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Optimal Enactment of a Stand-alone Hybrid Wind-Fuel Cell Based Distributed Generation System Through Fuzzy Logic Control

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Abstract - In this work, a hybrid distributed power generation (DG) system composed of two renewable energy sources, viz. a wind turbine and a fuel cell is proposed. A fuzzy logic controller has been introduced for optimal power management to provide electric supply to a residential load on a continuous basis based on the feasibility of economic power generation. This controller directs power to a fixed voltage bus in the power conditioning unit (PCU). The fixed voltage bus supplies the load, while the excess power is directed to the energy storage bank first and then to an electrolyzer, which is used to generate hydrogen for the fuel cell. Complete system modeling and simulation has been carried out through HOMER software, and hybrid controller has been simulated in Simulink/MATLAB environment. The simulation results proved the effectiveness of the hybrid fuzzy logic controller for real-time applications of intelligent methods in sustainable power and energy systems.

Index Terms – Distributed Generation, Fuel cell, Fuzzy logic controller, Wind energy

NOMENCLATURE

P_m : Mechanical output power of the turbine
Cp: Performance coefficient of the wind turbine
λ: Tip speed ratio of the rotor blade to wind speed
β: Blade pitch angle (^{o})
ρ: Air density (kg/m ^{3})
A: Turbine swept area (m ^{2})
V_{wind} : Wind speed (m/sec)
ηt, ηe, η r : Thermal, Electric and Reaction efficiency
n_{H2}: hydrogen produced (moles/sec)
,η_F : Faraday efficiency = $96.5e^{(0.009/i_e - 75.5/i_e^2)}$,
n_c : Number of electrolyzer cells in series,
F: Faraday constant (Ck/mol)
i_e : Electrolyzer current
u: Controller output; K_P: Proportionality constant;
K_I: Integral constant; *k* : is the k^{th} sampling time;
e(k): Error in the controller input i.e. $e(k)= V_{ref} - V(k)$;
Δ*e(k)*:Change of error in input signal i.e.$\Delta e(k)= e(k)-e(k-1)$;
Δ*u(k)*:Change of control output *u(k)* i.e. $\Delta u(k)= u(k)-u(k-1)$.

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1.0 INTRODUCTION

Energies like fossil fuel and electricity are the essence of the world. Nations have always tried to find ways to make them more efficient. The volume of fossil fuel available is limited; hence experts are trying to use different energy resources. The vision of reducing the world's reliance on fossil fuels is challenging [1]. Alternative energy industries, such as nuclear energy, hydroelectric energy, solar energy, wind energy and geothermal energy exist, but these energy sources currently only account for a combined 14 percent of energy consumed worldwide [2].

In the present day world, there are ample renewable energy resources, and a tremendous potential to boost the ability to handle the further expansion of the technology in the power generation, transmission, storage and distribution of energy and to identify large-scale application of these systems [3-6]. Average annual growth rate from 2003-2012 of different power sources is plotted in figure 1.

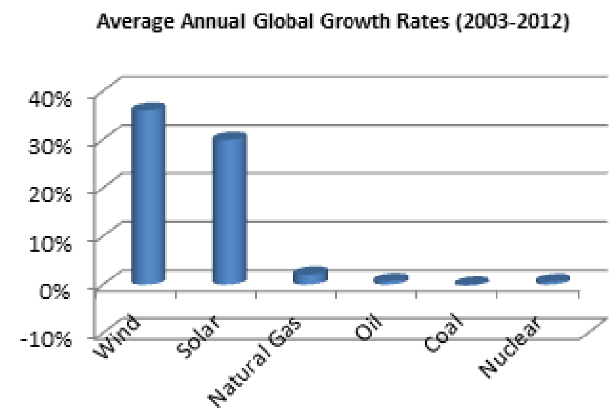

Figure 1: Average Annual Growth Rate [2].

