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Research Article

Optimization of Performance Characteristics of Hybrid Wind Photovoltaic System with Battery Storage

[1]C. Kathirvel and [2]K. Porkumaran
[1]Department of Electrical and Electronics Engineering, Sri Ramakrishna Engg College,
[2]N.G.P. Institute of Technology, Coimbatore, India

Abstract: This study concentrates on the Design and Implementation of a multi source hybrid Wind-Photovoltaic stand alone system with proposed energy management strategy. The method of investigation concerned with the definition of the system topology, interconnection of the various sources with maximum energy transfer, optimum control and energy management in order to maintain the DC bus voltage into a fixed value. An Energy management strategy was proposed using the Fuzzy logic controller such that enhancement in the performance of the system and optimization can be done. The Fuzzy logic controller takes the input from Solar (irradiation), Wind (speed), Power demand and the battery voltage which controls the respective subsystem and formulates into different operational modes of energy management. The role of Fuzzy threshold controller is to adjust continuously the threshold value for optimal performance based on expected wind, solar conditions, battery voltage and power demand. It is shown that when the fuzzy logic controller is used, the proposed DC bus voltage regulation strategy with different modes of operation have fast response and efficient operation which leads to a reduced operating cost.

Keywords: Battery, energy management, fuzzy control, hybrid energy system, PMSG, renewable energy, wind, WSHPS

INTRODUCTION

In this new era, the recent technological invasions have propelled the development of the entire world to its new heights. These developments have transformed the world into its new dimensions through technological aspects and impact. This is the main reason for power demand. The rate of world development in geometric ratio catalyses the need of extracting power from renewable energy resources and also the funny fact as another reason is the available of conventional energy resources is only up to 60-70 years. Out of the renewable energy resources such as Wind, Geothermal, Solar, Ocean, Biomass and Chemical resources, the Wind and Solar resources have its advancement due to its reliability, simplicity etc. Due to the frequent variation in the availability of these resources, the hybrid concept for power generation gains importance. Solar and wind power is an inexhaustible renewable energy source and they are widely available. Wind and solar power has a good application prospect in terms of development. The rational allocation of capacity for wind solar hybrid power system can increase reliability of power supply and reduce the system cost according to load characteristics of residential use and local environment condition. Both wind and solar generation systems can accomplish important features of sustainable resources and environmental protection. The production of pollution free electrical energy can be done and the advantage may extend up to the benefits of economics and developments. Battery units integrated with solar and wind sub systems can give a good reliability. In stand-alone WSHPS, the lead-acid batteries play an important performance as an energy storage component. Whereas charge/discharge strategies of battery storage directly affects the power supply quality in WSHPS since electrical energy from solar and wind turbine generator has fluctuation. Hence an energy management strategy should be introduced for the proper utilization of hybrid wind and solar energy resources along with battery source. This results in regulation of output DC bus voltage to a constant value. The objective of the proposed work is to design and implement a fuzzy logic based energy management strategy to a hybrid wind solar system for rural electrification.

Hybrid Wind-Photovoltaic power system is a new form of power generation unit which use the complementation of characteristics of wind, photovoltaic generation system, along with energy storage, thus guarantee the system reliability, decrease the power fluctuation, improve power quality and reduce the impact to power system. Hybrid energy

Corresponding Author: C. Kathirvel, Department of Electrical and Electronics Engineering, Sri Ramakrishna Engg College, Coimbatore, India

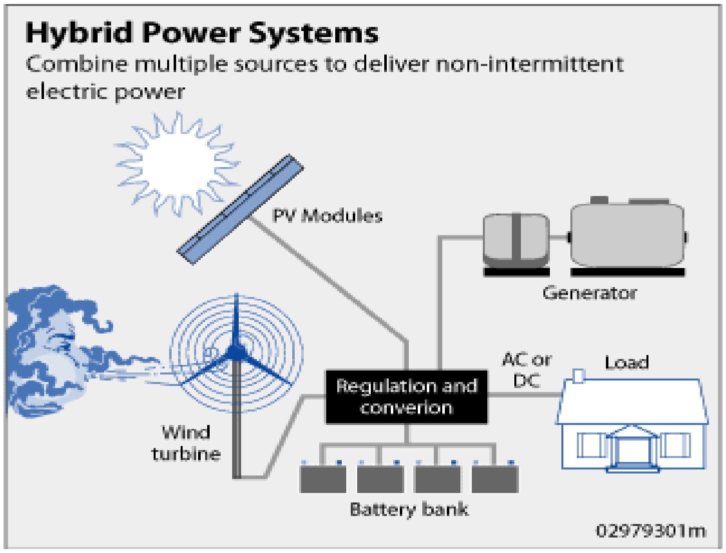


Fig. 1: General illustration of a wind-photovoltaic hybrid system

system is an excellent solution for electrification of remote rural areas where the grid extension is difficult and not economical. An average model of a hybrid wind-photovoltaic generating system has been presented. The Model is important for synthesizing the control strategy and analyzing the dynamic behavior of the system. The main intension is to provide 24 h demand quality power in remote rural communities. Hybrid Wind-PV system is highly efficient and requires very low maintenance. Among renewable energy technologies (Began and Billinton, 2005), photovoltaic cells and wind turbines are indeed the most popular, both featuring no pollution and being advantaged by a large availability of an inexpensive primary energy. However, in the last two decades the efficiency and reliability of photovoltaic and wind generators have been improved, while the costs have been noticeably lowered (Nabil *et al*., 2008; Ross, 1995).

