{-1}$]

K_r modeling constant [kmol (s A)$^{-1}$]

P_{H2} hydrogen partial pressure [atm]

P_{H2O} water partial pressure [atm]

P_{O2} oxygen partial pressure [atm]

q_{O2} input molar flow of hydrogen [kmol s^{-1}]

R universal gas constant [(1 atm) (kmol K)$^{-1}$]

T absolute temperature [K]

η_{act} activation over voltage [V]

η_{ohmic} Ohmic over voltage [V]

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.

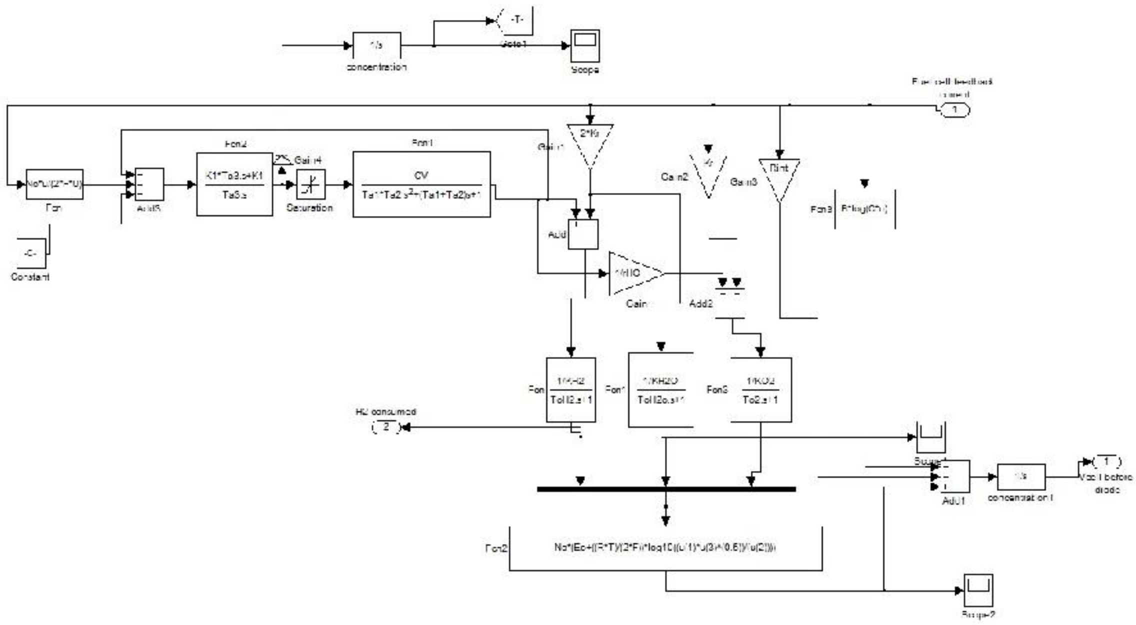


Fig. 3: Dynamic model of FC System

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)

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

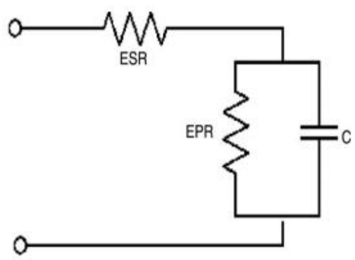
V_{uc-i} – initial voltage of capacitor before discharging starts

V_{uc-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

$\varepsilon_{uc} = \frac{1}{2}C\,(V_u^2{}_{-i} - V_u^2{}_{-f})$ - - -- - - - - - - - - - - - (11)



When the UC bank is supplied by 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,

$R_{uc} = n_s\frac{E_S}{n_p}$ ---------------------------------------(12)

$C_{uc} = n_p\frac{C}{n_s}$--(13)

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 $\longrightarrow$ $H_2 + \frac{1}{2}O_2$ - - - - - - (14)

The model involves following parameters

F – faradays constant

I_e – electrolyzer current

n_e – number of electrolyzer cells in series

η_f – faradays efficiency

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].

$$N_H = \frac{\eta_f \, n_e I_e}{2F} \text{ ------------------------- (15)}$$

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

$$\eta_f = 96.5e^{(0.0 \quad /I_e - 7 \quad .5/I_e^2)} \text{----------------(16)}$$

