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Comparative Study between Wind and Fuel Cell by Using Fuzzy Logic Control

C.A.Pradeep Kumar, A.Benuel Sathish Raj

***Abstract*— Due to ever increasing energy consumption, rising public awareness of environmental protection, and steady progress in power deregulation, alternative (i.e., renewable and fuel cell based) distributed generation (DG) systems have attracted increased interest. Wind and photovoltaic (PV) power generation are two of the most promising renewable energy technologies. Fuel cell (FC) systems also show great potential in DG applications of the future due to their fast technology development and many merits they have, such as high efficiency, zero or low emission (of pollutant gases) and flexible modular structure.**

This study presents different power management strategies of a stand-alone hybrid power system and controlled by using fuzzy logic control. The system consists of two power generation systems, a wind turbine and a proton exchange membrane fuel cell (PEMFC). Wind turbine is the main supply for the system, and the fuel cell performs as a backup power source. Different energy sources in the system are integrated through an AC bus. Therefore, continuous energy supply needs energy storing devices. The state of charge (SOC), charge-discharge currents are affecting the battery energy efficiency. The control algorithm is simulated using Matlab-Simulink.

***Index Terms*—Wind, Fuel cell, Fuzzy, Dynamic Simulation, MAT LAB Simulink modeling.**

I. INTRODUCTION

The demand for new and environmentally friendly energy system is growing rcurrent trend. To increase the energy reliability, wind and solar energy are used as dual energy sources. However, seasonal climatic conditions and geographic conditions affect the wind-solar energy output. Therefore, a third energy system is needed to improve the energy supply reliability. Thus, the PEMfuel cell ideally fulfills the need for any start up power. When the wind system energy output is insufficient, the fuel cell backups the supply system [1]-[3]. However, fuel cell lifetime is less than 2000 hrs for transportation and 20,000 hrs for stationary fuel cells. Frequent start-up and shutdown actions degrade the electrolyzer and the fuel cell performance. In addition, battery charge-discharge cycle and battery bank energy efficiency gains importance. Therefore, improved energy management strategies are improved by using Fuzzy logic controller, and Matlab/Simulink simulation results are presented. The strategies are implemented as a case study to a mobile house for two-member family.

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* Correspondence Author (s)

C A Pradeep Kumar was completed his BE degree from Park College Of Engineering & Technologies, Anna University, Tamil nadu. Now he is doing his master degree in Karunya University in Renewable Energy Technology

A.Benuel Sathish Raj completed his B.E degree in Electrical and Electronics from Bharathiyar University. His area of specialization is Applied Electronics & Renewable Energy Technologies. He is doing his Ph.D. in Renewable Energy.

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The evaluation of the power management strategy performance is evaluated using real weather data for the region of installation. In the literature, there are a few studies related to power management of hybrid power systems. This Power management strategy studied power fluctuations on a hybrid power system.

In this study, two new power management strategies are processing here. Their effects on battery bank energy efficiency and PEMFC membrane life span is truly investigated. At finally, here we the presented power management strategies and control algorithms of the hybrid power system of wind and fuel cell with the help of Fuzzy logic control.

II. HYBRID POWER SYSTEM

The hybrid system consists of two power generation systems, a wind turbine and a fuel cell. The wind turbines are used as the main power generation system for the system and the fuel cell is assigned as a backup power generator for the continuous power supply. The hybrid power system consists of a 1 kW wind turbine, and a 2 kW fuel cell [1]. It is controlled by FUZZY LOGIC. The below fig 1 shows the block diagram of the hybrid power system.

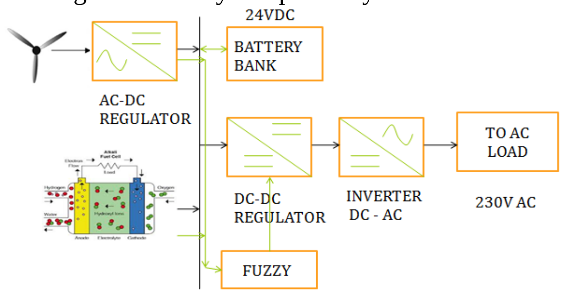

Fig 1: Block diagram of hybrid system

The below fig shows the simulated model of both wind and fuel cell. In this model Wind and fuel cell are connected to individual boost converters and it is connected to inverter. From the inverter it produced square pulse as output.