Although a full commercial competitiveness with conventional systems has not still reached, potential benefits of large scale production and the constant rise of the cost of fossil fuels could result in an acceptable level of competitiveness in a short time (Eftichios and Kostas, 2006). The system is used to produce electric power in remote areas that cannot be connected, for economical or technical reasons, to a main utility grid. In stand-alone, or island mode, applications the most critical requirement for an electric generator is the reliability of the power production, in order to always ensure a perfect balance between power demand and generated power. Among renewable savers, the wind undoubtedly is the more affected by variability and photovoltaic plants are heavily influenced by weather conditions. The Fig. 1 shows the general schematic diagram of the hybrid system.

The certainty of load demands at all times is greatly enhanced by hybrid generation systems, which use more than one power source. It is possible to achieve much higher generating capacity factors by combining wind turbine and photovoltaic arrays with a storage technology to overcome the fluctuations in plant output. Therefore, both photovoltaic arrays and wind turbines working alone cannot ensure the minimum level of power continuity required to supply uninterrupted power so that (Bogdan and Ziyad, 1997) an efficient energy storage system is required, to get constant power. This conversion might be realized by a battery bank or Energy Capacitor System (ECS). Both wind speed and solar radiation have complementary features and integration of both wind and PV systems may reduce the capacity of Battery Energy Storage System (BESS) (Gopal, 1989; Hansang *et al*., 2012).

MATERIALS AND METHODS

Modelling of the hybrid system: The wind subsystem has a capacity of 600 W wind generator equipped with a direct driven Permanent-Magnet Synchronous Generator (PMSG), a diode rectifier and a (DC/DC) buck converter to exert maximum power. The solar subsystem consists of a 400W photovoltaic panel which is built up of a combination of series and parallel individual photovoltaic modules. The DC output voltage of the panel varies, if the solar intensity varies. The DC/DC buck converter is used to control the variable DC output voltage of the panel before it is fed to the DC bus used for the optimal transfer of the power by regulating the output current I_{PV}. The common DC bus collects the total energy from the wind and photovoltaic systems and uses it partly to supply the required power as per load demand and partly to charge the battery bank. Under normal operating conditions of

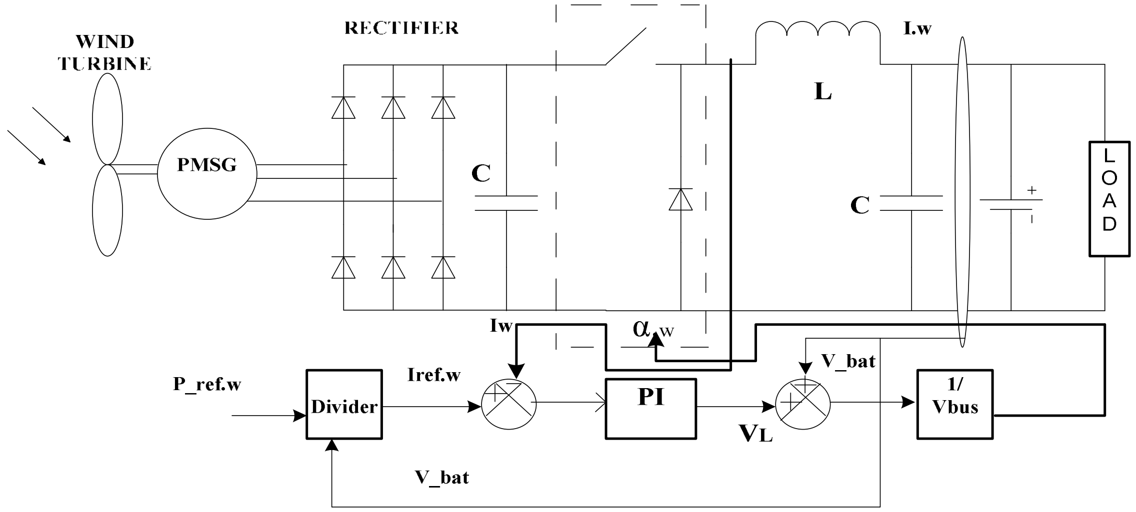


Fig. 2: Closed loop current control of DC/DC buck converter

wind velocity and solar intensity, the battery bank is an additional load to the system. It acts as an additional source to supply the demand during low wind velocities or solar intensities. Before defining the supervisor control concepts, a model description of each element in the hybrid energy conversion system is given. A brief description of wind and photovoltaic subsystem is specified below:

Wind energy conversion subsystem: The block diagram of the proposed maximum power control for the wind subsystem adopted in this study is shown in Fig. 2. The system comprises of a small wind turbine coupled to a Permanent Magnet Synchronous Generator (PMSG), the output voltage and frequency from the generator will vary for variable wind speed. The variable output power from the generator is first rectified using a diode bridge rectifier. A buck converter is used to exert the maximum power available from the wind energy system for a given wind velocity and to deliver this power to a 48 V DC constant voltage load. The voltage across the rectifier terminal is then variable relatively to the control of the Duty Cycle of the (DC/DC) converter. The system is designed to control the output current. By dividing the reference wind power $P_{ref.w}$ by the battery voltage V_{bat}, the reference battery current is calculated. The optimal reference value of the current $I_{ref.w}$ is imposed to the current controller of the (DC/DC) chopper by sensing the battery voltage and its operation is shown in Fig. 2.

The error resulting from the comparison between desired and actual values of the output current I_w is processed by the microcontroller through a PI regulator, issuing a value V_L of the inductance voltage (L). The sum of the inductance voltage V_L and the battery voltage V_{bat} is divided by the DC voltage V_{bus} to issue the duty-cycle α required for the IGBT switching operation, as shown in Fig. 2.