The below Simulink diagram is constructed using the Equations 15 and 16

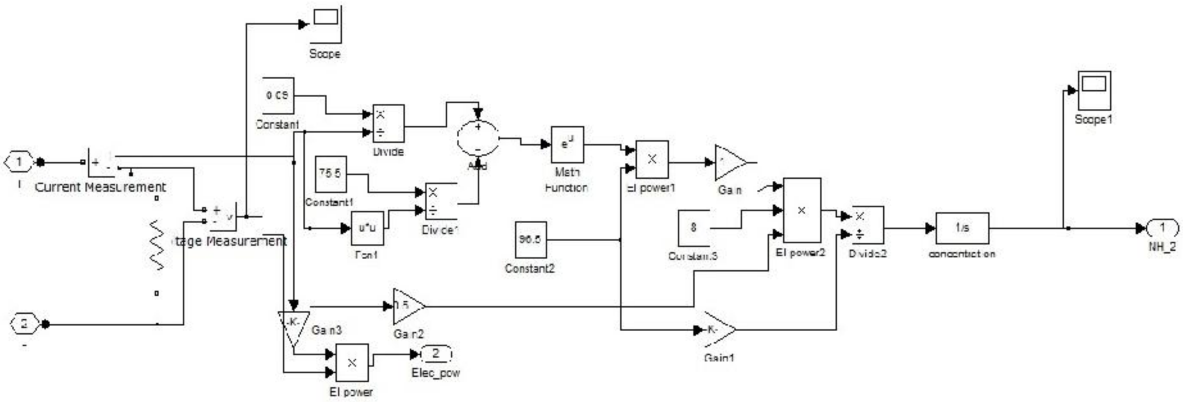


Fig. 5: Simulink diagram of Electrolyzer Model

The voltage current characteristics 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 such Electrolyzer units used in series(45A-400V).

Hydrogen storage system:

The electrolyzer directly supplies the required amount of hydrogen for the PEMFC depending on the relation between the output power and hydrogen requirement of the PEMFC. The excess amount of hydrogen produced (the difference in the amount of hydrogen required in the PEMFC to the amount produced in the electrolyzer) is directly stored in the Hydrogen Storage System.

The storage technique employed in this paper is physical hydrogen storage, this implicates use of tanks to storage either in compressed gas or liquid form of hydrogen. The hydrogen storage model is analyzed based on the Eq. 17 thus directly calculates the tank pressure using the ratio of inflow of hydrogen to the tank. The dynamics of the storage system are as follows

$$P_T - P_{Ti} = z\frac{N_h R}{M_h V_T} \text{ --------------------------- (17)}$$

The hydrogen storage system parameters are as follows

M_h – molar mass of hydrogen

N_h – hydrogen moles per second delivered to the storage tank

P_T – tank's pressure

P_{Ti} – storage tank initial pressure

R – Rydberg gas constant

T – operating temperature

V_T – volume of the tank

z – compressibility factor as a function of pressure

our calculations don't involve the influence of the compression dynamics or the compression energy requirements as they are neglected. In this dynamic storage model, we neglected the involvement of power for pump, valves, fan and compression motors. The Simulink model of the hydrogen storage system is illustrated below in Fig. 6

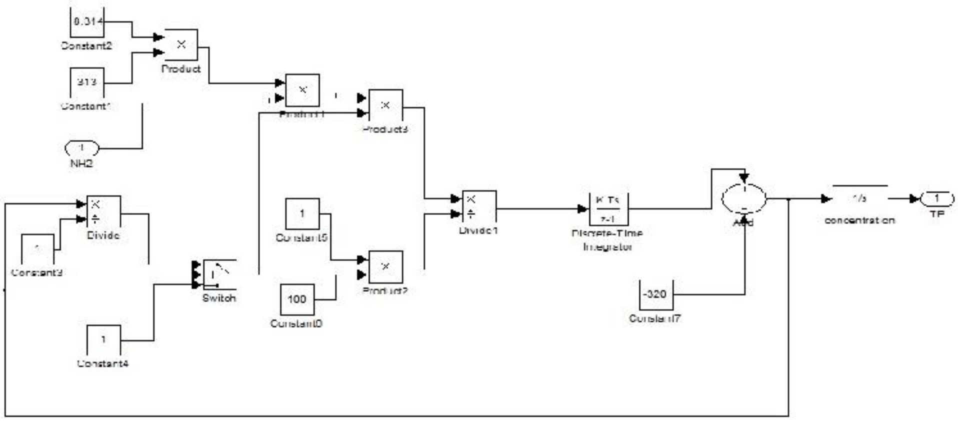


Fig. 6: Simulink model of Hydrogen system

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.

