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[Nagaiah* 7(6): June, 2020] ISSN 2349-4506
Impact Factor: 3.799

Global Journal of Engineering Science and Research Management

OPTIMAL OPERATION OF STANDALONE HYBRID SYSTEM CONTAINING SOLAR AND WIND GENERATING UNITS WITH THE HELP OF BOOST AND BIDIRECTIONAL CONVERTERS OPERATED BY ANFIS CONTROLLERS

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DOI: 10.5281/zenodo.3895567

KEYWORDS: Adaptive Neuro Fuzzy Inference System (ANFIS), Boost Converter, Bi-directional DC-DC Converter, Photo Voltaic (PV) Cells, Wind Energy Conversion System (WECS).

ABSTRACT
This paper proposes an Adaptive Neuro Fuzzy Inference System (ANFIS) Controller based Boost Converter for obtaining optimal generation from renewable energy sources like Solar and Wind units connected to common DC Bus. And also proposes Bi-directional DC-DC Converter controlled by ANFIS controller Between DC Bus and Battery Storage System. The PV-Wind source is equipped with unidirectional boost converter whereas, the battery storage system is connected to the DC Bus system with a Bi-directional DC-DC converter. The main novelty of this research is the ANFIS based DC-DC Bi-directional Converter which charges and discharges into the DC bus based on the total generation and load demand. The ANFIS controller based optimal operation is provided in the PV and wind energy conversion system (WECS) to grasp the maximum available power for the different irradiance and wind velocity conditions. A 500 W PV system and a 500 W Permanent magnet synchronous generator (PMSG) based WECS is implemented for its simplicity and high efficiency. The proposed control topology is designed and tested using MATLAB/Simulink.

INTRODUCTION
The hybrid renewable energy-based generation comprises of variable renewable energy and storage elements combination based on the availability and need. The hybrid energy system can be of standalone or grid connected system [2]. The standalone system is generally termed as the micro-grid which meets the demand of local loads which is equipped with the power electronics interface to ensure proper load sharing [7,8]. Standalone system requires a high rating and sufficient energy storage device to cope with the variable power generated by the renewable sources. The boost converter of the system is controlled using ANFIS based maximum power point tracking methodology. The main objective of the paper is to supply un-interruptible power to the load despite of the variable power generation. Ensure the proper charging of the battery during excess power generation and to discharge during low power production. The basic topology considered for this research is shown in Fig. 1.

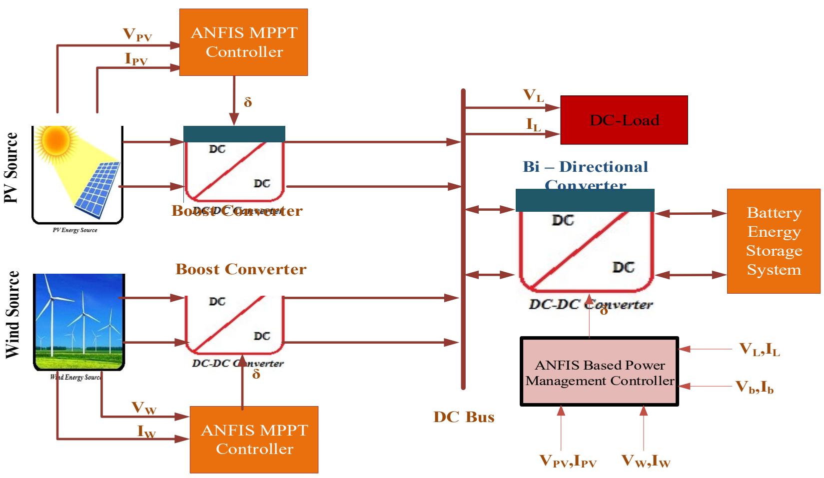

Fig.1 Basic Topology of the Proposed Hybrid System

DESIGN OF DC-DC BOOST CONVERTER

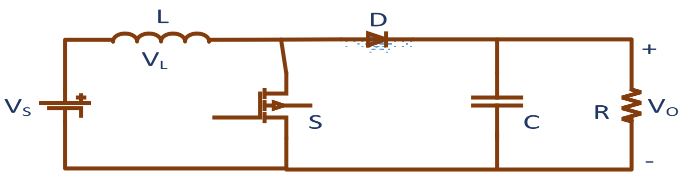

Fig.2 Boost Converter

The DC-DC boost converters are used to convert the unregulated DC input voltage, supplied by PV modules to a controlled DC output at a higher voltage level required by the loads shown in Figure 2. They generally perform the conversion by applying a DC voltage across an inductor for a period of time (usually in range of 20 kHz to 5 MHz) which causes current to flow through it and store energy magnetically, then switching this voltage off and causing the stored energy to be transferred to the voltage output in a controlled manner. The output voltage is regulated by adjusting the ratio of on/off time. This is achieved by using fast switching power components like IGBT or MOSFET which dissipate negligible power. Pulse-width modulation (PWM) allows control and regulation of the total output voltage. It is considered as the heart of the power supply; thus, it will affect the overall performance of the power supply system. The ideal converter exhibits 100% efficiency; in practice, efficiencies of 70% to 95% are typically obtained. The boost converter configuration consists of a dc input voltage source V_s, boost inductor L, controlled switch SW, diode D, filter capacitor C, and load resistance R. DC voltage gain of the boost converter is given as,

