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Dynamic modeling and control of a wind turbine generator with fuel cell, Ultra capacitor stack as an auxiliary storage

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Abstract -The world has turned its focus towards renewable energy sources due to the depletion of fossil fuels. Nuclear energy seems to hold the long term solution to this energy problem. However we know that nuclear energy has its own downfall in the production and the disposal of the radioactive waste produced. Wind energy and solar energy have gained considerable importance. The main problem associated with wind energy is that, due to unpredictable and varying wind speed, the system cannot be used to supply a constant load demand. This also leads to problems in attaching the wind generation system to a common bus. The same problem exists with solar power generation as well. To overcome this problem in this paper we have proposed a solution by adding a fuel cell, ultra capacitor stack as an auxiliary energy source. This energy source is used to supply the power demand during lack of wind. Furthermore the system is designed in such a way that these fluctuations are tolerated and the system is relatively free of harmonics in by using a new topology.

I. INTRODUCTION

The dependence of economy on depleting fossil fuels and the adverse environmental effects of conventional power generation systems created renewed interest in renewable energy sources toward building a sustainable energy economy in the next decade. Wind as a type of renewable energy has received considerable attention for producing electricity because of its cost competitiveness in comparison with other types of energy which are conventionally used for power generation[1–5]. Wind is a free and abundant source of energy and hence, is attractive in terms of the cost and energy security. However, wind is in nature intermittent and its energy has a large range of variations. This causes significant technical challenges for a wind energy conversion system, particularly when compared with the conventional energy Sources which have a controllable output power. Wind energy is the world's fastest growing energy source, expanding globally at a rate of 25–35% annually over the last decade [1]. 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. Another significant problem is to store the energy generated by wind turbines for future use when no wind is available but the user demand exists [2]. This is achieved by storing the energy generated by the wind by passing it through an electrolyzer. This electrolyzer splits water into hydrogen and oxygen. The hydrogen produced is then stored inside hydrogen storage tanks which can be later used. The generated hydrogen is then used as input to the fuel cell. Fuel cells produce a DC voltage corresponding to the input hydrogen. Thus the fuel cell is used as an auxiliary energy source. The concept of storing the excess wind energy as hydrogen is new and it is significant because hydrogen storage has higher energy density when compared to the use of a conventional battery. By using an electrolyzer, hydrogen conversion allows both storage and transportation of large amounts of power at much higher energy densities [3].

FC power plants use oxygen and hydrogen to convert chemical energy into electrical energy. Among the various types of FC systems, proton exchange membrane (PEM) FC power plants have been found to be especially suitable for hybrid energy systems with higher power density and lower operating temperature. However, assisting an FC power plant with a parallel ultra-capacitor (UC) bank makes economic sense when satisfying the peak power demands or transient events. Ultra-capacitors are electrical energy storage devices with extremely high capacitance values (a few Farads to several thousand Farads per cell) offering high energy densities when compared to conventional capacitors [8]. Without the UC bank, the FC system must supply all power demand thus increasing the size and cost of the FC power plant. This paper introduces a wind conversion system with integrated energy storage. The energy storage serves as an auxiliary source for the wind conversion system during dynamics resulted from the wind power fluctuations and/or load changes. A control strategy is developed that manages the flow of power among the wind-turbine generator, energy storage and the grid, so as the overall wind conversion system is turned into a dispatchable power source.

In this paper, a detailed dynamic model, design and simulation of a wind/FC/UC-based hybrid power generation system is developed using a novel topology to complement each other and to alleviate the effects of wind speed variations. The dynamic PEMFC/UC hybrid power system model reported in Ref. [14] is modified for this study, and integrated with the wind turbine, generator, electrolyzer and storage models. Modeling and simulations are performed using MATLAB, Simulink and SimPowerSystems software packages to verify the effectiveness of the proposed system. Performance of the wind conversion system is evaluated for various operation modes based on digital time-domain simulations in the PSIM software environment.