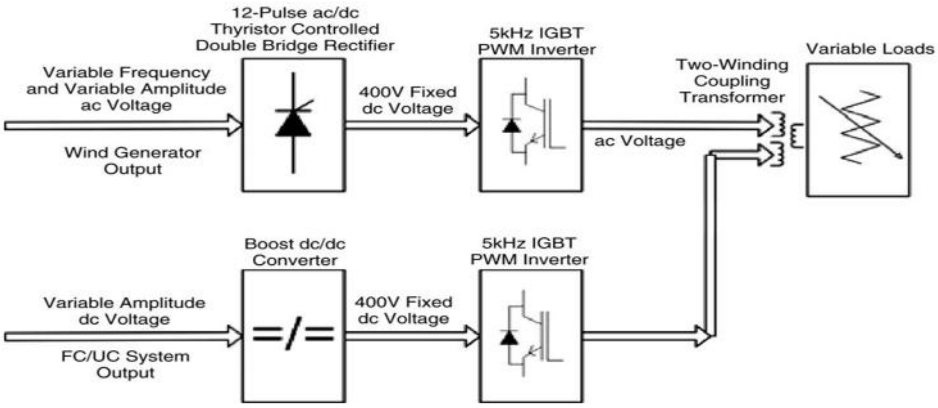


Fig. 7: power controllers of the system bus

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.

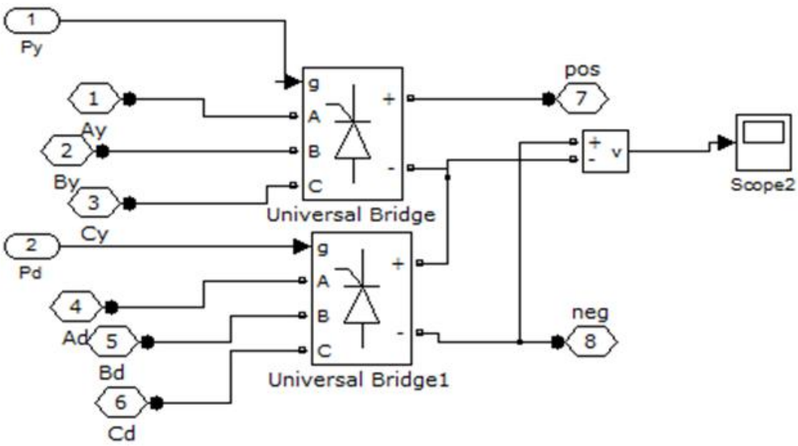


Fig. 8: Double Bridge thyristor-controlled AC-DC converter

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. The schematic double bridge rectifier is shown in Fig. 8

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 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.

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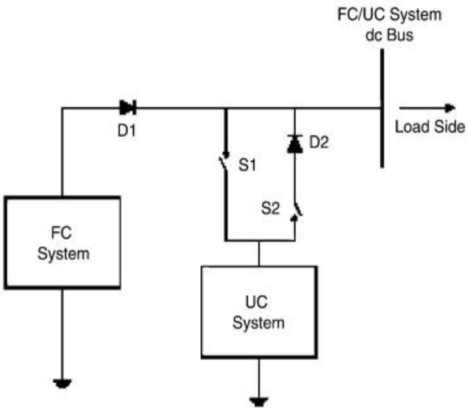

Fig. 9: FC-UC hybrid system

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

$V_{L-L} = \frac{\sqrt{3}}{2\sqrt{2}} m V_{Dc}$ -------------------- (18)

Where,

m – modulation index

V_{Dc} – inverter's DC input voltage

V_{L-L} – inverter line to line output voltage

Simulation results:

