Modeling and Control of an Autonomous Hybrid Power Generation System for Stand-Alone Application

M. Nayeripour and M. Hoseintabar

***Abstract*—In this paper a novel approach for power management and control strategy of a wind/fuel cell/battery-bank hybrid power generation/storage system are proposed. The system consists of a wind turbine and a proton exchange membrane fuel cell (PEMFC) as power generation systems, battery bank and electrolyzer, as long term and short term storage systems respectively and also different converters with different control strategy. The produced power of wind system is unpredictable. Due to this reason, a wind power system may be combined with other power sources. In this paper, wind power system is integrated with fuel cell due to its high efficiency, modularity and fuel flexibility. The battery bank is used to alleviate slow dynamics of fuel cell by providing excess power during transient event such as step load demand and also during above the maximum power available from fuel cell (FC) and wind turbine (WT) systems for short duration. Moreover, the proposed hybrid power generation can tolerate rapid changes in wind speed. In wind turbine, a comprehensive torque model for three-bladed wind turbine including effects of wind shear and tower shadow is considered. Simulation results with MATLAB software have been presented to point out the validity of proposed system.**

***Index Terms*—Component fuel cell, battery-bank; hybrid power generation, power management, stand-alone, wind turbine.**

I. Introduction

The ever increasing of global warming and oil price over the past years, have attracted more attentions to the renewable energy sources instead of conventional power generation system. Today, new advances in renewable power generation technologies encourage different country to produce power with the aim of renewable resources. Hybrid power systems combine with two or more power generation systems to improve hybrid power generation system reliability. WTs and FCs generation system are the most favorable renewable power generation technologies. However, these renewable energy sources have some weak points when used as grid independent energy sources. The wind energy systems are highly dependent on weather conditions, which make them unpredictable. To solve this drawback, WTs sources can be integrated with other alternative/renewable energy systems in a form of hybrid topologies, such as battery bank or FC-electrolyzer system [1-2].

Several kind of fuel cell can be classified as electrolyte type such as phosphoric acids (PAFC), molten carbonate (MCFC), solid oxide (SOFC) and proton exchange membrane (PEMFC). Among them PEMFC type is widely considered because of its low temperature, its high power density and its relatively short start up time. This type of FC system can be used in portable and residential application. However, the main weak point of fuel cell is very slow dynamic due to their slow dynamic in the fuel supply system, which contains pumps, valves or reformers. Therefore, in order to guarantee load leveling, assure braking energy recovery, good performances in transient operation, reduce cost and volume, energy storage devices such as batteries or ultra capacitor are almost necessary in fuel cell hybrid power generation systems.

In this paper, a novel approach for power management and control strategy of a stand-alone hybrid alternative energy system that contain WT/FC/Battery-bank system is proposed. Wind systems are primary power source and have priority to produce power, and the FC-electrolyzer system is used as a back-up energy storage system in long term and the battery bank is used to supply transient and peak power demand in short duration time.

The main contribution of this research is that a effective novel approach for power management and integration of power electronics interfacing under stand-alone applications is proposed.

This paper is organized as follows: in Section 2, system descriptions and methodology are investigated, power management and control strategy of whole system described in section 3. Simulation results are presented in section 4 and the paper will be concluded in Section 5.

II. System Description and Methology

Fig. 1 illustrates the overall system configuration for proposed hybrid power generation systems. Wind turbine is the primary energy source of the system and has priority to produce power of load demand. The proposed hybrid power generation system comprises wind turbine, PEM fuel cell stack, and a lithium-ion battery, which are connected to the same dc voltage bus through an appropriate power electronic interfacing devices.

Manuscript received April 2, 2011; revised May 2, 2012. This work was supported in part by Shiraz University of Technology, Shiraz, Iran.