II. SYSTEM DESCRIPTION

In this section, The dynamic system model is described for the wind/ fuel cell auxiliary storage. The system consists of a wind turbine which is coupled to an asynchronous induction generator. Power factor correction capacitors are installed to improve the power quality of the system. The generator is then connected to a double bridge thyristor controlled rectifier which is fired by pulses from a discrete pulse width generator. This forms the DC bus to which the electrolyser is connected. The electrolyser is then connected to the hydrogen storage system. The hydrogen storage system is connected to the fuel cell and ultra capacitor stack. Two IGBT controlled inverters are employed for inverting the DC voltage. This is then supplied to the load. The entire system is depicted as shown in the Fig 2.1

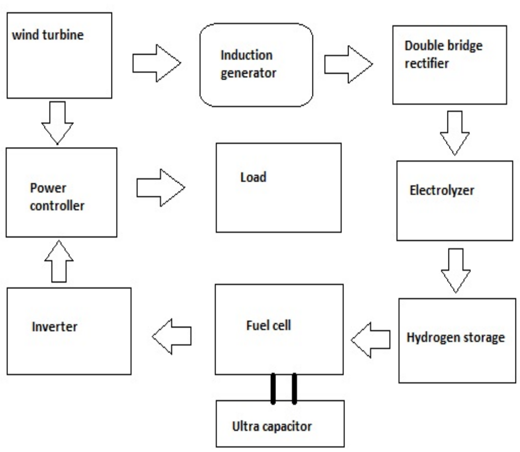

Fig 2.1 Block diagram of the system

III. DESIGN AND MODELLING

A. WIND TURBINE

The model proposed in this paper is based on the wind speed versus wind turbine output power characteristics. The parameters used in the mathematical modeling of the wind turbine are as follows:

A	turbine swept area [m^2]
c_p	performance coefficient of the turbine
c_p	pu per unit (p.u.) value of the performance coefficient cp
k_p	power gain for cp-pu = 1 and υwind pu = 1 p.u., kp ≤1
P_m	mechanical output power of the turbine [W]
$P_{m\text{-}pu}$	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 (m3)$^{-1}$]
υ_{wind}	wind speed [m s^{-1}]
$\upsilon_{wind\text{-}pu}$	p.u. value of the base wind speed. The based wind speed is the mean value of the expected wind (m s^{-1}).

The output power of the wind turbine is given by

$$P_m = c_p(\lambda,\ \beta)\frac{\rho A}{2}\upsilon_{wind}^3. \qquad (1)$$

The modified Simulink model of the turbine is illustrated in Fig. 2.

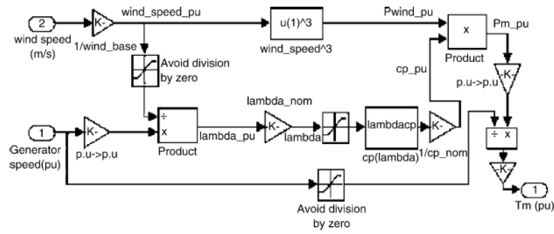

Fig 2.2 Simulink model of a wind turbine

B. ASYNCHRONOUS INDUCTION GENERATOR

The built-in SimPowerSystems block model of an asynchronous induction machine is used as a power generator driven by the wind turbine. The asynchronous induction generator model parameters used in this model are as follows:

f_n	nominal frequency
H	combined rotor and load inertia constant
I_s	stator current
n_s	synchronous rotations per minute
p	number of pole pairs
P_e	electrical power output
P_m	mechanical input power
$R^{'s}$	combined rotor and stator resistance and inductance
$L^{'s}$	referred to stator
S_n	apparent power output
T_e	electromagnetic torque
T_m	shaft mechanical torque
V_s	stator terminal voltage per phase
δ	power angle
θ_m	rotor angular position
ω_m	angular velocity of the rotor