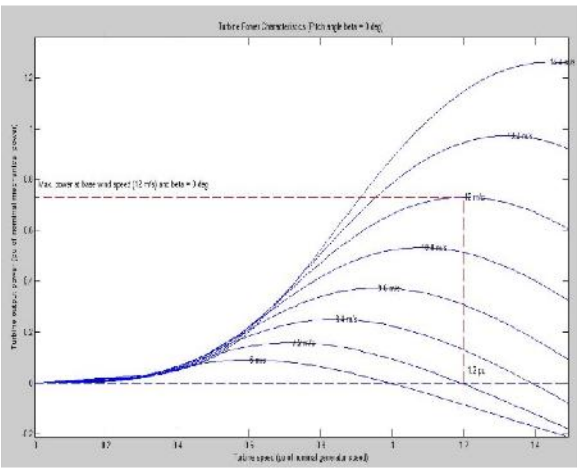

Fig.10 Wind turbine characteristics

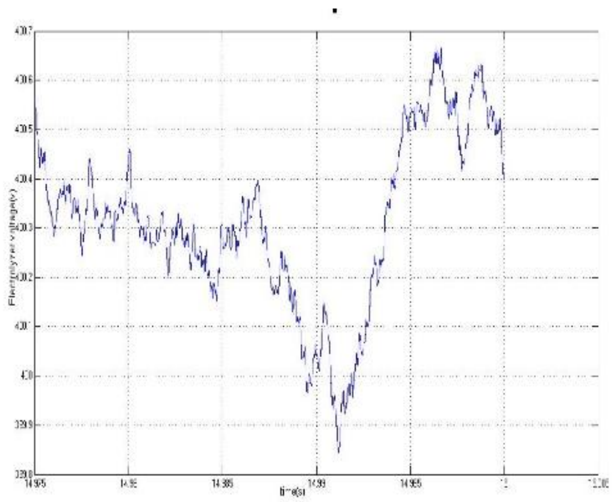

Fig.11 Electrolyzer voltage (dc bus voltage of wind turbine output)