$$M = \frac{V_O}{V_S} = \frac{1}{1-D}$$

Where, V_s is input voltage, V_o is output voltage, and D is the duty cycle of the pulse width modulation (PWM) signal used to control the ON and OFF states of IGBT. Selection of different components of converter is done as follow.

Table 1 PV Module and Simulation Circuit Parameters

Parameter Specifications of BP Solar SX3190 PV Module

Parameter Description	Rating
Maximum power (P_{MP})	500 W
Maximum current (I_{MP})	7.82945 A
Maximum voltage (V_{MP})	24.3003 V
Short circuit current (I_{SC})	8.51029 A
Temperature (T)	25^0 C
Open circuit voltage (V_{oc})	30.6021 V
Parallel strings	3
Series-connected modules per string	1
Solar irradiation (G)	1000 W/m^2

2.1 Design of ANFIS based MPPT

In neuro-fuzzy systems, neural networks are incorporated into fuzzy systems which can acquire knowledge automatically by learning algorithms of neural networks. Adaptive network based fuzzy inference system or adaptive neuro-fuzzy inference system (ANFIS), first proposed by Jang is one of the examples of neuro-fuzzy systems in which a fuzzy inference system is implemented in the framework of adaptive networks. ANFIS constructs an input output mapping based both on human knowledge (in the form of fuzzy if then rules) and on generated input output data pairs by using a hybrid algorithm that is the combination of the least-squares and back propagation gradient descent method. In this thesis ANFIS reference model is developed using ANFIS editor of MATLAB /Simulink software package.

The block schematic of the maximum power point tracking scheme is depicted in Fig. 3. It is constituted of solar PV module, DC-DC boost converter, proportional integral (PI) controller, PWM signal generator and ANFIS reference model.

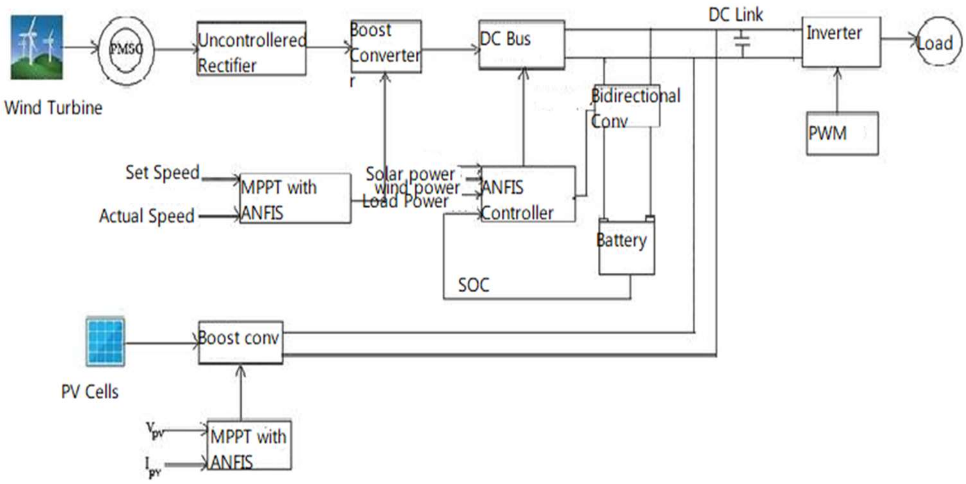

Fig.3 Block diagram of the proposed ANFIS based MPPT.

MATLAB / Simulink model of PV module is used to generate the training data set for ANFIS by varying the operating temperature in steps of 5°C from 15°C to 65°C and the solar irradiance level in a step of 50 W/m^2 from 100 W/m^2 to 1000 W/m^2. For each pair of operating temperature and solar irradiance, maximum available power of PV module is recorded. Thus, in total 209 training data sets and 2000 epochs are used to train the ANFIS reference model. The training error is reduced to approximately 6%. ANFIS constructs a fuzzy inference system (FIS) by using input/output data sets and membership function parameters of FIS are tuned using the hybrid optimization method which is a combination of least-squares type of method and back propagation algorithm. The ANFIS structure developed by the MATLAB code is shown in Figure 4.