As evident from Figure 1, there is a progressive growth in the deployment of renewable energy power generating systems like solar and wind energy systems. However, these DG systems need to address the applied aspects of what seems feasible from a commercial and cost-effective perspective [7]. The incompetence to pledge reliable, uninterrupted output at a cost that can be analogous to conventional nuclear, steam and coal based electric power generation has been the drawback of renewable based distributed generation systems [3-7].

To mitigate the availability of required wind speed or solar radiations, a number of off-grid hybrid systems, partaking attention from the worldwide energy community. Numerous proto type hybrid DG systems were installed and tested in the

past decades [4-6]. Many literature references have discussed how to determine the optimum combination of a hybrid energy system from the meteorological data for small loads (range from 10 W to 1kW) in a given location [5-6, 8-9]. The results clearly indicate that off-grid hybrid DG systems can compete with the grid power, in isolated locations where the grid is either not viable or nonexistent. Hybrid DG systems, are an effective option to solve the problem of power-supply for remote and isolated areas when compared to grids. [10-16]
The key challenge in operating the hybrid DG system is the optimum power management through the available renewable energy [6-13]. The main objective of this proposed work is to design an optimally controlled hybrid wind fuel cell power system. Two renewable energy based power generating sources, a wind turbine and a fuel cell are chosen to provide power to a typical house load. An energy storage unit is also implied for storing the excess energy and to supply the power during the peak load demand periods. Figure 2 shows the power flow diagram of the proposed hybrid wind -fuel cell DG.

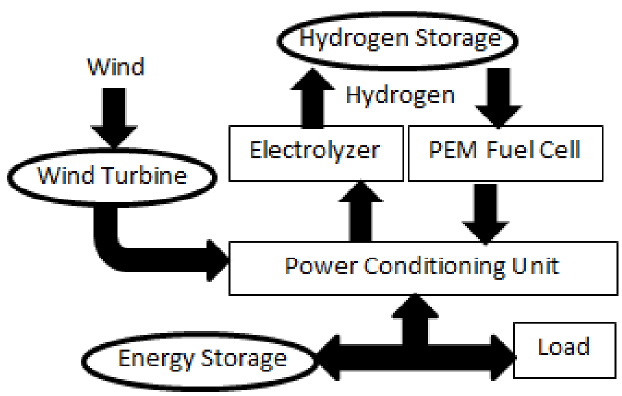

Figure 2: Power Flow Diagram of the Proposed Hybrid DG System.

As a first step towards the realization of this methodology, the proposed DG system is simulated in Hybrid Optimization Model for Electric Renewables (HOMER) environment [17]. Due to constraint limitations, reformer was not included in the preliminary simulation; electrolyzer is considered as the only source for the production of hydrogen. Simulation results are reported in this paper.
Based on a typical house load profile and the wind availability at various locations, it has been estimated that fuel cell in conjunction with energy storage unit, can provide supplementary power to meet the load demand in the absence of the required wind speed. Due to ambiguous and imprecise nature of the wind, house load demand, state of the charge of the energy storage unit, ambient temperature to operate fuel cell etc., it is impossible to provide a set of realistic control data to a conventional controller for optimal power management [18]. A conceivable option is to define the range of the control data and to set up the logic rules for the system and formulate a fuzzy logic based control. The proposed control system will be implied to handle the system level power managements under different load conditions.
Preliminary simulation results in Simulink/ MATLAB® environment show the aptitude of the approach. It is implied that this research will lead to enhancement in the operation of hybrid DG systems considering real-time weather conditions and intelligent control for robust load matching.
This manuscript is divided into five sections. System Architecture is defined in Section 2. Integration of the DG system and simulation in HOMER® is outlined in Section 3. In Section 4, proposed control strategy is developed, simulated and the obtained results are discussed. In section 5, conclusion is drawn based on the results of the proposed work.