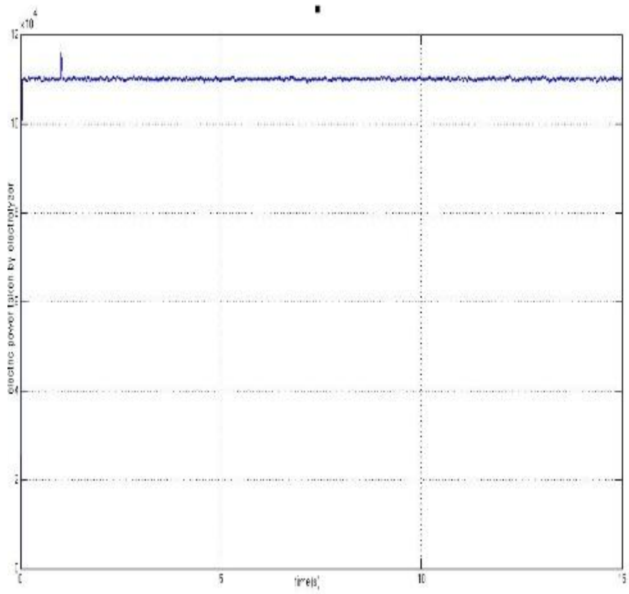

Fig.12 Electric power taken by electrolyzer

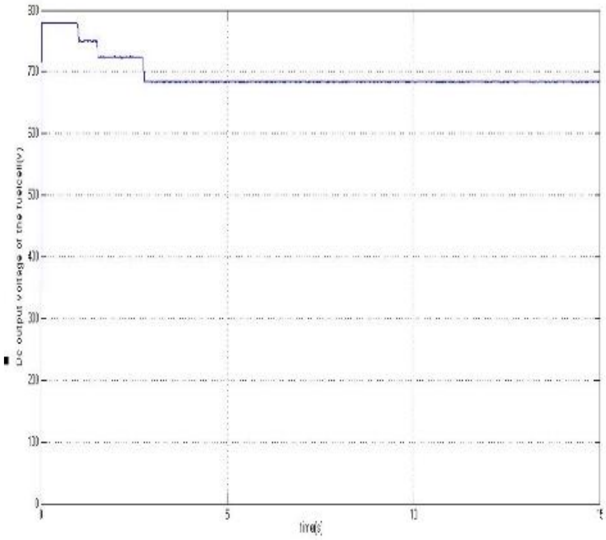

Fig.13 Output dc voltage of fuel cell

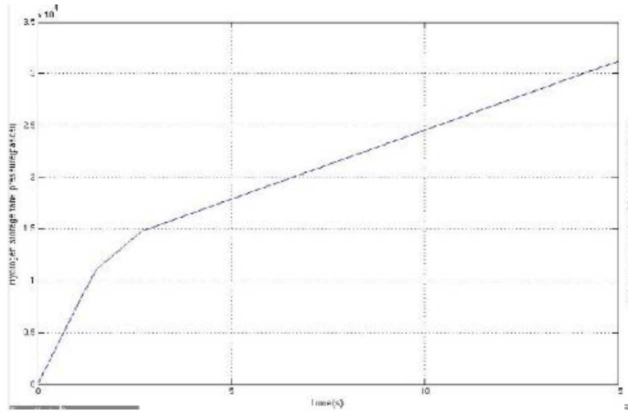

Fig.14 Hydrogen storage tank pressure

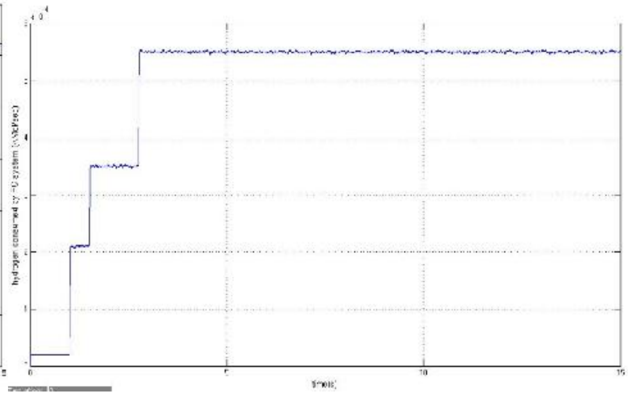

Fig.15 Hydrogen consumed by FC system

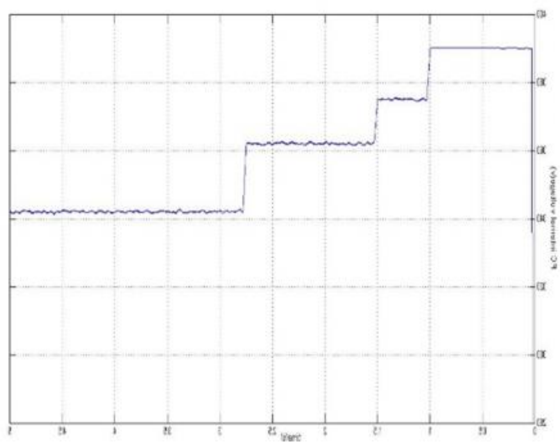

Fig.16 Internal voltage of FC system

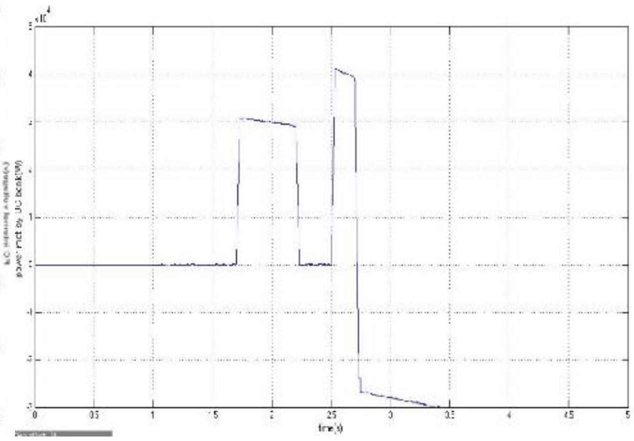

Fig.17 Power satisfied by the UC system

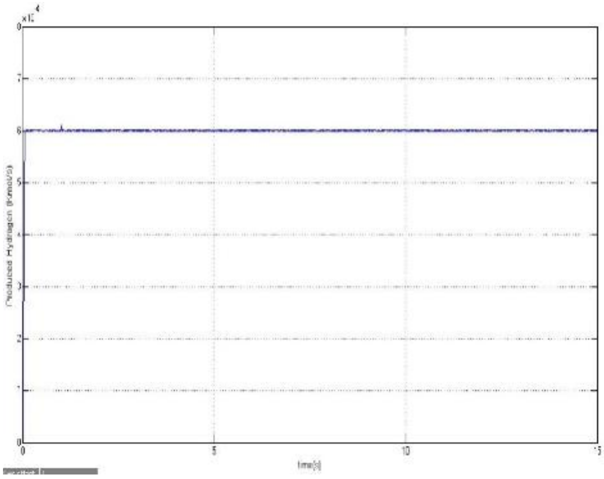

Fig.18 Produced amount of Hydrogen