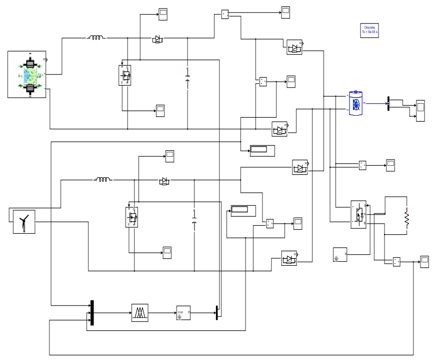

Fig 2: MATLAB Simulink model of Hybrid Power System

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A. SYSTEM COMPONENTS

The wind turbine generates 1 kW of rated power with a permanent magnet synchronous generator. Wind turbine AC/DC converter is a built in device. Electricity obtained from the wind turbine can be calculated using the wind speed data.The instantaneous power produced from wind is

$$P=\frac{1}{2} A \rho v^3 C_p(\lambda,\theta)$$

ρ is the air density, A the rotor sweep area, Cp the power coefficient, a function of tip speed ratio (k) and pitch angle (h), and V is the wind velocity.

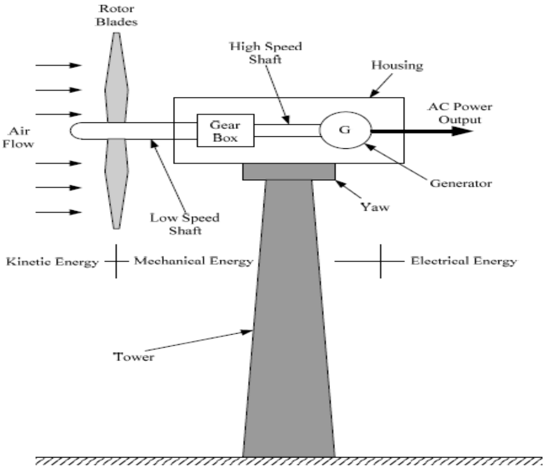

Fig 3. Block diagram of a typical wind energy conversion system

PEMFC is a common type of fuel cell, and traditionally uses hydrogen. PEMFC has been regarded as the most adequate system as a power source for many portable electric devices. PEMFC could also be a sustainable alternative for the power generation in zero-emission automotive applications as well as for stationary power stations. PEMFC technical specifications are at. The PEM air-cooled fuel cell is from the FutureE model Jupiter the rated power 2 kW.Peak values show the load demand current rate with respect to time. Hence, the wind turbine supplied the total load demand. A schematic diagram of a PEM fuel cell and its internal voltage drops are shown in below Fig 4.

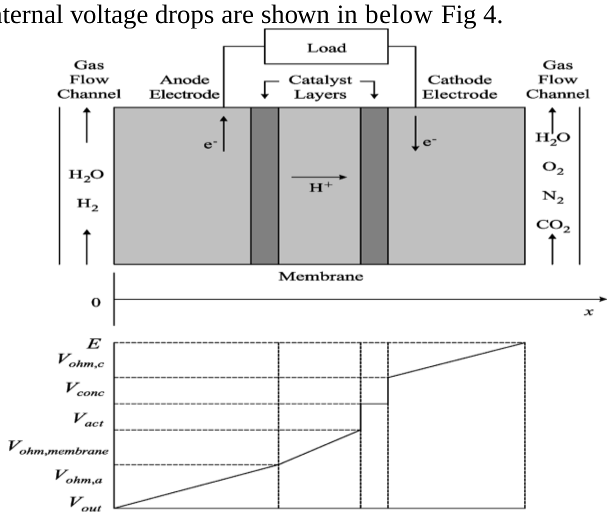

Fig 4. Block diagram of PEM fuel cell

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with un sharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

FLC is one of the most successful applications of, fuzzy set theory. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and large), may be represented by fuzzy sets. FLC's are an attractive choice when precise mathematical formulations are not possible.

