MPPT of Stand-Alone Hybrid System Using Fuzzy Logic Controllers

Syama.C (PG Student)
Department of Electronics and Communication
Adithya Institute of Technology.
Coimbatore- 641 107

G. Rayappan (*Assistant Professor*)
Department of Electronics and Communication
Adithya Institute of Technology.
Coimbatore- 641 107

***Abstract*—Renewable energy sources are clean, economically competitive with conventional power generation, were energy is gathered from self-renewing resources such as sun, wind etc. Hybridizing solar and wind energy sources can help in fulfilling the energy demands. This paper proposes a stand-alone hybrid energy conversion system combining photovoltaic and wind turbine for remote area applications. This hybrid system consists of wind turbines, photovoltaic panels and storage batteries. The wind and PV are used as the main sources, while the battery energy storage system is used to provide continous supply .These sources are connected to a dc bus line through DC-DC converters. Two individual DC-DC boost converters are used to control the power flow to the load from both sources and voltage controller is used to control the voltage to the battery. Effective Fuzzy controllers are used for Maximum Power Point Tracking (MPPT) controlling the switching of boost converters. Thus maximum power is extracted from both sources. Inverters are connected to the dc bus for AC loads .The modelling of hybrid system is developed in MATLAB/SIMULINK. Simulation result shows the comparison and proper performance of the proposed system.**

Keywords—* *Permanent Magnet Synchronous Generator (PMSG); Wind Energy Conversion System (WECS); Battery Energy Storage System (BESS); Maximum Power Point Tracking (MPPT); Fuzzy Logic Controllers (FLC);

I. INTRODUCTION

With depletion of fossil fuel reserves and increasing concern of global warming, many are looking at green energy solutions to reserve the earth for the forthcoming generations. Wind energy is able of delivering huge amounts of power but its presence is exceedingly erratic. Similarly, solar energy is present all over the day but the solar irradiation levels fluctuates due to unpredictable shadows cast by birds, clouds, trees, etc. and sun intensity. The general integral shortcoming of wind and photovoltaic systems are their alternating natures that make them variable. However, by merging these two energy sources and by integrating maximum power point tracking (MPPT) concepts, the system's power transfer reliability and efficiency can be improved significantly [2].

The standalone solar photovoltaic and wind systems have been promoted on a comparatively larger scale.The standalone wind energy system cannot comply with stable load demands due to momentous changes in the level of wind speeds from hour to hour all over the year. Therefore, in order to satisfy the continuous power demands energy storage systems will be required. Usually storage system is costly and the dimension has to be decreased to least possible for the renewable energy system to be cost effective. The power produced from both solar and wind is deposited in a battery bank for use whenever required. A hybrid renewable energy system make use of two or more energy generation methods, usually solar and wind power. The dependability of the system can be improved when wind and solar power making is used together.

Several electrical machines can be used to implement the electromechanical energy conversion and control, each of which presents different advantages and disadvantages. For small-power wind systems operating in remote and isolated areas, the study of permanent-magnet synchronous generators (PMSGs) has been the subject of much research. PMSGs are particularly interesting in low-power wind energy applications due to their small size and high power density. The primary advantage of PMSGs is that they do not need any external excitation current. A major cost benefit in adopting the PMSG is the fact that a diode bridge rectifier may be used at the generator terminals since no external excitation current is required. The system topology used in this paper is based on a PMSG connected through a diode bridge rectifier and a boost converter to the dc link for small- and medium-power ranges [1].

In this system wind and photovoltaic array is used as the energy sources. Wind turbine is connected to the pmsg which converts mechanical energy into electrical energy .This ac output is converted into dc by ac-dc converter and dc-dc boost converter is added to boost up the voltage ratio. Photovoltaic array is connected to a dc-dc converter which also boost up the voltage ratio and maximum power point tracking. All energy sources are commonly connected to the dc-bus line.