2.0 SYSTEM ARCHITECTURE

The key components of proposed hybrid wind- fuel cell DG system are a 20KW wind turbine, 5KW PEM fuel cell, 20KW battery bank, a power conditioning unit (PCU), a 30KW electrolyzer and a hydrogen tank of 0.50 Kg capacity. The ratings of these equipment are considered optimistically in the initial stage. The list of equipment is tabulated in Table 1
.

Equipment	Rating
Wind Turbine	20 KW
Fuel Cell	5 KW
Battery	20 KW
PCU (Converters)	20 KW
Electrolyzer	30 KW
Hydrogen tank	0.5 Kg

Table I: List of Hybrid DG System Components.

2.1 Energy from the Wind

The wind data considered in this simulation is based on the availability of wind at Mt. Clemens city, located at the Lake Huron front with coordinates 42° N and 82° W. The basic idea for this simulation was derived from a sample model on the HOMER webpage [17]. The power curve for the G20 wind turbine for the location considered is obtained from the wind resource data base of HOMER for a twenty four hour span and is given in Figure 3. The monthly wind profile for the whole calendar year is given in Fig. 4.

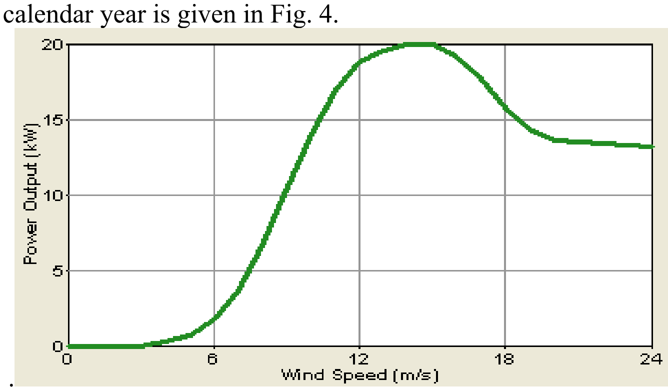

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Figure 3: Power Curve of the G20 Wind Turbine.

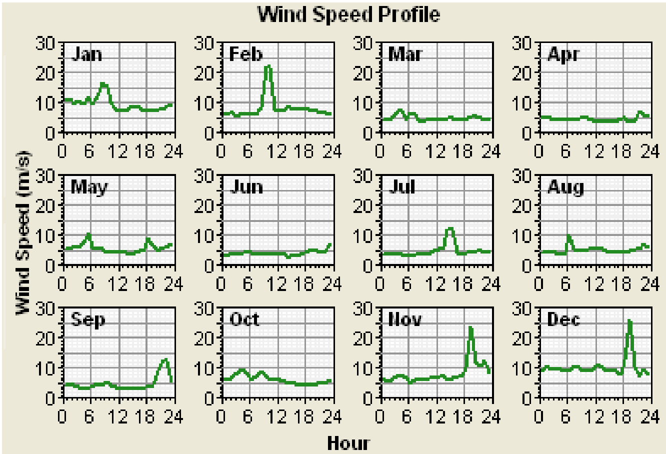

Figure 4: Annual Wind Speed Profile.

The output power of the wind turbine is given by (1) [18].

$$P_m = Cp\,(\lambda, \beta)\,(0.5)\,\rho\,A\,v^3_{wind} \qquad (1)$$

The AC power generated from the wind turbine will be transmitted to PCU (to the AC bus in PCU which is then converted through converter in PCU for transmission).

2.2 Energy Storage Unit

Energy Storage unit, like a battery bank cab, stores the power when DG system is producing more than the load demand, and will serve as the backup power supply during the peak load demand periods. For cost effectiveness, conventional lead acid batteries are considered [19].