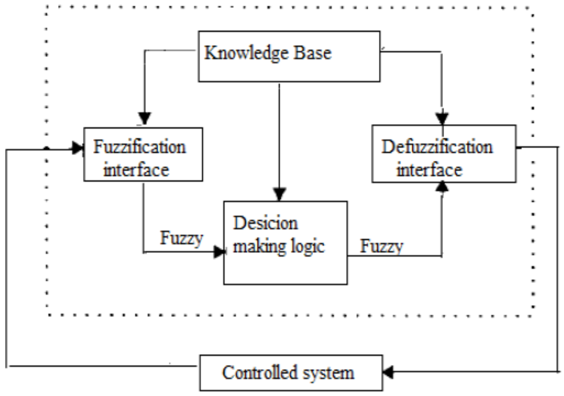

Fig 5. Block diagram of fuzzy logic

Power electronic (PE) interfacing circuits, also called power conditioning circuits, are necessary for a hybrid energy system. In this section, the electrical circuit diagrams, state-space models, and effective average-models (for long-time simulation studies) for the main PE interfacing circuits in this hybrid energy system discussing. They are AC/DC rectifiers, DC/DC converters, DC/AC inverters. A detailed model for a PE device together with the control switching signals will dramatically decrease the simulation speed using MATLAB/Simulink. The detailed models for PE devices, such as those given in the SimPowerSystems block-set, are not suitable for long time simulation studies. Effective average-models for PE devices will be developed in this section, which help improve the simulation speed significantly and at the same time keep the desirable accuracy.

Nickel-metal-hydride batteries are related to sealed nickel-cadmium batteries and only differ from them in that instead of cadmium, hydrogen is used as the active element at a hydrogen-absorbing negative electrode (anode). This electrode is made from a metal hydride usually alloys of Lanthanum and rare earths that serve as a solid source of reduced hydrogen that can be oxidized to form protons. The electrolyte is alkaline potassium hydroxide. Cell voltage is 1.2 Volts

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$$\eta_b=\frac{E_{out}}{E_{in}}X100$$

$$E_{out} = P_{out}\,t$$

$$E_{in} = P_{in}\,t$$

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III. OPERATING MODES

The main decision factors for the power management strategies are the level of the power provided by the renewable energy system wind and the state of charge (SOC) of the battery bank. The battery bank or the fuel cell should be capable of providing the needed power. Power energy generated by wind turbine (Pwind) is summed up at renewable energy system power (Pres). Load (Pload) is subtracted from the Pres and the excess power. The stand-alone system is composed from renewablepower sources. Therefore, the power management strategies became even more complex. The algorithms for strategy1, strategy2 are given below fig 6 & 7. At strategy1, SOCmax > SOC > SOCmin and Pexcess > 0, the electrolyzer will run and the battery bank will discharge. At strategy2, SOCmax > SOC > SOCmin and Pexcess, the fuel cell will not run, and the battery bank will be discharged. When, SOCmin, the battery bank will charged. At strategy2, SOCmax > SOC > SOCmin and Pexcess > 0, the electrolyzer will run, and the battery bank will be charged. If WIND power is available it charges the battery and the fuel cell will not run. Wind power is not available, the fuel cell will run, and battery bank discharges. The best result for the battery bank energy

In this mode fuel cell is in ideal position and wind is operating. Initially the load will compares with status of charge in capacitor soc, if the load demand is greater than soc and it is check with wind and fuel cell. If wind is available and it is operating otherwise it compare with battery also. The below flowchart shows the operating mode of wind.

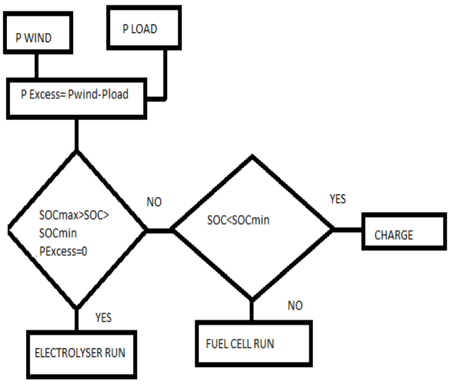

Fig 6. Flowchart for wind operating mode

In this mode wind is in ideal position and fuel cell is operating. Initially the load will compares with status of charge in soc, if the load demand is greater than soc and it is check with wind and fuel cell. If wind is not available and it is moved to fuel cell. Here initially it is check the status of electrolyser if it is available and fuel cell is operating. The below flowchart shows the operating mode of fuel cell.