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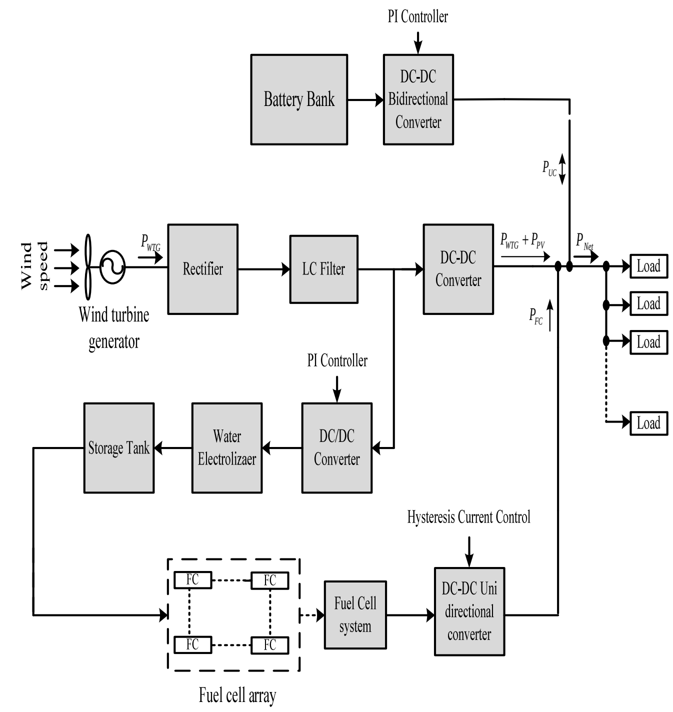

Fig. 1. Overall system configuration

A. Wind Energy Conversion System

The output torque of wind turbine is calculated from wind as follow [3]:

$$T(t,\theta)=\frac{1}{2}\rho A v^2 R\frac{C_p(\lambda)}{\lambda}+\frac{3k_s R^2}{2}\times[v_{eq_{ws}}+v_{eq_{ts}}+(1-m)V_H] \quad (1)$$

The parameters used in the mathematical modeling of WT are point out in Table I.

TABLE I: PARAMETERS OF WT SYSTEM

A	turbine swept area [m^2]
c_p	performance coefficient of the turbine
P_m	mechanical output power of the turbine [W]
β	blade pitch angle [degree]
λ	air density [kg(m^3)$^{-1}$]
ρ	tip speed ratio of the rotor blade tip speed to wind speed
v	wind speed (average) [m s^{-1}]
$V_{eq_{ws}}$	The effect of wind shear
$V_{eq_{ts}}$	The effect of tower shadow
V_H	The hub height wind speed
R	Radial distance from the blade to hub center

B. General Princiles, Design and Dynamic Modeling of PEMFC

Padulles et al. proposed a model for the PEMFC power plant [4], which is modified for this study. A detail dynamic model of PEMFC used in this study is indicated in Fig. 2.

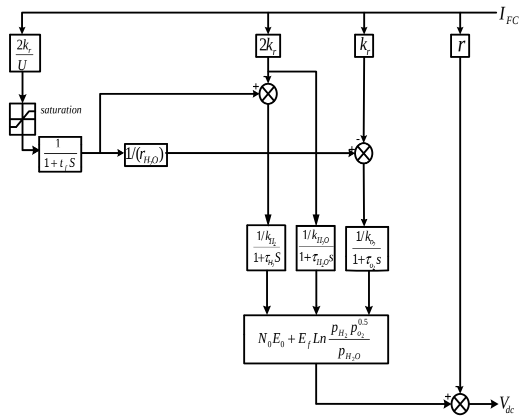

Fig. 2. The PEMFC dynamic model

C. Dynamic Modeling of Battery Bank

A lead acid battery is characterized by two indexes, i.e. the sate-of-charge (SoC) and terminal voltage. The SoC index indicates the fullness of the battery. The SoC can be calculated as:

$$SoC=\frac{Q_0\pm\int i_{battery}dt}{Q_n} \quad (2)$$

where Q_0 is the initial ampere-hour (Ah), Q_n is Ah value, and $i_{battery}$ is the battery's current. The battery current can be negative or positive depending on the mode of operation, e.g. charging or discharging condition [5].

D. Dynamic Model of Hydrogen and Electrolizer Tank

Electrolyzers are devices used to produce the hydrogen and oxygen of different users. Electrolyzers produce both H_2 and O_2 by electrochemical reaction.

The ratio between actual and theoretical maximum amount of hydrogen produced in the electrolyzer is showen as Faraday's efficiency.

$$\eta_F=96.5e^{(0.09/i_e-75.5/i_e^2)} \quad (3)$$

The excess amount of hydrogen, .i.e. the difference between the produced and consumed hydrogen, is sent to H_2 storage tank directly. The dynamic of the storage tank is expressed as follows [6]:

$$P_b-P_{bi}=z\frac{N_{H_2}RT_b}{M_{H_2}V_b} \quad (4)$$

The compression energy requirements and all auxiliary power requirements such as pumps, valves and compression motors are not considered in the dynamic model. These factors are outside the scope of this research.