Wind turbine: The output mechanical power of the wind turbine is given by the usual cube law:

$$P_W = 1/2.\rho.S.V_W^3.C_P.\lambda \tag{1}$$

where,

V_W = The average wind velocity in m/s
ρ = The air density (kg/m^3)
S = The surface of the turbine blades (m^2)
Cp = The power coefficient
λ = The tip speed ratio

The output torque *Tw* of the wind turbine is calculated from the following equation:

$$T_W = P_W / \omega_m = (1/2.\rho.S.V_W^2.C_P.\lambda)/\lambda \tag{2}$$

Design of the Permanent Magnet Synchronous Generator (PMSG) connected to the diode rectifier: A 600W, 400V, 300 rpm rated speed, Permanent Magnet Synchronous Generator (PMSG) is used in the wind subsystem. According to the wind speed variation the generator output voltage varies. Hence, the 3-phase output of the PMSG is rectified with a diode bridge rectifier, filtered to remove significant ripple voltage components and connected to the buck converter. For an ideal (unloaded and loss-less) PMSG, the line to line voltage is given as:

$$V_L = K_V.\omega_e.Sin(\omega_e.t) \tag{3}$$

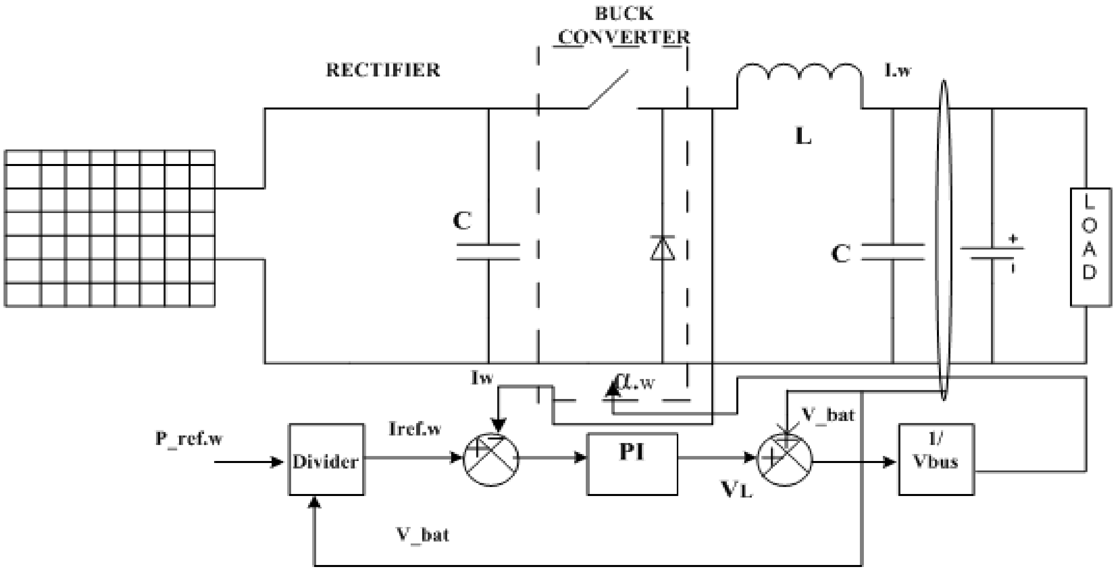


Fig. 3: Closed loop current control of PV side DC/DC buck converter

where, K_V is the voltage constant and e is the electrical frequency related to the mechanical speed m by the relation (4):

$$\omega_e = \omega_m.(n_P / 2) \tag{4}$$

where, n_P is the number of poles in PMSG.

Considering the overlapping effects, the DC rectifier voltage V_{dc} is given as Eq. (6):

$$V_{dc} = (3\sqrt{2}/\pi.V_{L.RMS}) - 3.\omega_e.L_S.I_{dc}/\pi \tag{5}$$

where, V_{Lrms} is the RMS value of the PMSG output voltage, I_{dc} is the average rectifier PMSG output current and Ls is the stator inductance. The rectified electrical power, P_{dc} is given below:

$$P_{DC} = V_{DC}.I_{DC} \tag{6}$$

DC/DC buck converter: The average output voltage of the buck converter is given by:

$$V_W = \alpha.V_{dc} \tag{7}$$

where, α is the duty cycle of the chopper.

The DC voltage at the converter output feds the battery DC bus which is nearly constant. Assuming negligible converter losses, the average output current I_s of the buck converter is given by Eq. (9) (Gopal, 1989; Hansang *et al.*, 2012):

$$I_W = I_{DC} / \alpha \tag{8}$$

Lead-acid accumulator: The energy storage system is provided through an array of four accumulators, connected in serial. Each accumulator consists of 6 2-V cells connected in series, thus providing a nominal voltage of 48 V. The internal terminal voltage, *Vs* in charge operation is given by (Kosko, 2004):

$$V_S = E_{bat} + I_{bat}.R_{bat} \tag{9}$$

where, I_{bat} is the battery current.

Photovoltaic energy conversion subsystem: The PV array exerts a 400 W peak power (75 V and 5.5 A at 1000 W/m² and 25°C). To obtain the required (48 V) voltage level, a buck (DC/DC) converter is used. This DC/DC Buck converter is controlled to extract the maximum power from the Photovoltaic generator. The closed loop operation of solar subsystem is shown in Fig. 3.

The objective of the control method is to adjust the voltage V_{PV} to have the extraction of maximum power. A PV array is defined as a group of various modules electrically connected in series and parallel combinations to generate the required current and voltage. Figure 4 shown a simplified equivalent circuit model of a PV. The performance of an equivalent PV array with NS×NP modules is given by Eq. (10).