2.3 Fuel Cell

Primarily, a fuel cell is an electro- chemical device wherein the chemical energy of hydrogen is directly converted into electric energy. The fuel cell is much more efficient than thermal power plants, converting up to 60% of the chemical energy in the fuel cell into electricity, whereas the normal maximum efficiency is 40% for conventional power plants. The over-all efficiency of a fuel cell in terms of generated power can be estimated through (2) [20-24].

$$\eta = \eta t * \eta e * \eta r \qquad (2)$$

In this modeling, fuel cell is working as back-up power source when the load demand is more than the available wind energy production and the stored energy in the energy storage unit.

2.3.1 Hydrogen Production and Storage

Hydrogen can be produced by the decomposition of water into its elementary components by passing the electric current. According to Faraday's law, hydrogen production of an electrolyzer can be estimated through (4) [22].

$$n_{H2} = 0.5\ \eta F * nc * ie\ /F \qquad (3)$$

2.4 Load

An average demand of a residential load of 8.4 kWh/day is considered. In this analysis, the load is modeled with a few peak demands of almost 8.9 kW and a load factor of 0.5 over a span of 24 hours. The residential load profile of a similar load is obtained through HOMER database and is shown in Figure 5

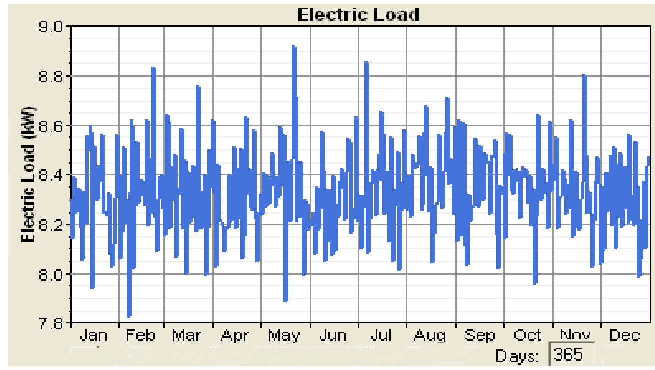

Figure 5: Load Variation of an Average House over a Year.

3.0 INTEGRATION OF HYBRID DG SYSTEM

The integration of hybrid wind-fuel cell DG system can be analyzed as a stand-alone Wind-Fuel cell system. The DC power produced from fuel cell is converted into AC power and fed to the AC Bus. The AC power generated from the wind turbines is directly fed to the AC Bus. The power conversion in the controller model is packaged in the power conditioning unit (PCU). Excess power is stored in the battery bank and to the electrolyzer, which generates hydrogen for storage in the hydrogen tank for the utilization by fuel cell in case of lack of generated power from wind source. The architecture of the generating side of the DG system simulated in HOMER is shown in Figure 6.

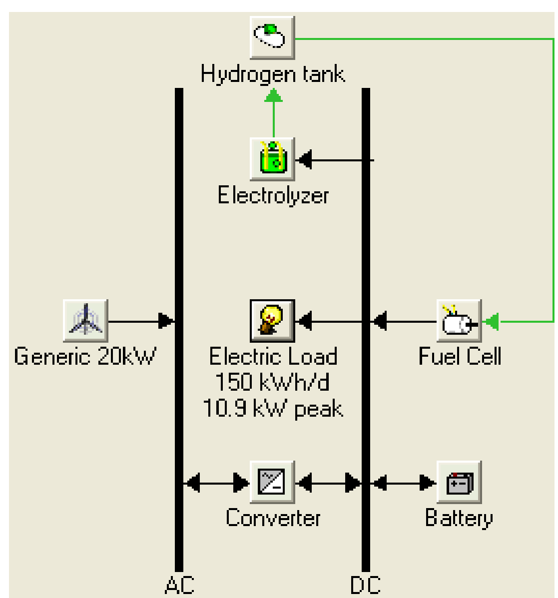

Figure 6: System Architecture of the Hybrid DG Systems.

The annual electric energy production and annual electric energy consumption is tabulated in Table II and III respectively. The production of power by individual renewable source is stated here as the percent fraction.