III. ENERGY MANAGEMENT AND CONTROL STRATEGY

For controlling power management and energy measurement a main controller is used. The data is collected through the sensors and produce's the commands for the power electronic interfacings connected to the power generation and storage sources. The rules used in this controller are as follows:

- To satisfy power demand, the WT system has priority to produce power over that provided by the FC system or battery bank.
- The electrolyzer system is supplied by the WT system continuously before supplying the power demand to generate hydrogen for FC system.
- After generating power by the WT system and supplying the electrolyzer system, the additional of this power and minimum power generation of FC (to keep FC system warm and in standby to response to step load in short duration time) may be used to satisfy the power demand. If this additional power and minimum FC power generation are exceeded from load demand, the battery bank store excess power and otherwise, the deficit of load demand will be satisfied by battery bank. This condition will be continued until the SoC reach to minimum level and then, FC system start to increase the power generation from minimum level to charge the battery bank and meet the load demand.
- If the SoC of the battery bank decrease below 75%, the FC system produces additional power to charge the battery bank until the SoC of the battery bank reaches 80.
- The battery bank not only generates the excess power demand but is also used for compensating the tracking mismatch and delay of the FC system.
- The electrolyzer is kept in operation as long as the tank pressure reaches to the value of 25000 Pa.

The overall algorithm utilized in the main controller is shown in Fig. 3.

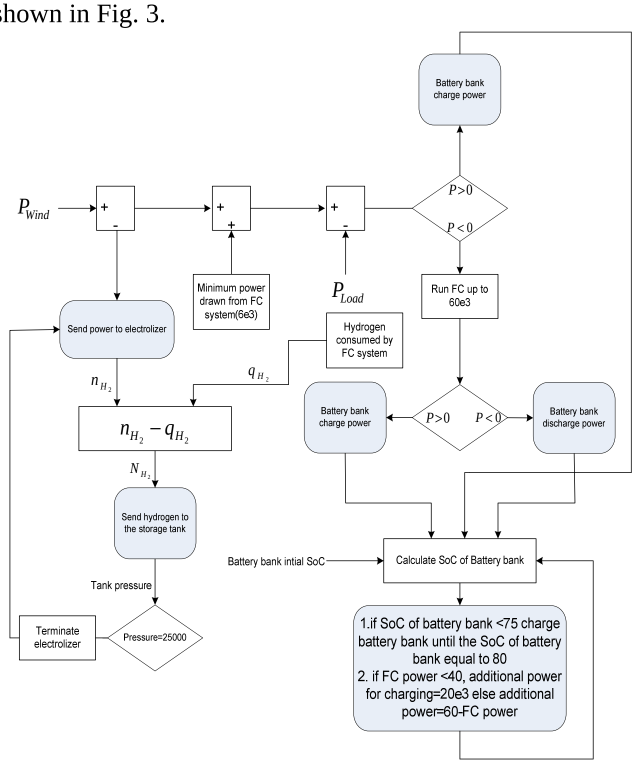

Fig. 3. The overall algorithm used in the main controller

IV. Simulation Results and Discusion

In this study, the load demand is supplied using the WT/FC/battery bank hybrid power generation described earlier. For indicating the effect of this integration of a WT, the FC system and battery bank are used in a new control strategy to meet the user load profile, as shown in Fig. 4.

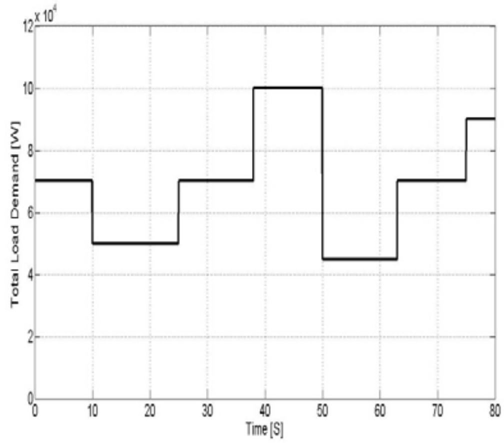

Fig. 4. Total load demand of the user

The dynamic models of the overall system as investigate in this section are developed in a MATLAB/SIMULINK environment to illustrate the effectiveness of the proposed system. The FC system is warmed up and kept in stand-by mode by drawn minimum power, 6kw, so that it can rapidly follow the command.