The system becomes a hybrid solar-wind energy system. For charging the battery, photovoltaic array is also used. A Battery Energy Storage System (BESS) is used to store the energy during higher wind speeds. A variable speed direct driven permanent magnet synchronous generator (PMSG) is used. Fuzzy Logic Controller (FLC) controllers are used to provide the necessary control strategy for the proposed system. Maximum Power Point Tracking methods are used for extracting maximum power from the energy sources. Fuzzy

Logic Controller (FLC) controllers is used to obtain maximum power from photovoltaic array. A Boost converter circuit is used to boost the voltage to desired level before ingesting the battery. The block diagram of proposed system is shown in Fig 1. The performance of a hybrid source depends on the efficiency of each component of the system. In a PV or Wind system, the output is dependent on the weather of the region in which the plant is located, and is hence highly variable and erratic. It is also available only during fixed hours of the day. To make up for this uncertainty and suitably meet the load demand when the renewable energy is scarce or unavailable, additional energy sources are required as backup to improve the reliability of the system if any, during day, and serve as a power source during night or when there is unmet load. Depending on the state of charge, and the availability of power after the load is met, batteries are charged by both sources.

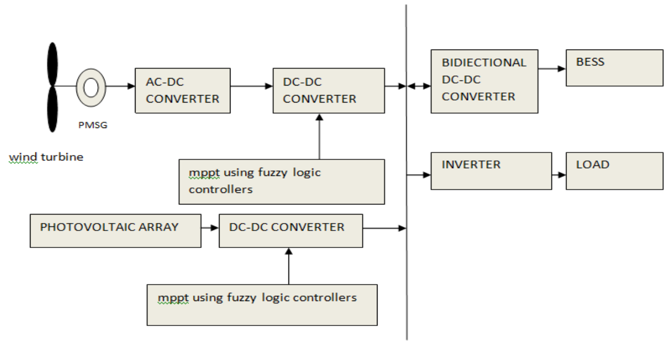

Fig. 1 Block diagram of proposed system

II. PHOTOVOLTAIC SYSTEM CONFIGURATION

A conventional in-built disadvantage of wind and solar systems is the discontinous nature of their energy sources. A solar cell is the most fundamental component of a photovoltaic (PV) system a solar cell is a P-N junction semiconductor diode that produces currents via the photovoltaic effect. PV arrays are fabricated by placing number of solar cells connected in series and in parallel. A PV cell is a diode of a large-area forward bias with a photo voltage and the equivalent circuit is shown by Fig 2.

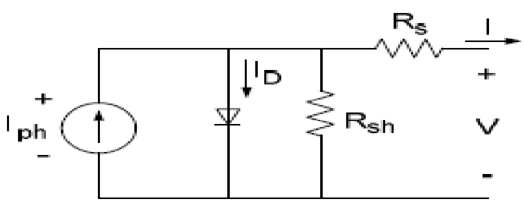

Fig 2. PV cell equivalent circuit

The ideal current-voltage characteristic of a solar cell is as shown in fig 3. Typically, the series resistance (Rs) is very small and the shunt resistance (Rsh) is very large. Therefore, in order to make clear and simplify the solar cell model it is common to neglect these resistances. The optimal voltage-current characteristic of a photovoltaic cell is given by the equation below and is illustrated in Fig 3.

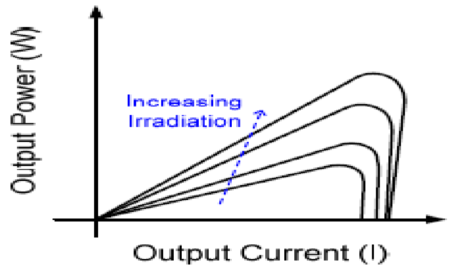

Fig. 3 .PV cell power characteristics

The equations are given by

$$I = I_{PH} - I_D \quad (1)$$

$$I = I_{PH} - I_0\left[exp\left(\frac{q(v + R_S I)}{A K_B T}\right) - 1\right] - \frac{V + R_S I}{R_{sh}} \quad (2)$$

Where
I_{PH} = photocurrent
I_D = diode current
I_0 = saturation current
A = ideality factor
q = electronic charge
K_B =Boltzmann's Constant
R_S = series resistance
R_{sh} = shunt resistance
I = cell current
V = cell voltage

Under various degrees of irradiation ,the typical output Since wind energy is a non-reliable and unpredictable source of energy varying from time to time, stringent conditions are to be imposed in designing the proposed configuration of WECS using pmsg with a BESS(1). Choosing the appropriate rating of the battery is of utmost importance as any discrepancy would lead to malfunctioning of the system. It includes the design of wind turbine and battery energy storage systems.wind energy system equipped with a direct-driven PM an ac/dc converter (diode rectifier bridge + boost converter) for the tracking of the maximum power from the available wind resource.