Parameter for the PV module model can be obtained from manufacturer's data sheet is given by:

$$I_P = N_P.I_{SC} - N_P I_d(\exp[(V_P + I_{PV}.R_S)/n.N_S.V_T] - 1) \tag{10}$$

where,

I_{PV} = Output current of PV panel [A]

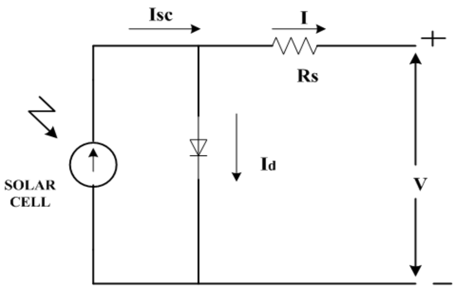


Fig. 4: Equivalent circuit of a solar cell

I_{SC} = Short circuit current of PV module [A]
I_d = Diode saturation current [A]
V_{PV} = Terminal voltage of PV panel [V]
Rs = Series resistance [Ω]
n = Ideal constant of diode (1~2)
V_T = Thermal potential of PV module [V]

Proposed energy management strategy using fuzzy logic based controller:

General description: Hybrid Wind/Photovoltaic systems are generally implemented in order to

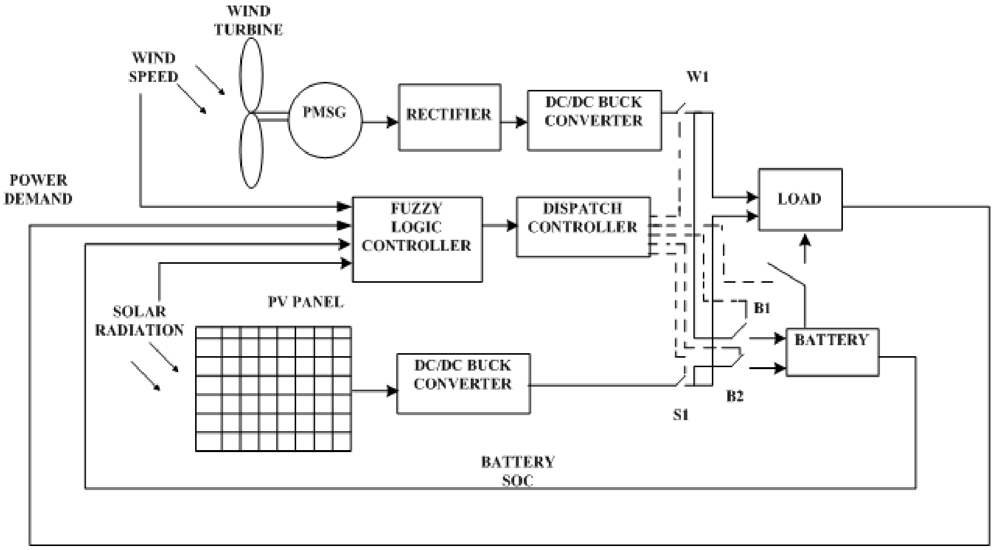
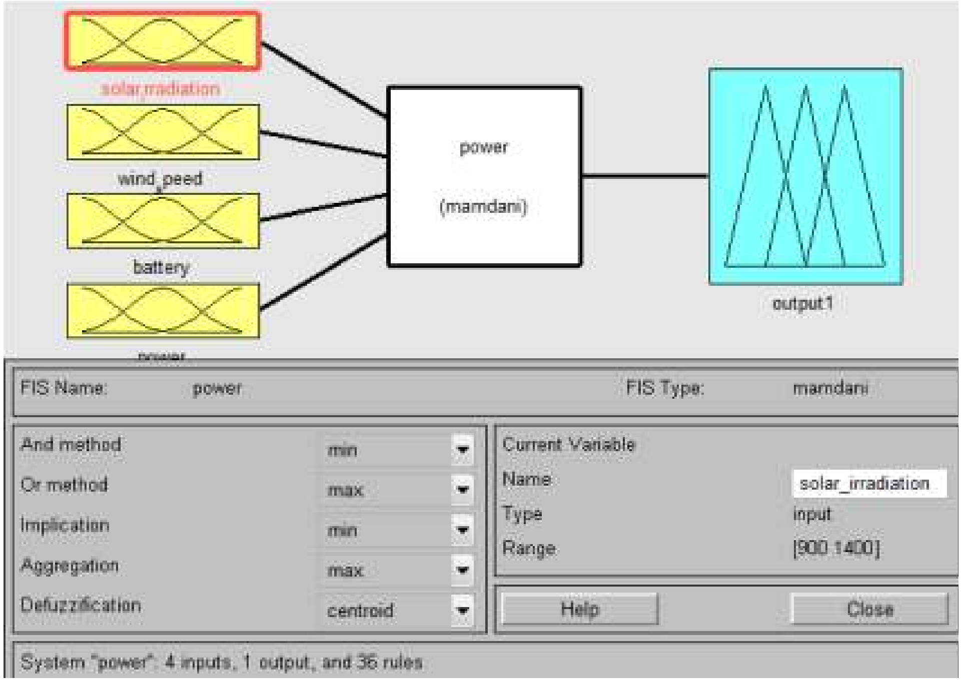


Fig. 5: Illustrates the functional block diagram



FIS Name: power
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: solar_irradiation
Type: input
Range: [900 1400]