We know that for an asynchronous machine the synchronous speed and the angular velocity of the rotor can be expressed as

$$n_s = \frac{60}{p} f_n, \quad (3)$$

$$\omega_m = \frac{2\pi}{60} n_s. \quad (4)$$

The mechanical torque which drives the rotor shaft of the generator yields the mechanical power output which is given by

$$P_m = T_m \omega_m. \quad (5)$$

The electrical power output of the machine is given by

$$P_e = 3\frac{E_s V_s}{\sqrt{R_s'^2 + (2\pi f L_s')^2}} \sin \delta. \quad (6)$$

In this study, the rotor windings of the generator are short circuited and the rotor shaft is driven by the wind turbine which produces the mechanical torque according to the wind and generator speed values. The loads are connected to the electrical power output of the generator.

C. PEMFC

This model is built using the relationship between output voltage and partial pressure of hydrogen, oxygen and water Units. The parameters used are as follows

E	Nernst instantaneous voltage [V]
E_0	standard no load voltage [V]
F	Faraday's constant [C $kmol^{-1}$]
I_{FC}	FC system current [A]
K_{an}	anode valve constant [K mol kg (atm s)$^{-1}$)]
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)$^{-1}$]
Kr	modeling constant [kmol (s A)$^{-1}$]
M_{H2}	molar mass of hydrogen [kg $kmol^{-1}$]
N_0	number of series fuel cells in the stack
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}]
q_{inH2}	hydrogen input flow [kmol s^{-1}]
$qout_{H2}$	hydrogen output flow [kmol s^{-1}]
q_{rH2}	hydrogen flow that reacts [kmol s^{-1}]
q_{reqH2}	amount of hydrogen flow required to meet the load change (kmol s^{-1})
R	universal gas constant [(1 atm) (kmol K)$^{-1}$]
R_{int}	FC internal resistance [Ω]
R_{H-O}	the hydrogen–oxygen flow ratio
T	absolute temperature [K]
U	utilization rate
V_{an}	volume of the anode [m^3]
V_{cell}	dc output voltage of FC system [V]
τ_{H2}	hydrogen time constant [s]
τ_{O2}	oxygen time constant [s]
τ_{H2O}	water time constant [s]
η_{act}	activation over voltage [V]
η_{ohmic}	Ohmic over voltage [V]

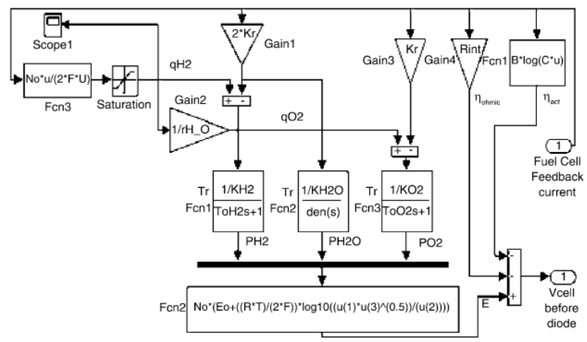

Fig 3. Simulink model of a fuel cell

D. ULTRA CAPACITOR BANK

The parameters used in the ultra capacitor modeling are as follows.

C	capacitance [F]
$C_{UC\text{-}total}$	the total UC system capacitance [F]
EPR	equivalent parallel resistance [Ω]
ESR,	R equivalent series internal resistance[Ω]
E_{UC}	the amount of energy released or captured by the UC bank [W s]
n_s	the number of capacitors connected in series
n_p	the number of series strings in parallel
$R_{UC\text{-}total}$	the total UC system resistance [Ω]
V_i	the initial voltage before discharging starts [V]
V_f	the final voltage after discharging ends [V]