The wind power is converted into the mechanical rotational energy of the wind turbine rotor. A wind turbine cannot "completely" extract the power from the wind. The wind turbine rotor is connected to the wind generator thus converting the mechanical energy into electrical energy. The generator's ac voltage is converted into dc voltage through an ac/dc converter. The rectifier is matching the generator's ac voltage to the dc voltage, while the boost converter provides the required level of constant dc voltage. The dc output voltage is fed to the battery bank and through an inverter further to the load. The voltage should stay constant for various wind speeds. When the wind speed is too high, the power excess supplied by the wind turbine is stored in the power characteristics of a PV array is illustrated by Fig 4.For each irradiation level there is a particular optimal voltage that corresponds to maximum output power. Therefore, maximum power from the array can be extracted by controlling the output current (or voltage) of the PV array. The mppt of photovoltaic array is done by using pi controllers. The amount of power generated by a PV depends upon the operating voltage of the array. A Photovoltaics maximum power point (MPP) varies with temperature and solar insulation.Its V-P and V-I curves specify a unique operating point at which maximum possible power is extracted. At the MPP, the PV operates at its maximum efficiency.

a. *Mppt of Pv using Fuzzy Logic Controllers*

Maximum power point tracker (MPPT) tracks the new modified maximum power point in its corresponding curve whenever temperature and/or insolation variation occurs. MPPT is used for extracting the maximum power from the solar PV module and transferring that power to the load. A dc/dc (step up/step down) converter acts as an interface between the load and the module. The MPPT is changing the duty cycle to keep the transfer power from the solar PV module to the load at maximum point. Maximum power point tracking system uses dc to dc converter to compensate the output voltage of the solar panel to keep the voltage at the value which maximizes the output power. Fig 4 shows the input variable.

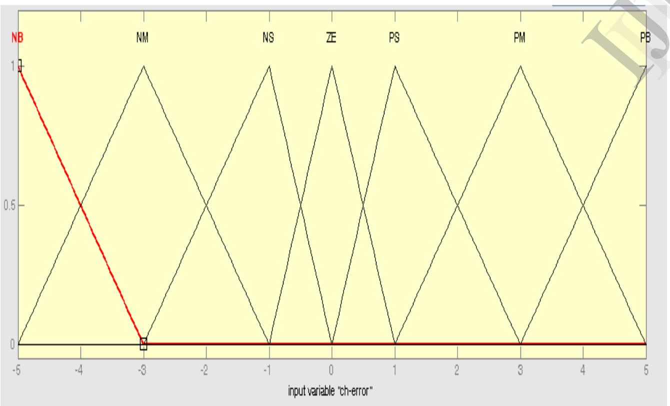

Fig 4 Change in input

MPP fuzzy logic controller measures the values of the voltage and current at the output of the solar panel, then calculates the power from the relation (P=V*I) to extract the inputs of the controller. The crisp output of the controller represents the duty cycle of the pulse width modulation to switch the dc to dc converter.fig 5 shows the change in input variable.