System "power": 4 inputs, 1 output, and 36 rules

Fig. 6: Implementation of input parameters

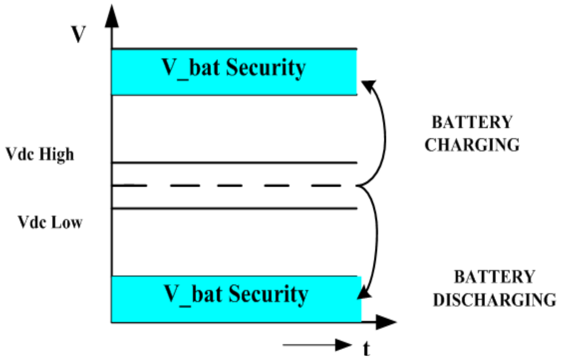


Fig. 7: Regulation strategy of DC bus voltage

improve the reliability of electric power generation in stand-alone operations. The functional block diagram of the proposed system using Fuzzy Logic controller is shown in Fig. 5 (Lin *et al*., 2013; Mehdi *et al*., 2011).

Since wind and solar energy are variable in nature, a strategy for energy management is required with supervisory control. The main objective of the hybrid system is to properly utilize the renewable energy for power generation when it is available.

Supervisory control of energy management: The proposed DC bus voltage regulation strategy has been integrated into the Fuzzy controller. The implementation of this strategy requires wind speed, solar irradiation and battery voltage as Fuzzy inputs and decisions were made accordingly. The Fig. 6 shows the implementation of input parameters into Fuzzy inference system.

The utility of the energy management supervisor is to control the battery voltage level by keeping the DC bus voltage, V_{bus}, between two imposed limits (54V, 43V) around the rated battery voltage level (V_{bat_nom} = 48V). Figure 7 illustrates the model diagram of the given DC bus voltage regulation strategy.

A fixed voltage with high V_{dc}, high and low bounds V_{dc}, low is exists which shows the reference power will remain unchanged, if the DC bus voltage falls inside the bounds. If the DC bus voltage is higher than V_{dc_high} then the supervisory control will stop charging battery: the reference power and the DC bus voltage should be pulled down. On the other hand, if the DC bus voltage is lower than V_{dc_low}, the supervisory control will stop supplying power to the load; the reference power switches to the maximum power generation and the DC bus voltage will be increased.

Operational strategy in to different modes of operation: A detailed energy management regulated by Fuzzy Logic Control is essential to efficiently manage the operation of the generation subsystems according to those modes (Barley, 1996). The system supervision strategy is proposed into following different modes.

Table 1: Mode of operation

Mode	S1	W1	B1	B2	Power demand
Solar	On	Off	On	Off	Low
Solar	On	Off	Off	On	High
Wind	Off	On	On	Off	Low
Wind	Off	On	Off	On	High
Solar-wind	On	On	On	Off	Low
Solar-wind	On	On	Off	On	High
Battery	Off	Off	Off	On	Low/high

Solar mode: The solar mode comprises the operation of solar subsystem alone when wind is not available. This mode supply power to load and charges the battery. Secondly in this mode when battery gets charged and load demand becomes higher, then the load demand is satisfied along with solar subsystem and battery.

Wind mode: The Wind mode is concerned with the operation of wind subsystem alone when there is insufficiency of solar power. This mode supply power to load and charges the battery similarly as in Solar mode. In wind mode when battery gets charged and load demand becomes higher, then the load demand is satisfied along with wind subsystem and battery.

Solar and wind mode: Solar and wind mode will be in operation when both resources are available and satisfies the load demand. This mode supply power to load and charges the battery. In solar and wind mode when battery gets charged and load demand becomes higher, then the load demand is satisfied along with wind-solar subsystem and also uses the battery voltage if required.

Battery mode: This is an emergency mode which concerned with battery operation. Since the battery is used as a backup source, this mode operates when both wind and solar source is not available. This mode can also be called as Security Mode. The battery is not only exclusively used in the system to operate in Battery mode but also can be utilized in other modes as per the load demand and resources availability.

The different mode of operation is given in Table 1. The parameters in the operation such as switch S1 connects Solar side and load, W1 connects Wind side and load, B1 connects solar/wind power to battery and B2 connects battery and load.

Experimental setup: The below block diagram shows the hardware implementation of the proposed system. The entire experimental setup is illustrated in Fig. 8.

Power generation from wind side subsystem: The experimental setup uses a separately excited DC