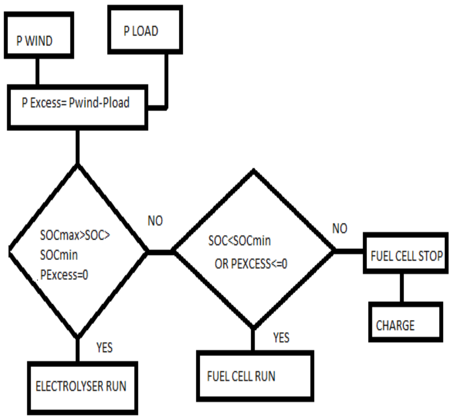

Fig 7. Flowchart for Fuel Cell operating mode

IV. SIMULINK MODEL OF SYSTEMS.

A. Proton Exchange Membrane Fuel Cells

PEM fuel cells show great promise for use as distributed generation (DG) sources. The dynamic modeling of fuel cells with emphasis on the electrical terminal characteristics [5]. A detailed explanation of the electrochemical properties of fuel cells and a simple equivalent electrical circuit including a capacitor due to the double-layer charging effect inside fuel cells are reported.The dynamic models are presented for PEM fuel cells using electrical circuits. First, through mechanistic anal- ysis, the equivalent internal voltage source and equivalent resistors for activation loss, ohmic voltage drop, and concen- tration voltage drop are given. Then, the double-layer charging effect is considered by adding an equivalent capacitor to the circuit. The thermodynamic characteristic inside the fuel cell is also integrated into the model according to the energy balance equation.

The overall reaction in a PEM fuel cell can be simply written as

$$H_2 + \frac{1}{2} O_2 = H_2O_{(t)}$$

According to assumption (5), the corresponding Nernst equation used to calculate the reversible potential is

$$E_{cell} = E_{o,cell} + \frac{RT}{2F} ln\left[P^*_{H_2}.\left(P^*_{O_2}\right)^{0.5}\right]$$

where $E_{o,cell}$ is a function of temperature and can be expressed as follow

$$E_{o,cell} = E^o_{o,cell} - k_{E*}(T - 298)$$

Where $E^o_{o,cell}$ is the standard reference potential at standard state, 298 K and 1-atm pressure.

To simplify the analysis [9], a voltage $E_{d,cell}$ is considered to be subtracted from the right side of the above equation Ecell, for the overall effect of the fuel and oxidant delay discussed in part B. The steady-state value of $E_{d,cell}$ is zero, but it will show the influence of the fuel and oxidant delays on the fuel-cell output voltage during load transients. It can be written as

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$$E_{d,cell} = \lambda_c\left[i(t) - i(t) * exp\left(-\frac{t}{T_e}\right)\right]$$

$$E_{cell} = E_{o,cell} + \frac{RT}{2F} ln\left[P^*_{H_2}.\left(P^*_{O_2}\right)^{0.5}\right] - E_{d,cell}$$

where E_{cell} , calculated from the above equation is actually the open-circuit voltage of the fuel cell. However, under normal operating conditions the fuel-cell output voltage is less than E_{cell} . Activation loss, ohmic resistance voltage drop, and concentration over potential are voltage drops across the fuel cell.

$$V_{cell} = E_{cell} - V_{act,cell} - V_{ohm,cell} - V_{conc,cell}$$

Applying assumption 7), the output voltage of the fuel-cell stack can be obtained as

$$V_{out} = N_{cell}V_{cell} = E - V_{act} - V_{ohm} - V_{conc}$$

To calculate the fuel-cell output voltage, the following estimations are used:

Activation voltage drop

Tafel equation, given below, is used to calculate the activation voltage drop in a fuel cell

$$V_{act} = \frac{RT}{\propto zF} ln\left(\frac{I}{I_o}\right) = T.[a + bln(I)]$$

On the other hand, an empirical equation for V_{act} is given in, where a constant η_o is added to as follows

$$V_{act} = \eta_o + (T - 298).a + T.bln(I)$$

Ohmic voltage drop

The ohmic resistance of aPEM fuel cell consists of the resistance of polymer membrane, the conducting resistance between the membrane and electrodes, and the resistances of electrodes. The overall ohmic voltage drop can be expressed as

$$V_{ohm} = V_{ohm,a} + V_{ohm,membrane} + V_{ohm,c} = IR_{ohm}$$

Concentration voltage drop

During the reaction process, concentration gradients can be formed due to mass diffusions from the flow channels to the reaction sites (catalyst surfaces). At high current densities, slow transportation of reactants (products) to (from) the reaction sites is the main reason for the concentration voltage drop. Any water film covering the catalyst surfaces at the anode and cathode can be another contributor to this voltage drop. The concentration over potential in the fuel cell is defined as

$$V_{conc} = -\frac{RT}{zF} ln\frac{C_s}{C_B}$$

Where C_s is the surface concentration and C_B is the bulk concentration. The below fig 8 & 9 shows the simulink model of fuel cell with the output graph.