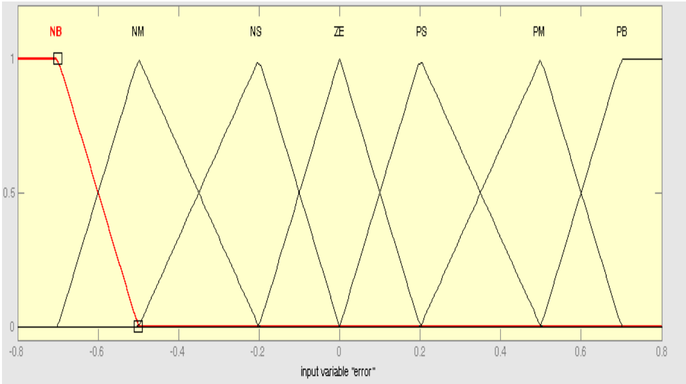

Fig 5 Input variable

The FLC examines the output PV power at each sample (time k), and determines the change in power relative to voltage (dp/dv). If this value is greater than zero the controller change the duty cycle of the pulse width modulation (PWM) to increase the voltage until the power is maximum or the value (dp/dv) =0, if this value less than zero the controller changes the duty cycle of the PWM to decrease the voltage until the power is maximum as shown in Figure 3.FLC has two inputs which are: error and the change in error, and one output feeding to the pulse width modulation to control the DC-to-DC converter. The two FLC input variables error E and change of error CE at sampled times k defined by:

$$E(K) = \frac{P(K) - P(K-1)}{V(K) - V(K-1)} \qquad (3)$$

Change (K)=E(K)-E(K-I) (4)

Where P (k) is the instant power of the photovoltaic generator. The input error (k) shows if the load operation point at the instant k is located on the left or on the right of the maximum power point on the PV characteristic, while the input CE (k) expresses the moving direction of this point. The fuzzy inference is carried out by using Mamdani method, FLC for the Maximum power point tracker. FLC contains three basic parts: Fuzzification, Base rule, and Defuzzification.fig 6 shows the duty ratio which is the output variable.

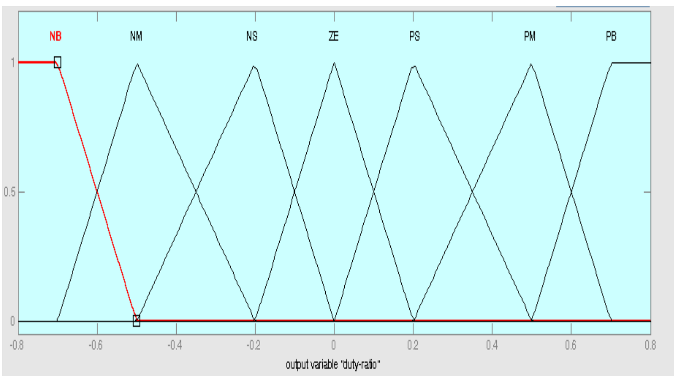

Fig 6 Output variable

The knowledge base defining the rules for the desired relationship is between the input and output variables in terms of the membership functions. The linguistic variables used are: NB: Negative Big. NM: Negative Medium NS: Negative Small ZE: Zero.PS: Positive Small.PM: Positive Medium. PB: Positive Big.

III. WIND ENERGY SYSTEM CONFIGURATION

Since wind energy is a non-reliable and unpredictable source of energy varying from time to time, stringent conditions are to be imposed in designing the proposed configuration of WECS using pmsg with a BESS(1). Choosing the appropriate rating of the battery is of utmost importance as any discrepancy would lead to malfunctioning of the system. It includes the design of wind turbine and battery energy storage systems.wind energy system equipped with a direct-driven PM an ac/dc converter (diode rectifier bridge + boost converter) for the tracking of the maximum power from the available wind resource. The wind power is converted into the mechanical rotational energy of the wind turbine rotor. A wind turbine cannot “completely” extract the power from the wind. The wind turbine rotor is connected to the wind generator thus converting the mechanical energy into electrical energy. The generator’s ac voltage is converted into dc voltage through an ac/dc converter. The rectifier is matching the generator’s ac voltage to the dc voltage, while the boost converter provides the required level of constant dc voltage. The dc output voltage is fed to the battery bank and through an inverter further to the load. The voltage should stay constant for various wind speeds. When the wind speed is too high, the power excess supplied by the wind turbine is stored ithe battery when the wind speed is low, continuous power to the load supplied by the battery. The dc loads are supplied directly from the dc circuit. At high speeds, the turbine control system stops the energy production. The same protection is activated also in the case when the battery is fully charged and energy production exceeds consumption. At low wind speeds, load shedding is used to keep the frequency at the rated value. The storage system is composed of a LAB and a full-bridge single-phase inverter that converts the dc voltage of the battery to ac voltage. Furthermore, this voltage is applied to a single phase transformer, which boosts up the voltage to 230 V. The inverter controls the power transfer.