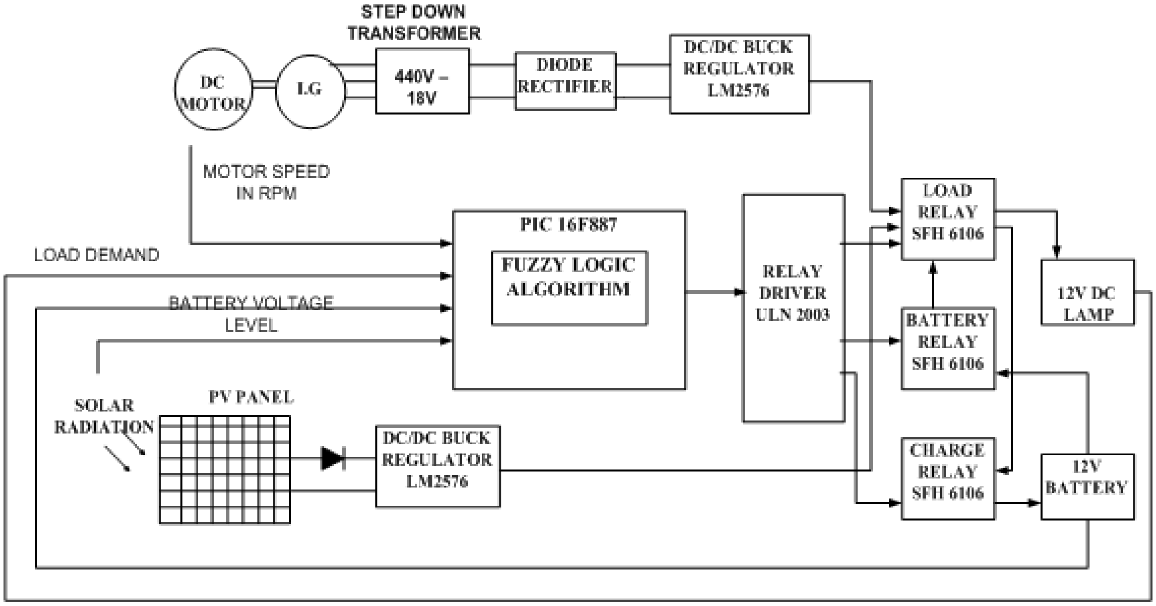


Fig. 8: Illustrates the block diagram of the entire experimental setup

Table 2: DC motor ratings

Parameter	Value
Motor type	DC separately excited
Armature voltage	220V
Armature current	4A
Field voltage	220V
Rated speed	1350 RPM

Table 3: PV panel ratings

Parameter	Value
Power	75W
Voltage	25V
Current	3A

Fig. 9: Photo of the motor generator set with excitation capacitors

motor as the prime mover in place of Wind turbine and it is coupled to an Induction machine. The rating of the dc motor is given in Table 2.

Since in normally designed motor, the maximum speed can be allowed up to twice rated speed (Mohamad *et al*., 2004), the motor is made to run at 1520 RPM using field flux control. At the above synchronous speed the Induction machine acts as generator and generates a three phase voltage of 440V with the help of excitation capacitors. The excitation capacitors were connected in star to build up the voltage generation on the induction machine terminals. Thus the generated AC voltage is given as input to the wind side subsystem in the power electronics circuit. As illustrated in the Fig. 9 the motor speed is given as one of the input to the Fuzzy intelligent controller. In order to sense the speed of the motor, a proximity sensor is used which is one of the important parameter to implement the energy management strategy in the microcontroller.

The motor speed is sensed and it is given as one of the inputs to the microcontroller from the wind side subsystem. The LCD on the microcontroller module displays the speed which decides the modes of energy management operation based upon the speed (High or Low) conditions (Mohamad *et al*., 2004).

The generated three phase AC voltage from the Induction generator is given to a three phase step down transformer (440V-18V AC) which is rectified using a Diode bridge rectifier to DC voltage. In order to maintain a regulated output of 12V DC in the bus, the rectifier output is given to a voltage buck regulator (LM 2576) which further connects to the dispatch module (Musgrove, 1987).

Photovoltaic subsystem: The Photovoltaic panels composed of several solar cells connected in series and parallel combination to form the PV array and the rating of PV panel is shown in Table 3 (Ramakumar *et al*., 2008).

The Fig. 10 shows the Photograph of voltage measurement in the PV panel using multimeter.

Fig. 10: Photograph of the voltage measurement using PV panel

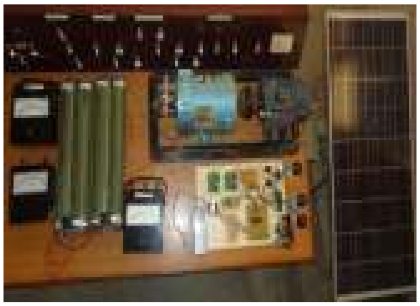


Fig. 11: Photograph of the entire experimental setup

The Light Dependent Resistor is used to sense the solar radiation. The Solar subsystem consists of mainly a Light Dependent Resistor (LDR) and the voltage regulator (LM2576) connects to the dispatch module. The rated DC output from the Photovoltaic panel is given to the voltage buck regulator (LM 2576) which step down and regulate the DC output voltage to 12V. This subsystem further connects to common DC bus and the dispatch module (Nabil and Masafumi, 2006; Nabil *et al*., 2008).

Interface of microcontroller with dispatch module: The dispatch module takes the input from common dc bus voltage line to the relay. The relay (SFH 6106) which functions as a switch and the ON/OFF control of it is decided by the microcontroller. The control signals to the relay are obtained from the relay driver (ULN 2003) which drives from the microcontroller output 5V to 12V. The dispatch module consists of three relays mainly Load relay, Battery relay and Charge relay. The Load relay connects the DC bus of the Solar and Wind subsystem to the lamp load where the Battery relay connects the battery and the load. The Charge relay connects the DC bus of the Solar and Wind subsystem to charge the battery in case of battery discharge (Testa *et al*., 2010). The load used in this system is DC lamp and its rating is shown in Table 4. The entire experimental setup is shown in the Fig. 11.

Table 4: DC lamp ratings

Parameter	Value
Power	7-10 W
Voltage	12 V
Current	0.83 A

The microcontroller takes the input details such as motor speed, Solar radiation, Battery voltage level, Load demand from the above mentioned sensors and also displays these details in the LCD display for continuous monitoring. An energy management strategy is programmed in the microcontroller using Fuzzy logic concept which properly utilizes these inputs and given to the load (Tomonobu *et al*., 2010).

RESULTS AND DISCUSSION

Simulation results: According to the different mode of operation as per the Fuzzy rules the main objective such as maintenance of constant DC bus voltage with respect to the availability of renewable resources was done. The output waveform of PV side and wind side DC bus voltage is shown in Fig. 12 and 13.