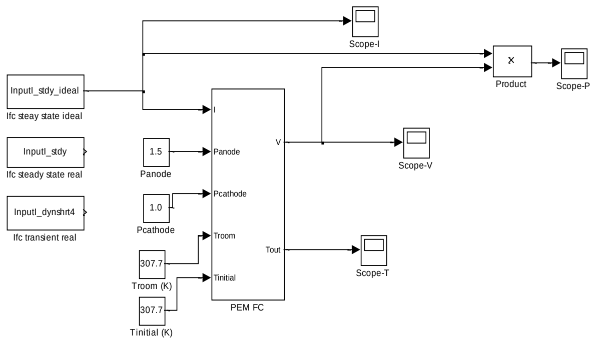

Fig 8. Simulink model of fuel cell

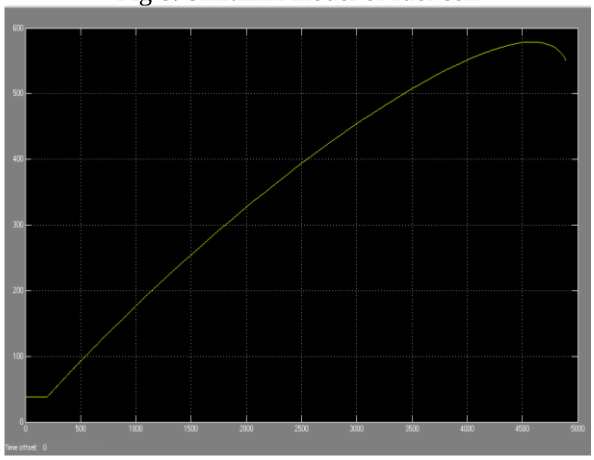

Fig 9. Power curve of fuel cell

B. Wind Turbine

Wind energy systems harness the kinetic energy of wind and convert it into electrical energy or use it to do other work, such as pump water, grind grains, etc.

Wind Turbine Characteristics [4], The power Pwind (in watts) extracted from the wind. It is rewritten here as:

$$P_{wind} = {}^1/_2 A\, \rho\, v^3 C_p(\lambda,\Theta)$$

Where ρ is the air density in kg/m3, A is the area swept by the rotor blades in m2, v is the wind velocity in m/s. Cp is called the power coefficient or the rotor efficiency and is function of tip speed ratio (TSR) and pitch angle (Θ).

The maximum rotor efficiency Cp is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine. The rotor must turn at high speed at high wind, and at low speed at low wind, to keep TSR constant at the optimum level at all times.

$$C_p = C_1(C_2 - C_3\Theta - C_4)\exp(-C_5)$$

Where Θ is the pitch angle.

Generator input and output

For any load conditions as represented by the output per phase is

$$P = V\,I\cos\emptyset.$$

The electrical power converted from mechanical power input is per phase

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$$P1 = E_t \ I \cos(\emptyset + \sigma)$$

Resolving E_t along I

$$P1 = E_t I \cos(\emptyset + \sigma) = (V \cos \emptyset + I_r).I$$

$$= V I \cos \emptyset + I_2 R$$

The electrical input is thus the output plus the I2R loss, as might be expected. The prime mover must naturally supply also the friction, windage and core losses, which do not appear in the phasor diagram.

In large machines the resistance is small compared with the synchronous reactance so that$\emptyset$ = arc tan(xs/r) ≈ 90◦, it can be shown that

$$\frac{V}{\sin\left(90 - \overline{\emptyset + \sigma}\right)^2} = \frac{Z_s}{\sin\sigma}$$

and hence, P=P1=EtI cos($\emptyset + \sigma$) ≈(Et/Xs).Vsin σ

Thus the power developed by a synchronous machine with given values of Et. V and Zs is proportional to sin σ: or, for small angles, to σ, and the displacement angle σ representing the change in relative position between the rotor and resultant pole- axes is proportional to the load power. The term load-, power- or torque-angle may be applied to σ.

An obvious deduction from the above Eqn. is that the greater the field excitation (corresponding to Et) the greater is the output per unit angle σ: that is, the more stable will be the operation. The below fig 10 and 11 shows the simulink model of wind turbine with the voltage and current curves.