A. *PMSG MODEL*

The dynamic model of PMSG is derived with respect to the direction of rotation from the two-phase synchronous reference frame in which the q-axis is 90◦ ahead of the d-axis,. The electrical model of PMSG in the synchronous reference frame is given by the output power of the turbine and the wind velocity has the nonlinear relation. The output power of the turbine is given by the following equation

$$\frac{di_d}{dt} = -\frac{r_a}{l_d} id + w_e \frac{l_q}{l_d} i_q + \frac{1}{l_d} v_d \quad (5)$$

$$\frac{di_q}{dt} = -\frac{r_a}{l_q} iq - w_e \left(\frac{l_d}{l_q} id + \frac{1}{l_d} \varphi_{pm}\right) + \frac{1}{l_q} v_q \quad (6)$$

where subscripts d and q refer to the physical quantities that have been transformed into the d–q synchronous rotating reference frame; Ra is the armature resistance; ωe is the electrical rotating speed which is related to the mechanical rotating speed of the generator as ωe = np · ωg, where np is the number of pole pairs; and ψPM is the magnetic flux of the permanent magnets and electromagnetic torque is given by

$$T_e = 1.5 n_p \varphi_{pm} i_q \quad (3)$$

B. Boost Converter Model

The unidirectional boost converter achieves an interface between the battery and the rectifier capacitor and ensures the rapid transfer of power. A simplified model of the boost converter is shown in Fig. 7.

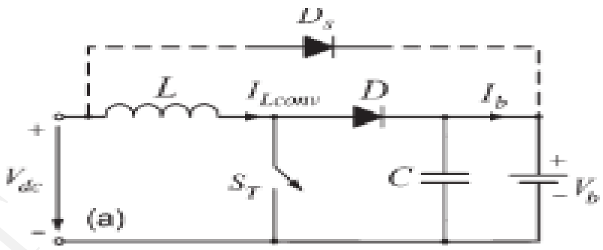

Fig 7 Boost converter circuit

The voltage and current relationship between the primary and secondary sides is given by Equation (4) and (5)

$$V_b = \frac{v_{dc}}{1-D} \quad (7)$$

$$I_b = I_{l\,conv}(1-D) \quad (8)$$

Where D is the pulse-width modulation (PWM) modulation factor.

When Vdc ≥ Vb, the boost converter is not working, and the current provided by the generator is channeled through the bypass Schottky diode Ds. it is assumed that there is no power loss in the converter. The input and output signals of the boost converter are modeled by two controlled current sources.

The reference current (I*Lconv) is supplied by the maximum power point tracking (MPPT). The error between the reference current and the measured current (ILconv) is applied to a proportional integrator (PI) regulator. The output of the regulator is summed with the positive voltage reaction, which realizes1 Vdc/Vb. The modulation factor D is obtained, which is used as a reference for the PWM generator, as shown in Fig. 6. The modulation factor provides the control signal for the converter’s switching device ST.

C. MPPT of WECS using Fuzzy Logic Controllers

To obtain maximum power from a controlled WECS, this has to operate in the variable-speed mode. Thus, an adequate controlling method, based on MPPT, must be used, in order to maximize the electric output power and to adjust the generator speed.

Several studies have been dedicated to small turbines, including different architectures with their associated complexity and implementing different control strategies giving certain energy efficiency values. Knowing the optimal characteristics allows maximizing the energy transfer by controlling the torque speed, or power. In fact, energy efficiency not only depends on the control strategy but is also influenced by the system topology and its losses.

Depending on the wind speed, the MPPT control adjusts the power transferred, bringing the turbine operating points onto the "maximum power curve,". In the case of the system studied, both in the simulations and in the experiments, the converter control system did not allow obtaining maximum power over the entire range of wind speeds, but only from 3 to 6 m/s, due to current limitations introduced by the motor inverter which emulated the wind turbine. A FLC regulator is used to implement the MPPT function, which provides the reference power for the boost converter, based on the wind speed measurements (vp.u.) and the turbine generator speed (np.u.).