The model consists of a capacitance (*C*), an equivalent series resistance (ESR, *R*) representing the charging and discharging resistance, and an equivalent parallel resistance (EPR) representing the self-discharging losses. The EPR models leakage effects and affects only the long-term energy storage performance of the UC. The amount of energy drawn from the UC bank is directly proportional to the capacitance and the change in the terminal voltage [8], given by the following expression

$$E_{UC} = \frac{1}{2}C(V_i^2 - V_f^2). \quad (7)$$

The total resistance and the total capacitance of the UC bank may be calculated as follows

$$R_{UC\text{-total}} = n_s \frac{ESR}{n_p}, \quad (8)$$

$$C_{UC\text{-total}} = n_p \frac{C}{n_s}. \quad (9)$$

E. ELECTROLYSER

The parameters used in the design of the electrolyzer are as follows.

F Faraday constant [C $kmol^{-1}$]
i_e electrolyzer current [A]
n_c the number of electrolyzer cells in series
η_F Faraday efficiency
n_{H2} produced hydrogen moles per second [mol s^{-1}]

Water can be decomposed into oxygen and hydrogen by passing electricity through it. This reaction is given by the following equation

$$H_2O(l) + \text{electrical energy} \Rightarrow H_2(g) + \frac{1}{2}O_2(g). \quad (10)$$

According to Faraday's law, hydrogen production rate of an electrolyzer cell is directly proportional to the electrical current in the equivalent electrolyzer circuit [2].

$$n_{H_2} = \frac{\eta_F n_C i_e}{2F}. \quad (11)$$

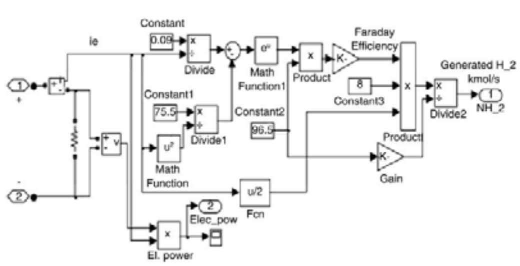

Fig.4 Simulink model of the electrolyzer

F. HYDROGEN STORAGE TANK

The parameters used in the hydrogen storage tank system are as shown below

M_{H2} molar mass of hydrogen [kg $kmol^{-1}$]
N_{H2} hydrogen moles per second delivered to the storage tank [kmol s^{-1}]
P_b pressure of tank [Pa]
P_{bi} initial pressure of the storage tank [Pa]
R universal (Rydberg) gas constant [J ($kmol\ ^\circ K)^{-1}$]
T_b operating temperature [$^\circ$K]
V_b volume of the tank [m^3]
z compressibility factor as a function of pressure

The amount of hydrogen required by the PEMFC is sent directly from the electrolyzer system according to the relationship between the output power and the hydrogen requirement. One of the hydrogen storage techniques is physical hydrogen storage, which involves using tanks to store either compressed hydrogen gas or liquid hydrogen. The hydrogen storage model is based on Eq. (12) and it directly calculates the tank pressure using the ratio of hydrogen flow to the tank.

$$P_b - P_{bi} = z\frac{N_{H_2} R T_b}{M_{H_2} V_b}. \quad (12)$$

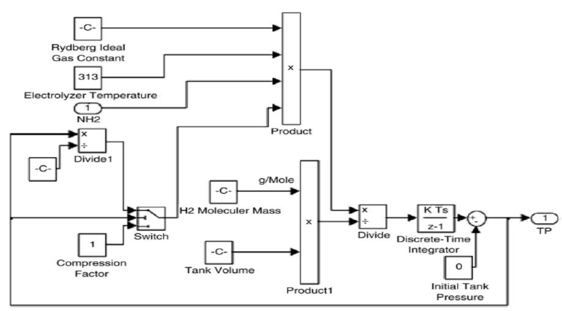

Fig 3. Simulink model of a Hydrogen storage tank

IV. POWER CONDITIONING OF THE SYSTEM

Power conditioning forms a major aspect of this hybrid power generation system. Firstly the output power from the wind generator is rectified by using a double bridge thyristor controlled rectifier system [5]. The main advantage of using the double bridge rectification is that it reduces harmonics. This DC voltage is then fed to the electrolyzer and the hydrogen storage tank. The fuel cell utilizes hydrogen from this system and the amount of hydrogen used can be seen in the storage tank. The fuel cell outputs a DC voltage which is then fed to an IGBT controlled inverter[5]. This inverter inverts the DC voltage into an AC voltage which is then fed to the load.