The dynamic behavior of this system is investigated under step change in a wind speed with a fall at about 14 seconds to show the effectiveness the proposed control strategy in transient events. This sudden step change in wind speed affects the power generated by the induction generator coupled with the wind turbine, electrolyzer voltage and battery bank power. The wind turbine delivered power to the DC link through the dc/dc boost convertors as shown in Fig. 5.

The amount of hydrogen moles produced per second based on electrolyzer voltage and electrolyzer voltage and power are consumed expressed in Fig. 6-7 respectively. The electrolyzer systems are continuously in our system and produce hydrogen. A dc/dc converter is used to set the electrolyzer voltage in constant value.

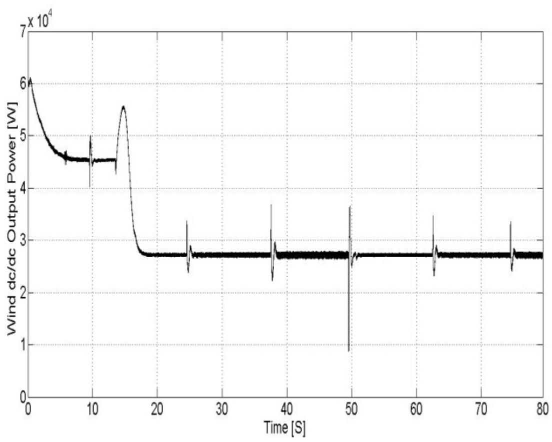

Fig. 5. Power delivered to the dc link from wind turbine

In this paper, the minimum power drawn from PEMFC system is set to be 6 KW to keep FC system in stand-by mode. This is because to keep the FC system warm to provide a larger amount of power in sudden step changes. The DC/DC boost convertor is used to kept DC voltage at 450 V for the DC bus and electrolyzer system. After wind power decreases, the difference power between load demand and wind power produced by WT is provided by the FC system. The FC power is delivered to the DC bus through DC/DC full-bridge convertor with hysteresis current control. In Fig. 6 at time 14 sec when wind speed decreases, the FC system produces the power mismatch with the aid of battery bank to satisfy load power.

Corresponding to the load profile depicted in Fig. 4. The load increment causes to the FC system to increase power generated up to its maximum value as illustrated in Fig. 6.The hydrogen consumed by the FC system sends to the FC system directly from the hydrogen tank to store on it.

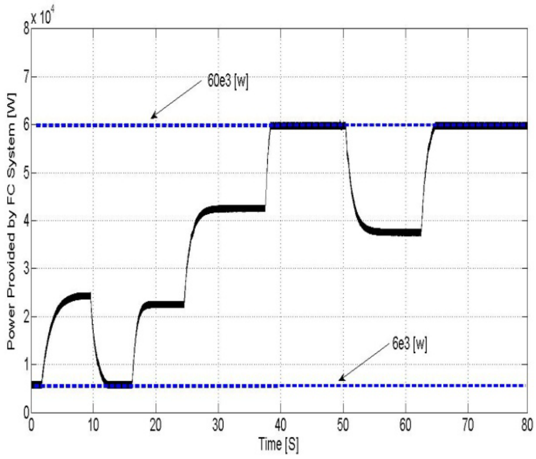

Fig. 6. Power produced by FC system

The difference between the hydrogen produced by the electrolyzer and hydrogen consumed by the FC system for producing power will be stored in a storage tank. The hydrogen storage tank pressure variation corresponds to the hydrogen produced by the electrolyzer or consumed by the FC system, is shown in Fig. 7.

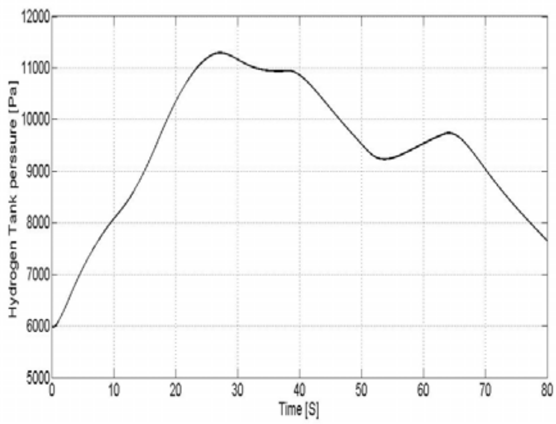

Fig. 7. Hydrogen tank pressure

Power of battery bank is shown in Fig. 8, where the positive power region indicates the power drawn from the battery bank, and the negative region represents the power captured by the battery bank through bi-directional DC/DC converter to store in battery bank. At 105 sec, the integration of FC and WTs system produce power lower than load demand. In this condition, the battery bank provides excess power to satisfy load demand completely.