Renewable Energy Source	Energy Production (kWh/ yr.)	Annual Energy Fraction
Wind Energy	4368.2	82.9 %
Fuel Cell	898.1	17.1%
Total Energy	5266.3	100%

Table II: Annual Electric Energy Production.

Constraints	Energy Value (kWh/yr)
Excess Electricity	1065.2
Unmet Load	301.4
Capacity Shortage	263.3

Table III: Annual Electric Energy Consumption.

The results obtained through HOMER simulation can be considered promising. The excess load was 1065 kWh per year, unmet load was only 301.4 kWh and there is a capacity shortage of only 263.3 kWh annually. The major share in power production is of wind power with an annual estimate of 82.19%. The fuel cell has only a 17.1% share in the power production, which is obvious because only a 5 kW fuel cell was considered and also fuel cell is meant only for back-up power. However, as the consideration of equipment was done optimistically for the desired house load, further detailed economic analysis is required for practical implementation

4.0 DESIGN OF CONTROLLER

In order to transfer maximum power from the hybrid system at any time, a specific load has to be applied at that time. The flow chart depicting the control action is drawn in Figure 7.

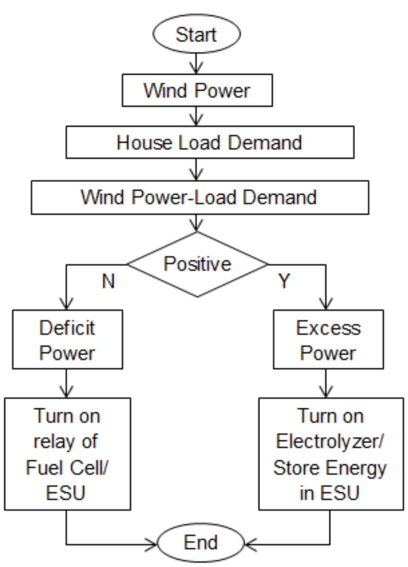

Figure 7: Flow Chart Governing the System.

The control output needs to control and monitor the power supply to the daily energy loads, activate the fuel cell and energy storage as a backup power supply and be able to turn on electrolyzer and maintain hydrogen flow from electrolyzer to fuel cell.

Due to the inconsistency of the wind energy, a power conditioning unit which consists of converters that provide a fixed output voltage by properly adjusting its duty cycle is implied to interface the hybrid system and the load. The power conditioning unit mainly consists of AC/DC and DC/DC and DC/AC converters. The detailed overview of the mechanism of the converters is outlined in [25]. For optimal power management, the control method implied to regulate such a system should have the following characteristics:

1. To minimize the error in the output voltage $V(k)$ by appropriate control of the duty cycle $D(k)$,T
2. To provide a smooth control process near the reference point such that the transients in the controller output, i.e. duty cycle, should not affect the output of the dc-dc converter.

The control action of a conventional PI controller can be expressed as

$$u= K_P * e + K_I * \int_t edt \quad (4)$$

Upon differentiation, the discrete-time based description of the above equation can be described as

$$\Delta u(k)= K_P * \Delta e(k)+K_I *e(k) \quad (5)$$

The essential characteristics of the desired control system mentioned above must have variable gains over the range of operation near the reference point. This leads to a multi-PID controller causing chattering effect. This conventional multi-PID control system is not suitable for this application because of the continuous nature of variables and high-frequency switching requirement of dc-dc converter. A practical alternative for various challenging control applications for uncertain nonlinear dynamical systems is Fuzzy Control [26]. Fuzzy Control is based on Fuzzy set theory [27]. Basics of FLC are described in [28]. Through the processing of heuristic information, a fuzzy logic controller (FLC) interpolates among the consequent of all the rules according to their firing strength. Therefore, a FLC can be seen as multiple PID/PI controllers with smooth interpolation capability without chattering phenomena for real-time applications. For an effective micro grid, the successive-time state transition probabilities of the renewable energy sources are required to control in order to avoid any mismatch between the power supply and demand.