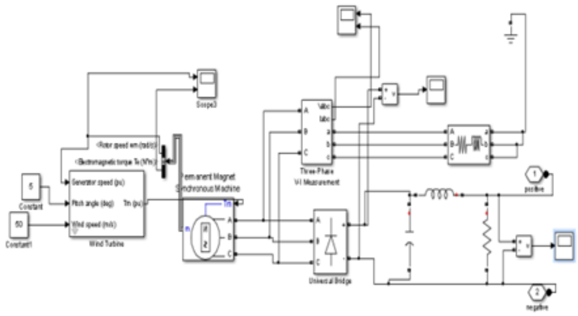

Fig 10. Simulink model of Wind

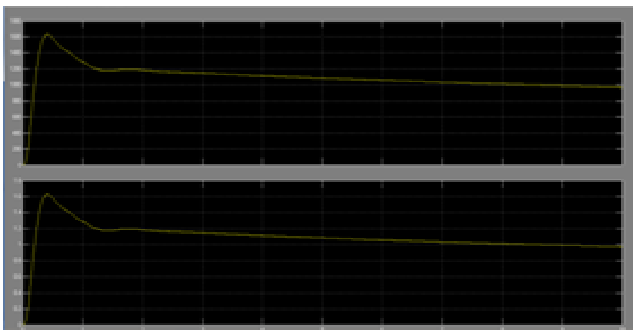

Fig 11. Voltage and current curves of Wind

C. Power Electronics

Power Electronic interfacing circuits, also called power conditioning circuits, are necessary for a hybrid energy system. In this section, the electrical circuit diagrams of DC/DC converters, DC/AC inverters.

DC/DC Converters

The below Fig 12 shows the circuit diagram of a boost DC/DC converter [8]-[9]. The output voltage regulation feedback is also given in the fig. At steady-state, the average value of the output voltage is given as:

$$V_{dd\_out} = \frac{V_{dd\_in}}{(1-d)}$$

where d is the duty ratio of the switching pulse.

Since 0 ≤ d <1 , the output voltage is always higher than the input voltage. That is why the circuit is called a boost DC/DC converter. The controller for the converter is to regulate the DC bus voltage within a desirable range. The output voltage is measured and compared with the reference value.

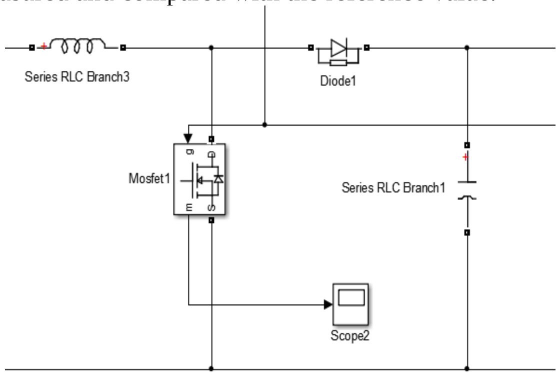

Fig 12. Simulink model of BOOST Converter

Inverters

Inverter is used to convert the DC Supply into AC Supply[10]. A DC–AC converter is commonly known as an inverter. The power semiconductor devices perform the switching action, and the desired output is obtained by varying their turn-on and turn-off times. They must have controllable turn-on and turn-off characteristics.

The below fig 13 shows the simulink model of INVERTER with the output power cureve.The circuit has the following two states

State1: S1&S2- On : S3&S4- Off

State2: S1&S2- Off : S3&S4- On

For full bridge inverter, $v_o = v_s \ldots\ldots\ldots 0 < t < \frac{T}{2}$

$= -v_s \ldots\ldots\ldots \frac{T}{2} < t < T$

The load current is, however dependent upon the nature of load. In this circuit, load current would finally settle down to steady state conditions would vary periodically as shown in fig. It is seen from these waveforms that

$$i_o = \pm I_o \ldots\ldots\ldots\ldots\ldots at\ t = 0, T, 2T \ldots\ldots$$

$$i_o = \pm I_o \ldots\ldots\ldots at\ t = T/2, 3T/2, 5T/2 \ldots\ldots$$

The voltage equation of the circuit model in the time of 0<t<T/2 is given by

$$v_s = Ri_o + L + \frac{1}{C}\int i_o dt + V_{c1}$$

In this equation V_{c1} is the initial voltage across capacitor at t=0. For T/2<t<T, or 0<t'<T/2 and the voltage equation becomes

$$-v_s = Ri_o + L\frac{di}{dt'} + \frac{1}{C}\int idt' + V_{c2}$$

In this equation V_{c2} is the initial voltage across capacitor at t'=0.