A power control strategy is used here in such a way that for load demands greater than 32KW the fuel cell ultra capacitor stack is used to supply the demand along with the wind turbine and for values less than 32KW the wind supply alone supplies the system charging the Ultra capacitor and the fuel cell. This mechanism is implemented in MATLAB by using a compare to constant function to which the value of 32KW is given as input. A combination of switches and this block enables the implementation of the above logic.

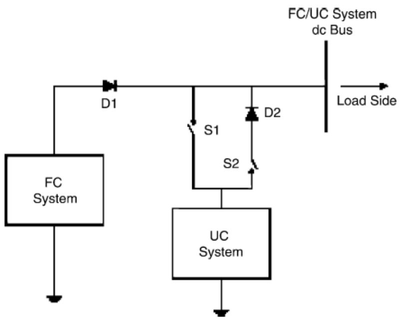

Fig.6 FC/UC hybrid system

V. SIMULATION AND RESULTS

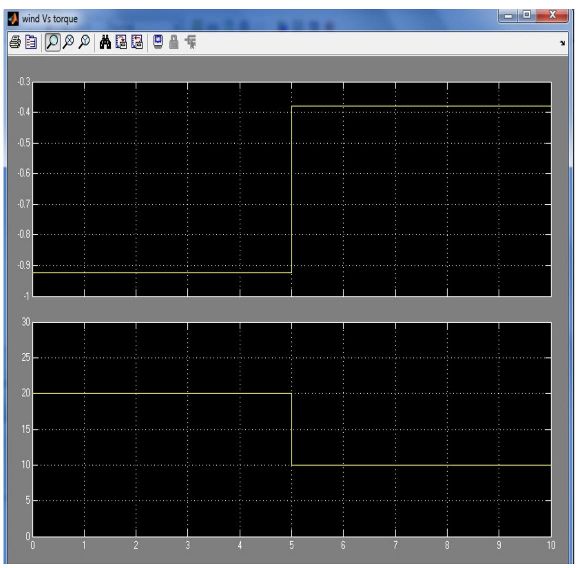

Fig.7 Wind speed Vs Torque developed

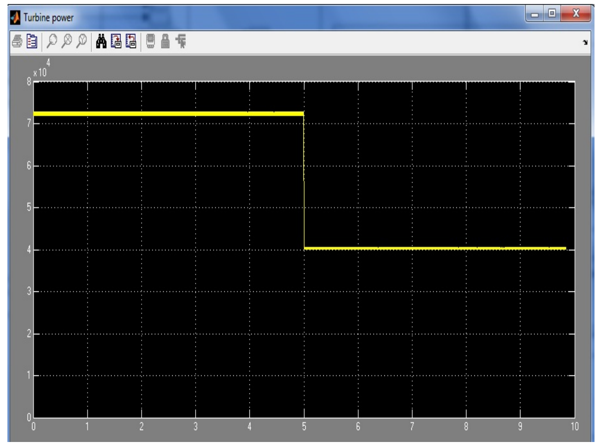

Fig.8 Wind turbine power output

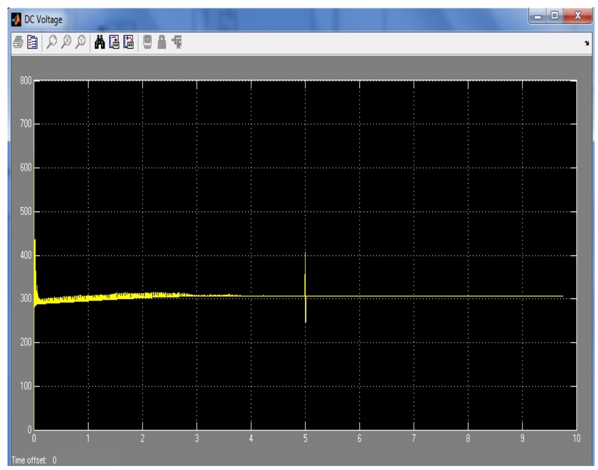

Fig.9 DC Voltage output

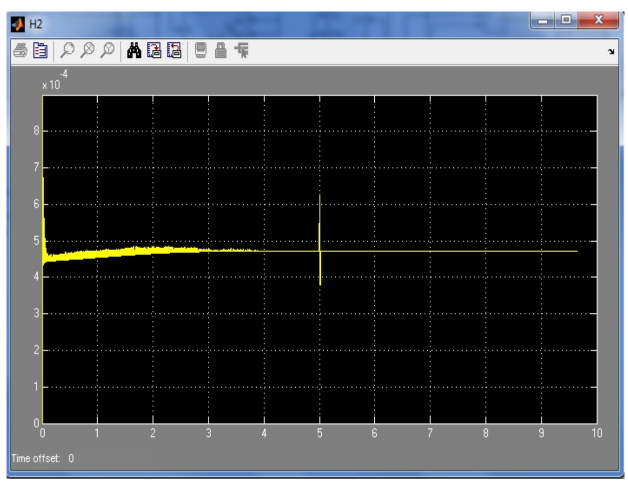

Fig.10 Hydrogen moles stored

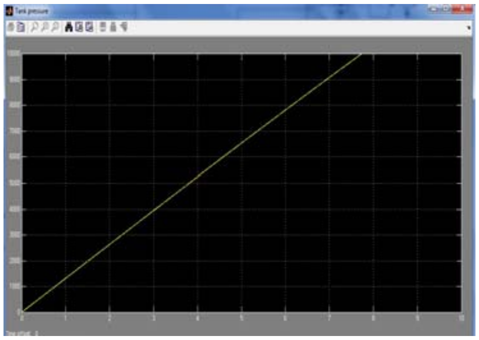

Fig.11 Hydrogen storage tank pressure

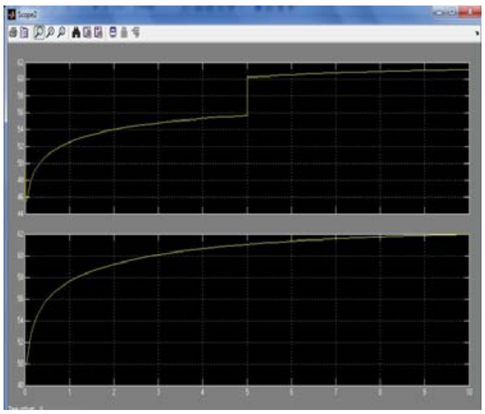

Fig.12 FC/UC combined characteristics

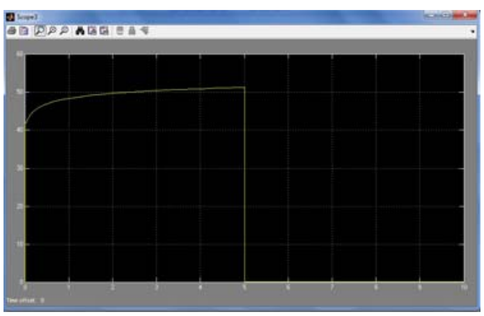

Fig.13 Ultra capacitor charging

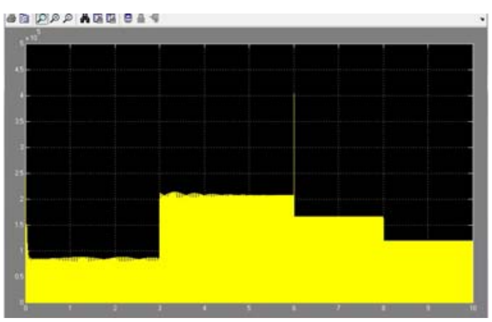

Fig.14 Load characteristics

The torque output of the and the power delivered by the wind turbine are as shown in the fig above. We can see from the output that there is a fluctuation in the DC voltage produced by the rectifier this fluctuation is due to the change in the wind speed. The PI controller is responsible for reducing the fluctuation thereby not affecting the system.