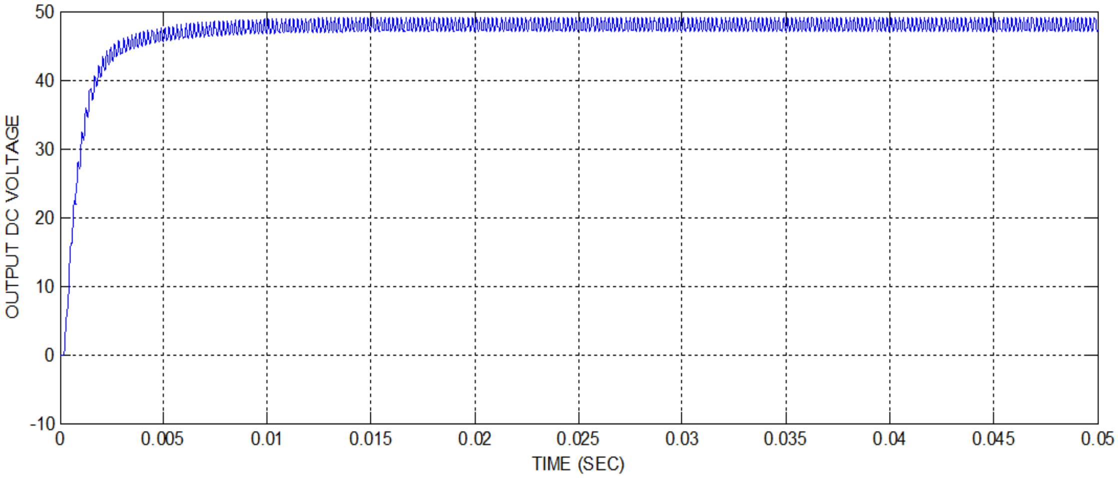


Fig. 12: Simulation waveform of PV side DC bus voltage

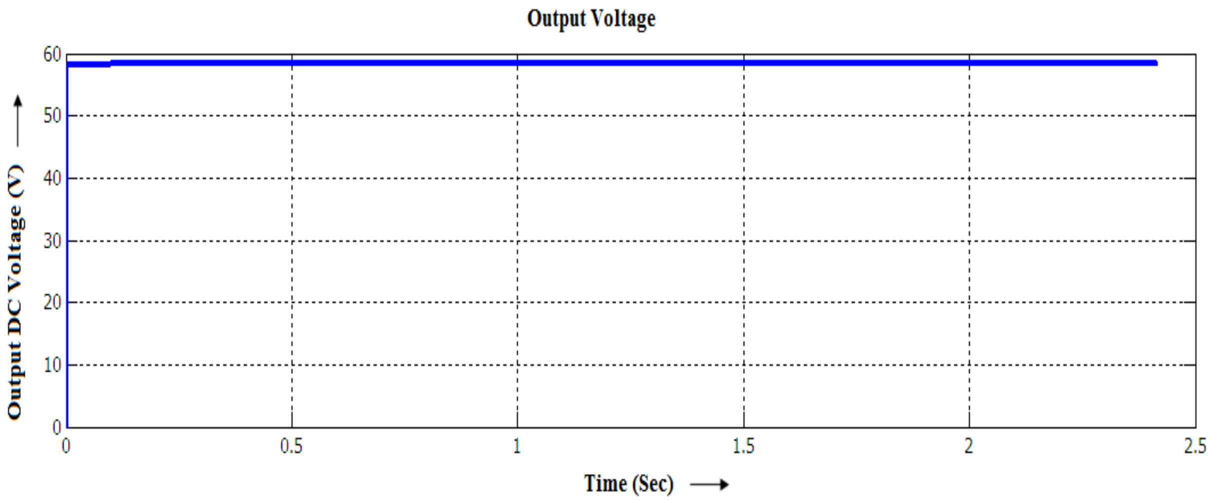


Fig. 13: Simulation waveform of wind side DC bus voltage

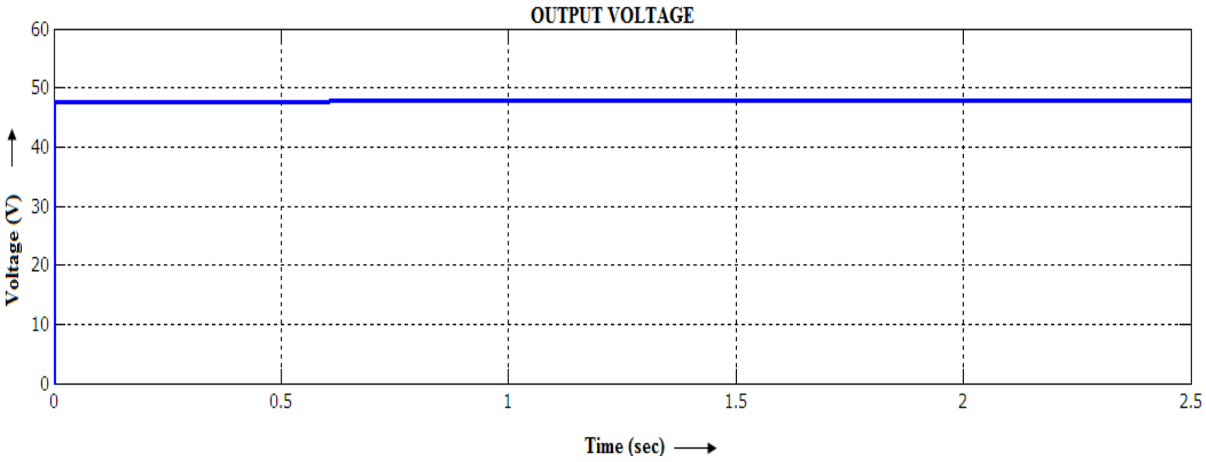


Fig. 14: Simulation waveform of the DC bus voltage

The output waveform of the DC bus voltage supplying to the load is given in Fig. 14.