The proposed FL controller is shown in Fig. 8. Its input variables are: change in mechanical power (ΔP), change in rotating speed ($\Delta\omega$) and the sign of $\Delta P_{mm}/\Delta\omega$. The output variable is the change in dc reference current (ΔI^*). The considered mechanical power (P_m) it is composed by:

$$Pm = Pg + J.\omega. \qquad (9)$$

Where P_g: PMSG mechanical (input) power [W], resulting the dynamic power versus rotating speed curve.

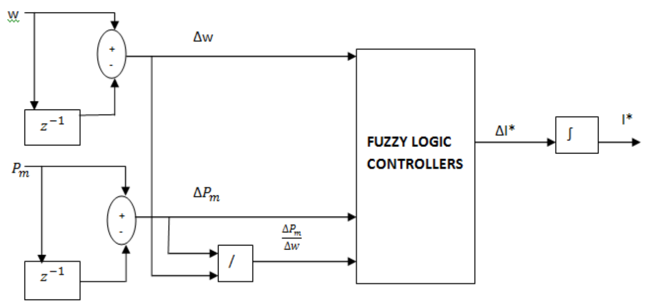

Fig 8 MPPT of wind using fuzzy logic controllers

The MPPT – FLC has to extract the maximum available power from the wind by increasing or decreasing the reference rectified PMSG current. Changing the PMSG current changes the PMSG torque, which will modify the rotating speed according to (6). In the steady state, if the operating point is on the left side of the maximum power point on the curve ,to attain the optimum power operating point, the controller has to decrease the reference current and, as a result, the rotating speed increases. In this way the operating point will shift to the right to a higher power point. In the other case, when the operating point is on the right side of the maximum power point, the reference current needs to be raised. In this way the speed will fall and the operating point will shift to the left, to a upper power point.

These input and output variables are normalized in the range of [-1 1], according to the system behaviour in order that the FLC block to be universal for other wind turbine systems. The used scale coefficients are k_w, k and the integrator gain k. The FLC algorithm is characterized by "if then" rules as shown in Table I. The fuzzy basic rules, which associates the fuzzy output to the fuzzy input, is derived from the desired system behaviour and the designed control strategy. The rules are designed so that the controller always seeks a maximum power point, without stopping.

The fuzzy values are: *N* (negative), *NS* (negative small), *Z* (zero), *PS* (positive small) and *P* (positive). The output fuzzy sets are then identified using a fuzzy implication method, which is a *MIN-MAX* method. The trapezoidal and triangular membership functions of the FLC are used. The centroid (center of gravity) defuzzification method was also implemented. Table 1 shows the rules of the fuzzy logic controllers used in this paper

Table 1. Fuzzy rules

ΔP_m / Δw		ΔP_m				
		N	NS	Z	PS	P
Δw	N	P	P	Z	N	N
	NS	P	P	Z	N	N
	Z	Z	Z	Z	Z	Z
	PS	N	N	Z	P	P
	P	N	N	Z	P	P

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IV. ENERGY STORAGE SYSTEM

The energy storage system is composed of a single-phase MOSFET inverter and a bank of LABs 12 V each (gel type) connected in series to provide the desired value of the inverter battery voltage. The LAB is able to supplement the power provided to the load by the wind turbine, when the wind speed is too low. The equivalent electrical model of the LAB contains a controlled voltage source (Eb), connected in series with the internal resistance (Rint) and the LAB voltage (Vb). It is known that the Eb voltage depends on the charging state, battery type,

$$E_b = E_{bo} - \frac{k.Q}{Q-\int_0^T I_b\,dt} \qquad (10)$$

Where Eb0 is the no-load battery voltage at the rated charge, K is the polarization voltage, Q is the battery capacity, and I is the battery current. The input of the charging/discharging controller is used as a parameter—the state of charge (SOC) of LAB and is defined as b If the LAB is fully charged, SOC =1, and if the battery is discharged at the maximum value, SOC = SOCmin .For instance, the maximum recommended discharge for LABs used in such applications is 80%; thus, SOCmin =0.2.Asthefull discharge is not recommended for LABs, a SOCmin = 20% will be considered in the regulator’s implementation. The calculation algorithm uses one variable parameter (I). With a discrete-time integrator block, the mathematical operations, and an initial SOC value, the LAB SOC and one constant block (Q[%] is obtained in min b).