The block diagram in Fig.8 represents the proposed scheme for optimal power management of hybrid wind-PV fuel cell system under uncertain environmental conditions. The block diagram of the proposed hybrid wind fuel cell DG system consists of three power sources, supplementary hardware components and the buses. The power sources are (P1) wind energy, (P2) fuel cell and (P3) energy storage unit (ESU), while supplementary hardware components are electrolyzer and hydrogen storage. Functional buses are the power flow buses in black; control input bus in green, control output buses in red, and their relays R_1- R_3 for activating the respective power sources based on the controller output.

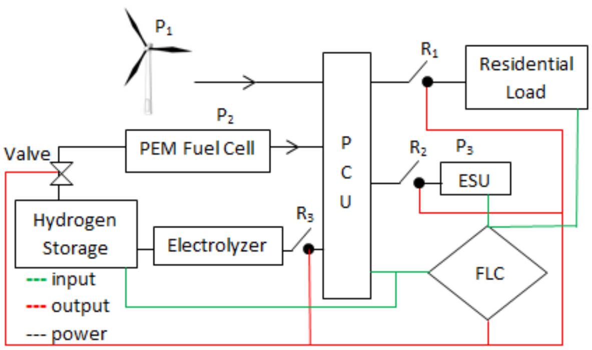

Figure 8: Schematic Diagram of Hybrid Fuzzy Logic Control

As evident from figure 8, the inputs to the FLC are the power available through the wind, fuel cell, energy storage unit and the power demand from the house. The instantaneous output voltage of the PCU ($V_{out}=V_k$) is compared with the reference voltage (V_{ref}). The error in voltage ($\Delta V_k= V_{ref} - V_{Boost}$) is input as error ($e_k$) and change in voltage error ($d\ (\Delta V_k)/dt = \Delta V_k - \Delta V_{k-1}$) is input as change of error (ce_k). The error 'e_k' and change in error 'ce_k' are input to the FLC. The output of F LC is the change in duty cycle 'du_k'. At any instant, duty cycle D_k is expressed as $u_k= u_{k-1}+ du_k$, which is used as control signal for switching of the converters in PCU and the relays for determining the actual load as seen by the PCU.

4.1 Execution of the Control Strategy

The Knowledge base of FLC consists of rule-base and database. The schematic diagram of an FLC is shown in Fig 9.

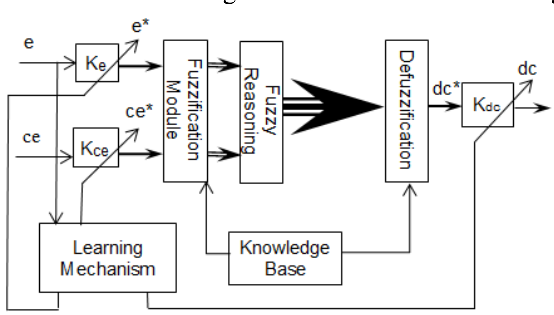

Figure 9:Schematic Diagram of Fuzzy Logic Controller [31].

The rule-base for an FLC can be developed by the observation of error and change of error of the system. Further, these rules have to be associated with the proper membership functions [28-35]. The universe of discourse (*UoD*) membership functions are normalized over the range *-1 to +1* as shown in Figure 10 and 11.

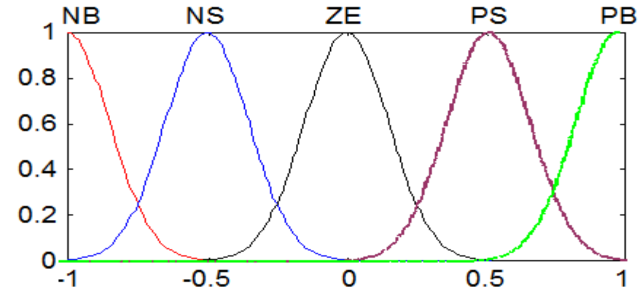

Figure 10: Gaussian Membership Functions for Inputs e & ce.