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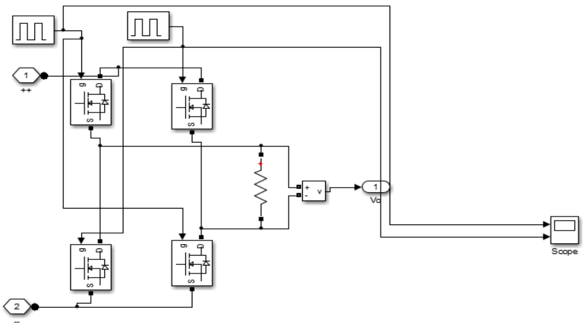

Fig 13. Simulink model of Inverter

D. *FUZZY Logic Control*

FLC is one of the most successful applications of, fuzzy set theory [6]. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and large), may be represented by fuzzy sets.

The first step in the design of a fuzzy logic controller is to define membership functions for the inputs. Seven fuzzy levels or sets are chosen and defined by the following library of fuzzy-set values for the wind, fuel cell and demand. They are as follows,

- NB negative big;
- NM negative medium;
- NS negative small;
- ZE zero equal;
- PS positive small;
- PM positive medium;
- PB positive big.

The below table 1 shows the rules for this controller.

Table 1. FUZZY rules for various operating conditions

WIND	FUEL CELL	LOAD	OUTPUT
PB	Z	PM	PB
PM	Z	PS	NS
NS	Z	Z	NS
NB	PB	Z	Z
NB	PM	NS	NS
NM	PB	PS	PS
NS	NM	NM	NB
Z	NM	NS	NM
Z	PM	PS	PM
NS	PB	NS	PM
Z	PB	NM	PM
Z	PB	NM	NS
PS	NM	PS	NS
PM	PS	Z	PB
PS	Z	Z	PS
PB	PB	NB	PB
PM	NB	NS	NS
PM	NS	PS	PS
PS	PB	NS	PB
PS	Z	NS	PS
PM	Z	NM	Z

For WIND operating modes

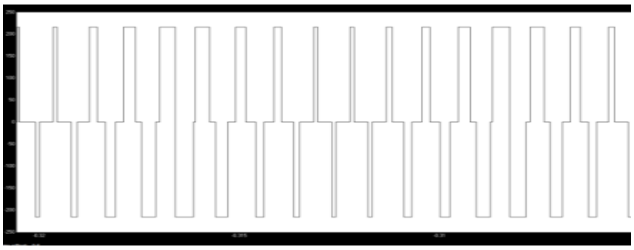

Fig 14.

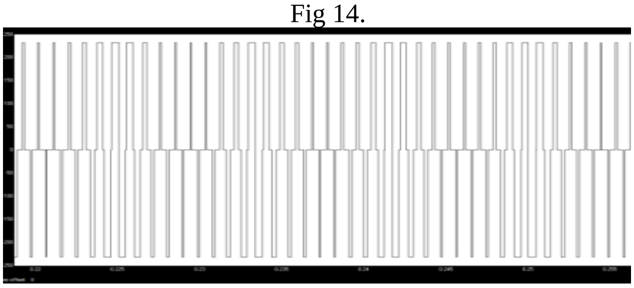

Fig 15.

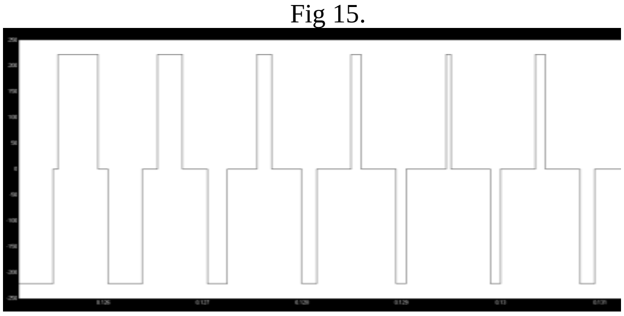

Fig 16.

The above Fig shows the various operating conditions of Wind operating mode controlled by fuzzy. The Fig 14 shows If wind is PB, fuel cell is Z, Load is PM and output is PB. The Fig 15 shows IF wind is PB fuel cell is Z, load is NS and output is PB. The Fig 16 shows IF wind is NS, fuel cell is Z, load is Z and output is NS.