The output of the hydrogen storage tank constant increasing due to the continuous supply of DC voltage to the electrolyzer. The main purpose of using the ultra capacitor along with the fuel cell is that, The Ultra capacitor has very good transient characteristics and can supply a very large amount of power for a very short duration of time.

VI. CONCLUSION

In this paper a new method of combating the fluctuations of the wind speed from affecting the system is developed by using a combined hybrid system comprising of an electrolyzer, hydrogen storage model and a fuel cell ultra capacitor stack. The components were modeled in the SimpowerSystems block of MATLAB Simulink. The simulations were carried out for a period of 10 seconds with a change in the wind speed in the 5th second. It can be noted that as designed by the power controller the wind turbine supplied power to the system for values upto 32KW and for power over that value the combined system was used. 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 nonideal wind speed characteristics.

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REFERENCES

[1] ***The Energy Foundation Annual Report,The Energy Foundation, San Francisco,CA, 2001.***

[2] ***M.J. Khan, M.T. Iqbal, Dynamic modeling and simulation of a small windfuel cell hybrid energy system, J. Renewable Energy 30 (3) (2005) 421–439.***

[3] ***H. De Battista, R.J. Mantz, F. Garelli, Power conditioning for a windhydrogen energy system, J. Power Sources 155 (2) (2006) 478–486.***