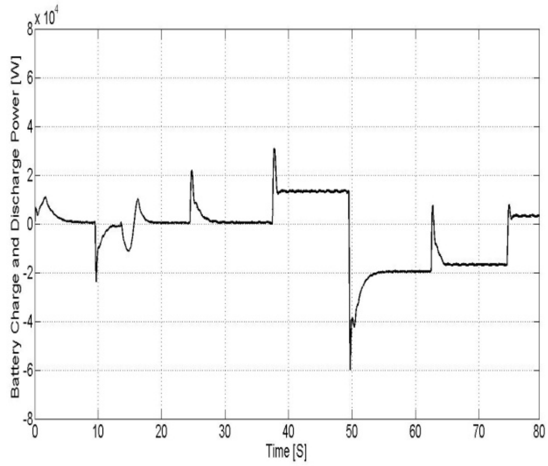

Fig. 8. Battery bank charge and discharge power

The charging and discharging of battery banks correspond to the SoC battery bank. If the SoC of battery bank<75%, the FC system produced excess power to charge the battery bank until the SoC of battery bank is equal to 80 %. At 125 second to 180 second the FC system provides 20 KW excess powers to charge the battery bank as shown in Fig. 5 and 6. The index of SoC in this research is shown in Fig. 9. The power delivered to the load side by the hybrid topology system is also shown in Fig.10.

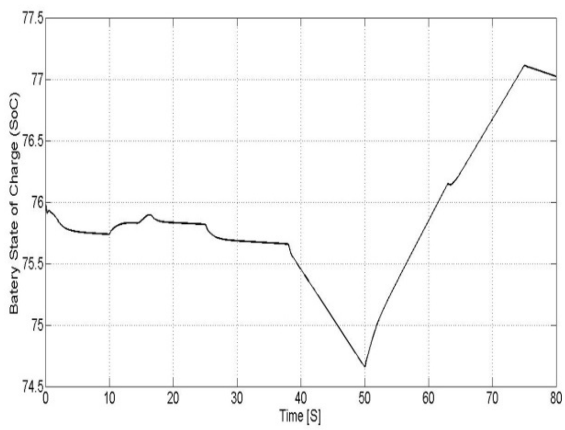

Fig. 9. Battery state of charge with respect to the current

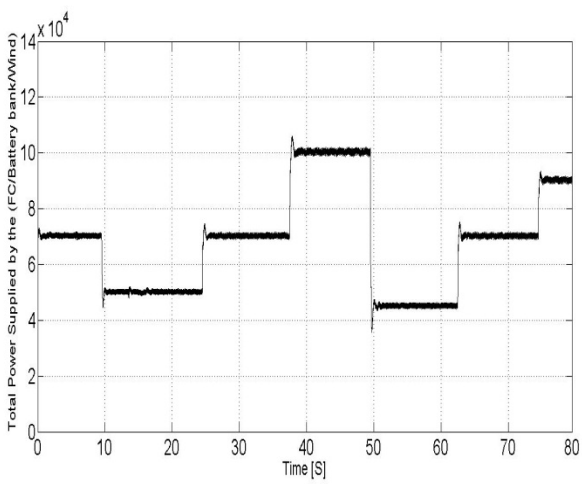

Fig. 10. Power delivered to load side by the hybrid topology system

V. Conclusion

In this paper a novel approach for power management and control strategy of a wind/fuel cell/battery-bank hybrid power generation/storage system are proposed. The produced power of wind power generation system is highly dependent on weather conditions. To solve this problem, the WT energy source is integrated with FC and battery bank through appropriate power electronic interfacing in form of new topology. The proposed hybrid power generation can be used for non-interconnected remote areas or grid independent power system applications. The simulation results show the effectiveness of proposed hybrid power generation in different conditions.

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