For FUEL CELL operating modes

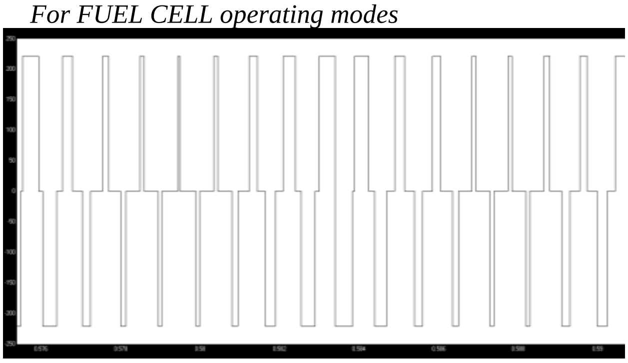

Fig 17

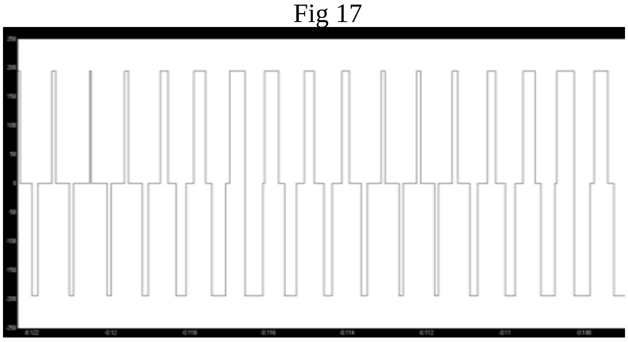

Fig 18

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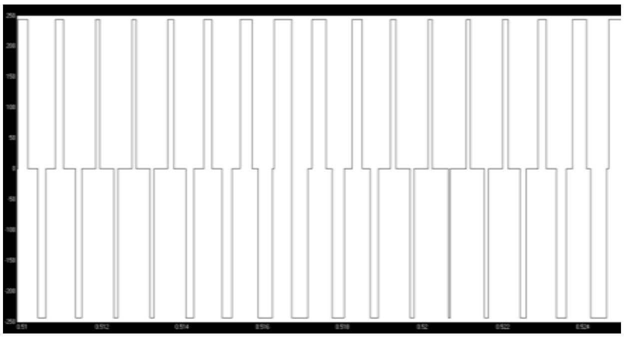

Fig 19

The above Fig shows the various operating conditions of Wind operating mode controlled by fuzzy. The Fig 17 shows IF wind is NS, fuel cell is PB, load is NS and output is PM. The Fig 18 shows IF wind is Z, fuel cell is PB, load is NM and output is PM. The Fig 19 shows IF wind is Z, fuel cell is PB, load is Z and output is PB.

V. CONCLUSION

Using stand-alone wind-solar energy system has become popular in recent years. Stand-alone power system depends on the geographical and meteorological conditions of the installed region. Therefore, the wind turbine and solar cells may not meet the energy demand. So, a third power supply source might be needed. This source should not be affected from any geographical or meteorological conditions. PEMFC is an ideal power generation system for such implementations. However, the price of PEMFC is high and its membrane lifetime is short. Thus to increase the operation time of the membrane and to enable the continuous energy flow, two power management strategies are implemented. This power management strategies for the hybrid power system satisfy the load and battery bank SOC. All these strategies have enhanced the energy efficiency of the battery bank, and the results are compared. The best result for energy efficiency is obtained with strategy2 as Fuel cell operating mode. The FUZZY logic will helps in a very linear manner. The output of the whole system is 15% increased while it is used. The output DC Voltage of these system is increased upto 103V from 85V. After all these, at finally here we compared the operating status of wind and fuel cell by using fuzzy logic control.

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C A Pradeep kumar was completed his BE degree from Park College Of Engineering & Technologies, Anna University, Tamil nadu. Now he is doing his master degree in Karunya University in Renewable Energy Technology. He is having 3+ years of working experience in induction motors His main interest is in Hybrid Vehicles, Fuel cells and Wind Energy.

A.BENUEL SATHISH RAJ completed his B.E degree in Electrical and Electronics from Bharathiyar University. His area of specialization is Applied Electronics & Renewable Energy Technologies. He is doing his Ph.D. in Renewable Energy. Now he is working as Assistant Professor in Karunya University. He completed M.B.A in Human Resources Management. He is having more than 10 years of Teaching Experience.

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