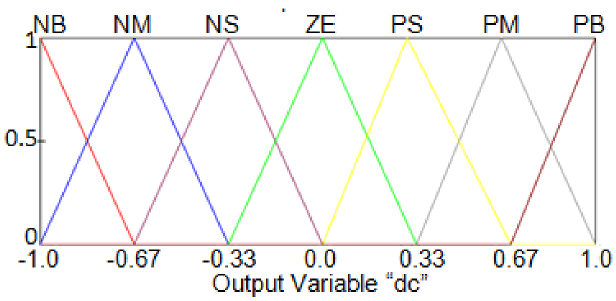

Figure 11: Triangular Membership Functions for Output du*.

In the proposed FLC, the error e_k , the change in error ce_k are partitioned into five fuzzy sets that lead to a maximum of twenty five rules, and the output variable du_k is partitioned into seven fuzzy sets. The choice of this number of portioning is to achieve tradeoff between the explosion of fuzzy rules and high *discretization* [28-31]. The comprehensive set of fuzzy membership function is plotted in Figure 12.

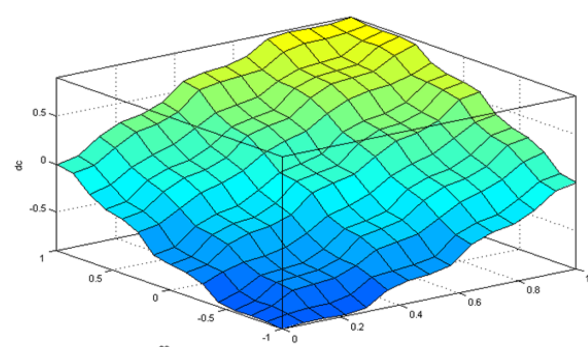

Figure 12: Surface of the Fuzzy Membership Function.

Based on the selection of input and out membership functions, a 25 rule base is developed. Entries in the set of rules are fuzzy sets associated with consequent variable *du* .The "product-sum" inference mechanism is used for mapping the rule-base to the consequent fuzzy set. The center-of sums method is used for the defuzzification of the FLC output. A sample rule of the rule-base is of the form:

IF e(k) is………AND ce(k) is……..THEN du is……….. (6)

4.5 Simulation, Results and Discussion

A system level model based on the schematic in Figure 8 is developed in MATLAB/Simulink® environment. The component models for wind turbine, fuel cell, battery and converter available in the Simpower® toolbox of Simulink® are selected. The Fuzzy logic controller is then developed in conjunction with the components models based on the FKBC developed in section 4.4. A sample test case simulation is presented to demonstrate the efficacy of the proposed hybrid fuzzy logic control scheme.

Firstly the behavior of the load demand with the power generating capacity of the hybrid system based on the environmental condition is studied with HOMER and to analyze the performance of the FLC, simulation of the system model is observed for a duration of 2 hours with an assumption of constant temperature in fuel cell and electrolyzer. For a rated wind speed of 12.5 m/sec and 50% state of the charge of the battery bank and 3 phase ac load of a typical household, the phase voltage at the residential load obtained is shown in Figure 13. The balanced 3 phase input ac voltage available at the house load in Figure 13 through the adequate operation of the relays by the controller shows the successful operation of the proposed FLC.

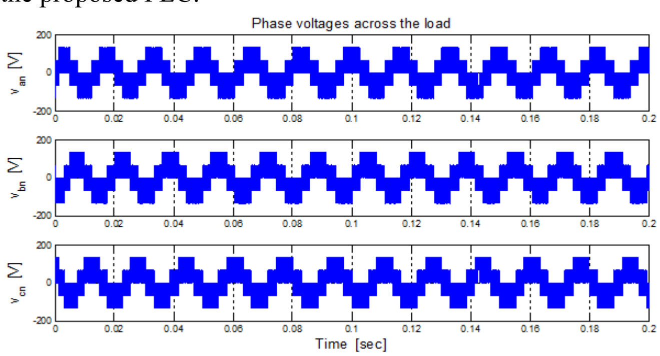

Figure 13: Phase Load Voltages.