V. SIMULATION RESULTS

The circuit is simulated using MATLAB SIMULINK, An MPPT control is used to control the operation of switch of the boost converter circuit. Fuzzy Logic controller is used in MPPT control.This method uses the PV arrays, it knows that the maximum power point is reached and thus it stops and revert the equivalent value of operating voltage for MPPT. This method tracks rapidly changing irradiation conditions.

Fig.9 shows the implementation of hybrid model using MATLAB SIMULINK.V-I Measurement blocks are used at various points to measure the values of voltages and currents. Scope is used to obtain the output waveforms.it consists of the wind and solar energy connected to individual dc-dc boost converters and battery through a charge controller all are connected to a dc bus line.to connect these to a ac loads an inverter is connected to the dc line which converts dc to ac.

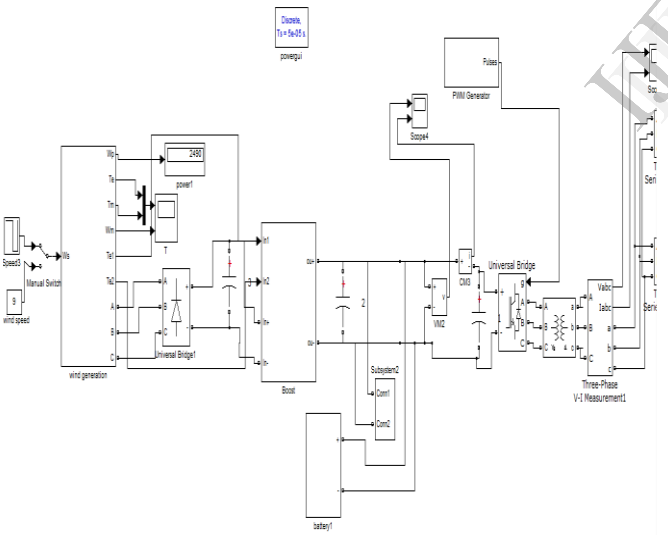

Fig 9 Implementation of hybid model

Fig. 10 shows the overall simulink model of the input side boost converter model of solar energy sources .In which it contains of gating pulses of the boost converter is supervised by mppt controller.

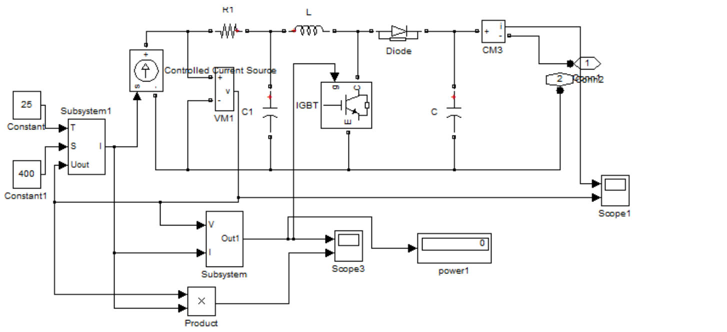

Fig 10 Boost converter model of PV

The proficiency of a solar cell is very low. In order to raise the efficacy, techniques are to be take on to tone with load and the source properly. One such technique is the Maximum Power Point Tracking (MPPT). This is a method used to obtain the maximum available power from a rapidly changing source. In photovoltaic systems the I-V curve is non-linear, thereby making it problematic to be used to power a particular load. This is done by making use of a boost converter whose duty cycle is changed by using a MPPT algorithm. A boost converter is used to boost the power produced and is in the generating side and a solar panel is used to power this converter.

Implementation of mppt using fuzzy logic controllers in wind energy sources is given in fig 11. The main function of the mppt controllers is that to maximum power to be tracked.the generator speed and rotor speed is taken and its differnce is given to the fuzzy logic controller and also the output voltage of boost and input voltage of battery is considered.