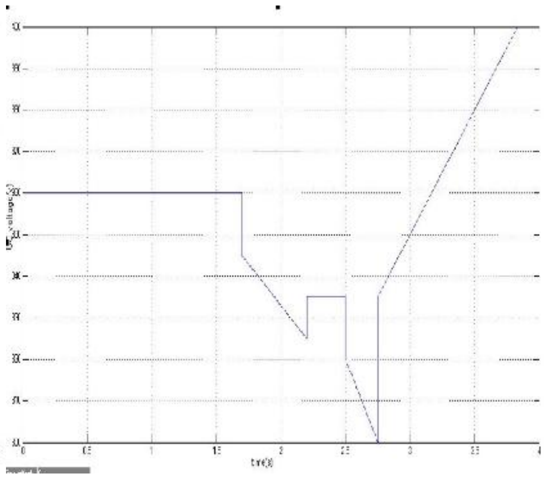

Fig.19 UC bank voltage variation as a function of time

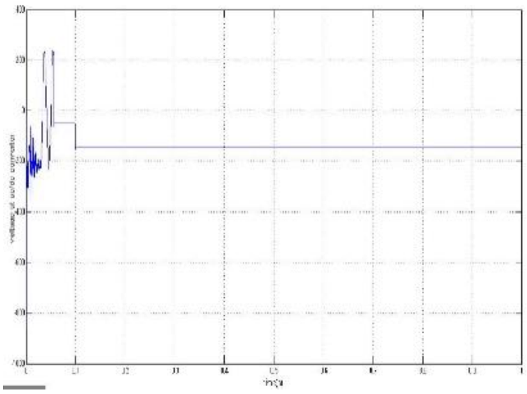

Fig.20 voltage at ac/dc converter system

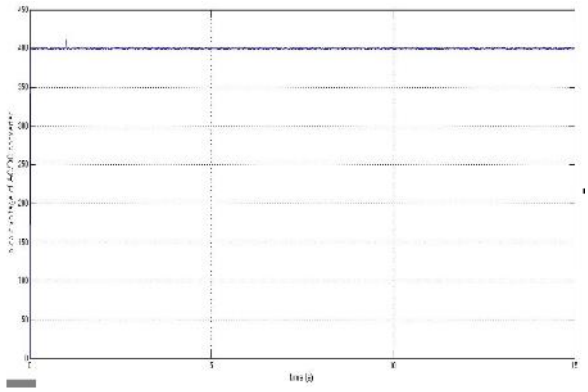

Fig.21 Output voltage of ac/dc converter

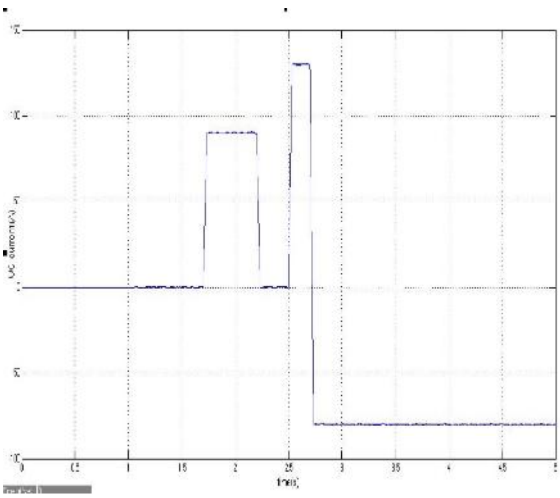

Fig.22 UC current change with respect to power demand

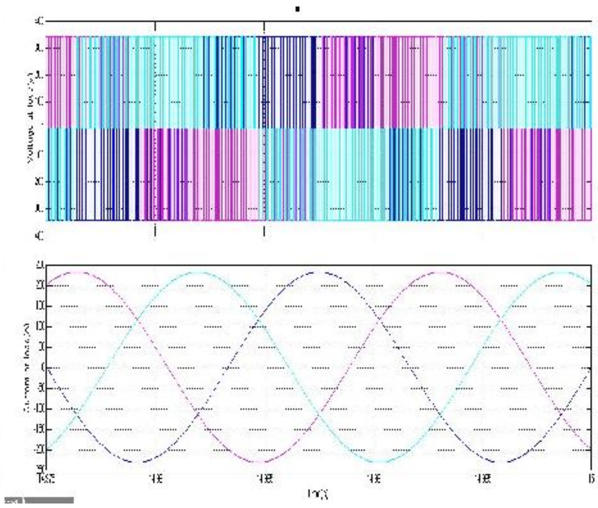

Fig.23 Voltage and current met by load

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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