Hardware results: The system is operated under different modes of operation as per the proposed energy management strategy and the results are shown below. The entire hardware design was made to operate three 12V DC lamps (load) as per the energy availability. Here it is considered as low power demand if two lamps are connected and high if all the three lamps are connected.

Solar mode: The solar mode comprises the operation of solar subsystem alone when wind is not available. This mode supply power to load and charges the battery which is shown in given Fig. 15 for low power demand operation and during high power demand.

The LED indication on the dispatch module in the Fig. 15 shows the operation of Load relay and Charge relay which supply power to lamp and charges the battery, respectively.

Wind mode: The Wind mode is concerned with the operation of wind subsystem alone when there is insufficiency of solar power. This mode supply power to load and charges the battery which is shown in given Fig. 16.

Solar and wind mode: Solar and wind mode will be in operation when both resources are available and satisfies the load demand. This mode supply power to load and charges the battery which is shown in Fig. 17.

Battery mode: This is an emergency mode which concerned with battery operation. Since the battery is used as a backup source, this mode operates when both wind and solar source is not available which is shown in Fig. 18.

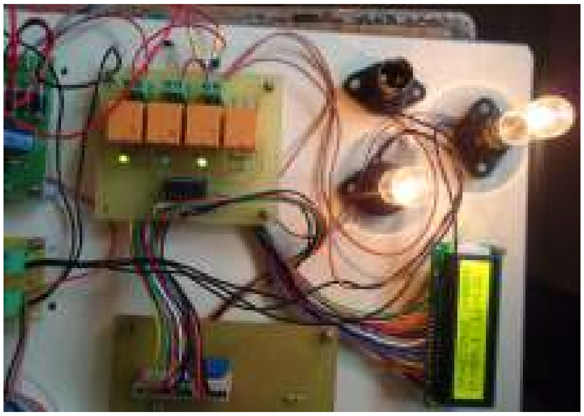


Fig. 15: Solar mode operation

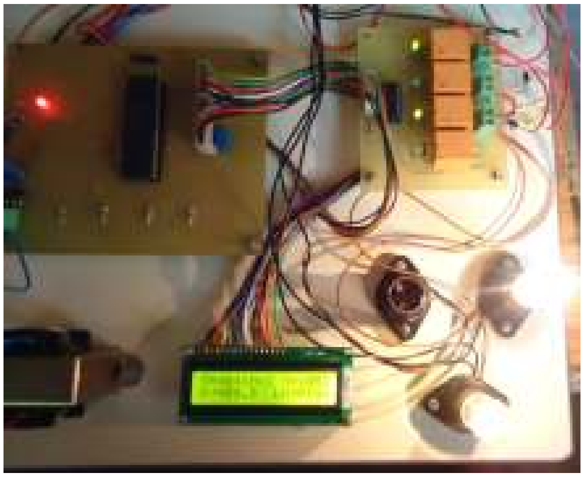


Fig. 16: Wind mode operation

Fig. 17: Solar wind mode operation

The LED indication in the Fig. 18 on the dispatch module illustrates the operation of load relay and battery relay which supply power from battery to load. The main objective of this energy management strategy is to regulate the 12V DC output voltage in the bus during different modes of operation. The experimental output wave form of DC bus voltage is shown in Fig. 19.

Fig. 18: Operation of battery mode

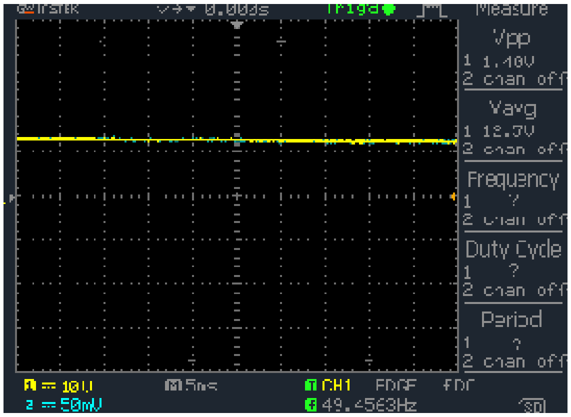


Fig. 19: Experimental output waveform of DC bus voltage (X axis 1 div = 5 ms, Y axis 1 div = 10V)

CONCLUSION

This project mainly investigates the design and energy management strategy of a multi-source hybrid system. The entire hybrid system is composed of the interconnection of the photovoltaic panel and wind turbine generator with power electronic based interfaces for optimal transfer of DC power was analyzed. In this proposed system, an energy management strategy is implemented in microcontroller using Fuzzy logic program in order to guarantee a stable and safe operation in accordance with the remote grid specifications as the Fuzzy logic supervisor control is capable of efficiently managing the diverse renewable energy resources. The implementation of this strategy requires wind speed, solar irradiation, battery voltage and load demand as Fuzzy inputs and decisions were made accordingly. The whole hybrid wind-photovoltaic micro-generation system has been numerically simulated and implemented in hardware for different mode of operation derived in the energy management strategy. The results show good performance of the designed system and confirm the effectiveness of the proposed hybrid energy management strategy for all the operating modes due to the impact of Fuzzy logic controller which makes fast and precise decision analysis.

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