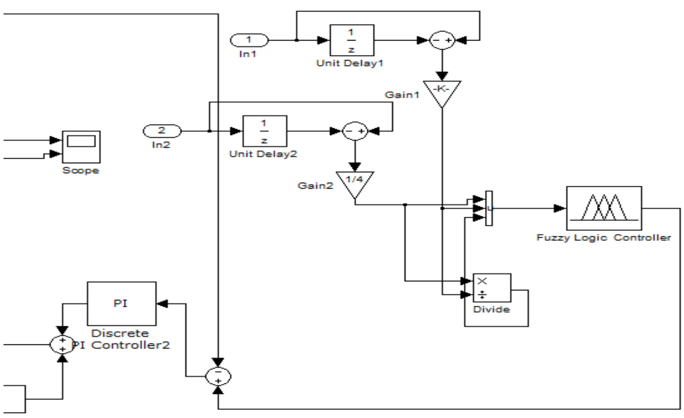

Fig 11 Implementation of fuzzy in WECS

Fig.12. shows the output current and voltage to the inverter. Inverter is connected to the dc bus line in order to connect to ac loads.

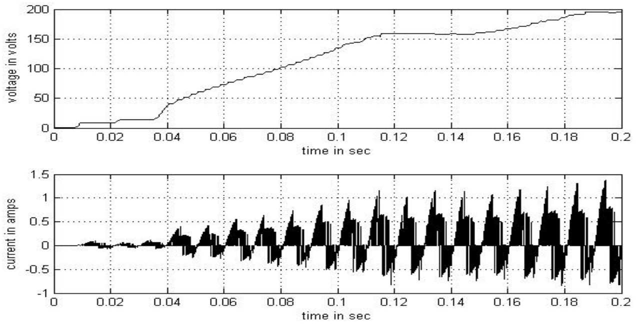

Fig 12 Inverter output

The battery output of the system is shown in Fig 13 in which it shows the performance of the system. Charging and discharging of the system. When both input are available it charges and when availability is less it discharges so that output power is always maintained constant and this is done more efficiently by using fuzzy logic controller as the maximum power point tracker.

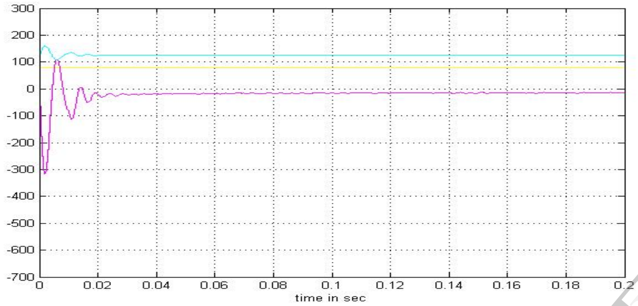

Fig 13.Battery output of hybrid system

The simulation result shows that of various wind speed the power of the system is maintained constant by adding PV array and lead acid batteries

VI. CONCLUSION

A hybrid solar – wind power conversion system in standalone has been proposed. The system has been modelled using MATLAB SIMULINK and output at various wind speeds were verified. Battery energy storage system is used in the circuit that guarentees constant power to the load. It has been observed that permanent magnet-based wind energy conversion system with battery energy storage system demonstrates satisfactory performance under different wind speed conditions.

The proposed configuration and control strategy, supplies a constant power to the load throughout, thus maintaining a constant flow of energy to the load irrespective of the variations in the wind speed. Moreover, the maximum power point tracking (MPPT) is used. Fuzzy Logic Controller has been used here. This method tracks rapidly changing irradiation conditions.

The system can be made more efficient and reliable by inclusion of photovoltaic array to obtain a hybrid system. The PV panel is used to charge the BESS. This helps to maintain output power constant even if the wind speed is low for extended periods. Also, it is possible to connect the PV system to load through a converter circuit. This makes the system more efficient and reliable system was analyses by varying the wind speed and finded out the power is maintained constant system is again analysed by using different load conditions and in that also current is varying with respect to the load.

The Maximum Power Point Tracking can be more smoothly if we connect other improved algorithm so that more efficiency can be obtained from this system.the variation of renewable source is the major problem in this system so that maximum power has to be tracked.

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