[4] ***U.S. Department of Energy, Energy Efficiency and Renewable Energy, Wind & Hydropower Technologies Program,Wind Energy Research Area, http://www.eere.energy.gov.***

[5] ***M.C. Williams, J.P. Strakey, S.C. Singhal, U.S. distributed generation fuel cell program, J. Power Sources 131 (1–2) (2004) 79–85.***

[6] ***R.M. Dell, D.A.J. Rand, Energy storage—a key technology for global energy sustainability, J.Power Sources 100 (1–2) (2001) 2–17.***

[7] B.D. Shakyaa, Lu Ayea, P. Musgraveb, Technical feasibility and financial analysis of hybrid wind-photovoltaic system with hydrogen storage for Cooma, Int. J. Hydrogen Energy 30 (1) (2005) 9–20.

[8] A. Burke, Ultracapacitors: why, how and where is the technology, J. Power Sources 91 (1) (2000) 37–50.

[9] F.I. Khan, K. Hawboldt, M.T. Iqbal, Life cycle analysis of wind-fuel cell integrated system, J. Renewable Energy 30 (2) (2005) 157–177.

[10] Delfino, F. Fornari, Modeling and control of an integrated fuel cellwind turbine system, in: Proceedings of the IEEE PowerTech Conference,Bologna, vol. 2, 2003, p. 6.

[11] D.A. Bechrakis, E.J. McKeogh, P.D. Gallagher, Simulation and operational assessment for a small autonomous wind-hydrogen energy system,

[12] J. Energy Conversion Manage. 47 (1) (2006) 46–59.

[13] F. Barbir, PEM electrolysis for production of hydrogen from renewable energy sources, J. Solar Energy 78 (5) (2005) 661–669.

[14] H. Gorgun, Dynamic modeling of a proton exchange membrane (PEM) electrolyzer, Int. J. Hydrogen Energy 31 (1) (2006) 29-38.