Further efficacy of the FLC controller is evident from the concurrence of the phase a, b, c output load currents and the reference input current as shown in figures 14, 15 and 16 respectively.

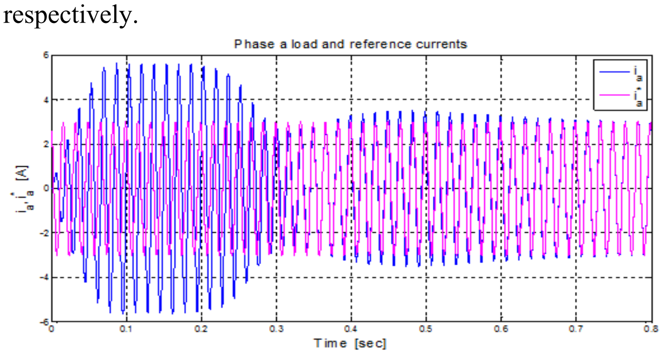

Figure 14: Phase *a* Load and Reference Current.

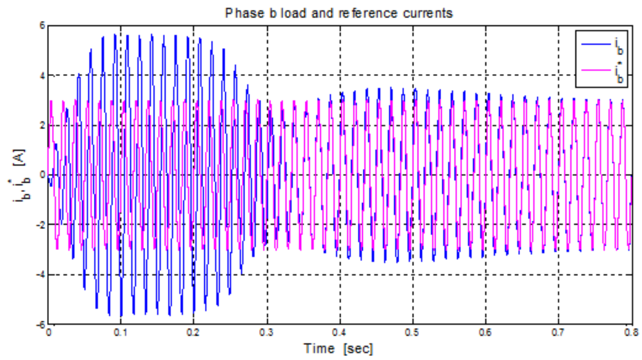

Figure 15: Phase *b* Load and Reference Current.

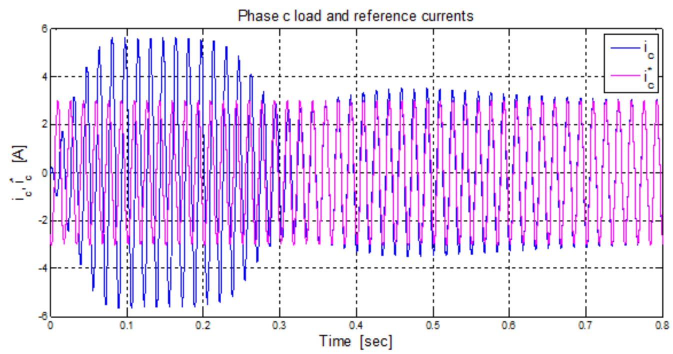

Figure 16: Phase *c* Load and Reference Current.

5.0 CONCLUSION

The application of hybrid wind-fuel cell based power system for consumption as stand-alone distributed generation systems, for a residential customer was studied. The feasibility study of the system was performed for various locations on the globe and a specific location of Michigan was presented. Based on the wind availability, hydrogen production and battery bank storage, it is concluded that such a system is a viable option for remote areas where there is no power supply available or it is very expensive to install transmission lines.

To optimize the power management of the hybrid wind-fuel cell system, a fuzzy logic based controller is developed. During the periods of adequate power availability from the renewable energy sources, FLC has exhibit a satisfactory performance in the power management. Further the control of the switching of the relays through FLC was successful by having a balanced 3 phase voltage and current available for the house load.

Hence, the proposed hybrid DG system is a promising option for remote areas and the proposed FLC has a tremendous potential in real-time applications of intelligent methods in sustainable power and energy systems.

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