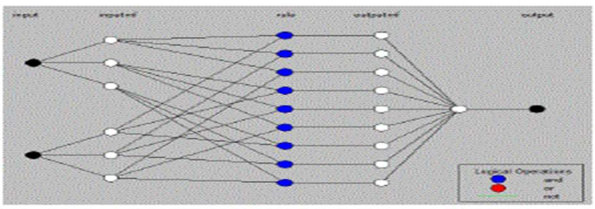
Fig. 4 The proposed ANFIS model structure.

It is a five-layer network with two inputs (irradiance level and operating temperature) and maximum power as one output. Each input parameter has three membership functions which are learned by ANFIS method. According to input output mapping of data sets, nine fuzzy rules are derived so as to produce maximum output power for each value of input temperature and irradiance level. The ANFIS generated surface is shown in Figure 5, which is a 3-dimensional plot between temperature, irradiance and maximum power. The ANFIS surface depicts that the maximum available power of solar PV module increases with increase in irradiance level and moderate temperature which verifies the non-linear behavior of PV module.

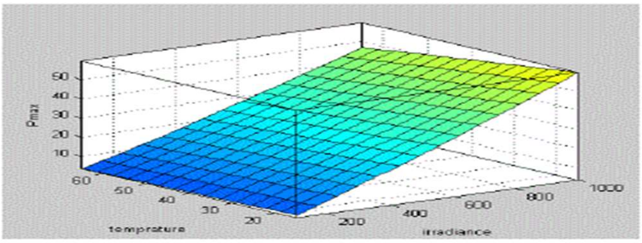

Fig. 5 Surface between two inputs (Temperature and Irradiance) and one output (Maximum power)

In the present work, ANFIS based MPPT is designed using user friendly icons from Simulink library of MATLAB.

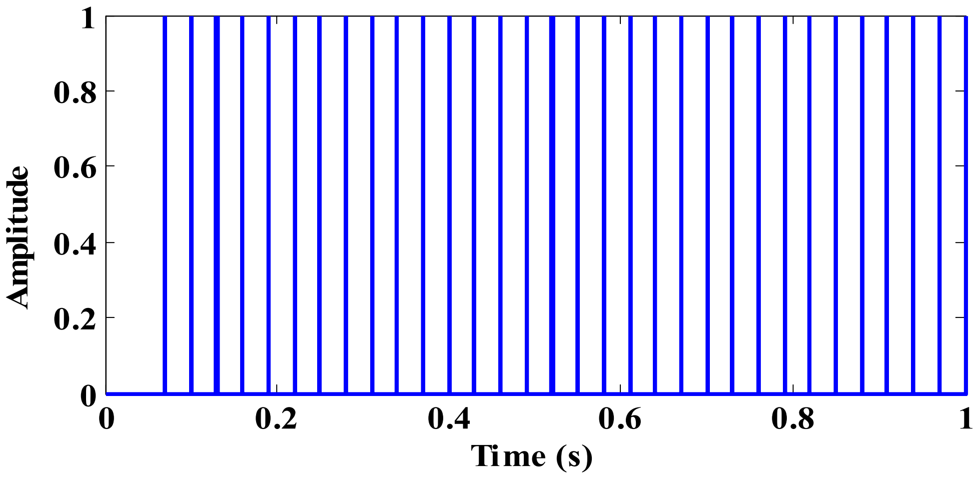

Fig. 6 Simulated gating signals to boost converter.

MAXIMUM POWER POINT TRACKING IN WIND ENERGY CONVERSION SYSTEMS (WEC)

Wind energy conversion systems have been attracting wide attention as a renewable energy source due to depleting fossil fuel reserves and environmental concerns as a direct consequence of using fossil fuel and nuclear energy sources. Wind energy, even though abundant, varies continually as wind speed changes throughout the day. The amount of power output from a wind energy conversion system (WECS) depends upon the accuracy with which the peak power points are tracked by the maximum power point tracking (MPPT) controller of the WECS control system irrespective of the type of generator used. This study provides a review of past and present MPPT controllers used for extracting maximum power from the WECS using permanent magnet synchronous generators (PMSG), squirrel cage induction generators (SCIG) and doubly fed induction generator (DFIG). These controllers can be classified into three main control methods, namely tip speed ratio (TSR) control, power signal feedback (PSF) control and hill-climb search (HCS) control. The chapter starts with a brief background of wind energy conversion systems. Then, main MPPT control methods are presented, after which, MPPT controllers used for extracting maximum possible power in WECS are presented.

3.1 Tip Speed Ratio Control

A wind speed estimation based TSR control is proposed in order to track the peak power points. The wind speed is estimated using neural networks, and further, using the estimated wind speed and knowledge of optimal TSR, the optimal rotor speed command is computed. The generated optimal speed command is applied to the speed control loop of the WECS control system. The PI controller controls the actual rotor speed to the desired value by varying the switching ratio of the PWM inverter. The control target of the inverter is the output power delivered to the load. This WECS uses the power converter configuration shown in Fig. 7.

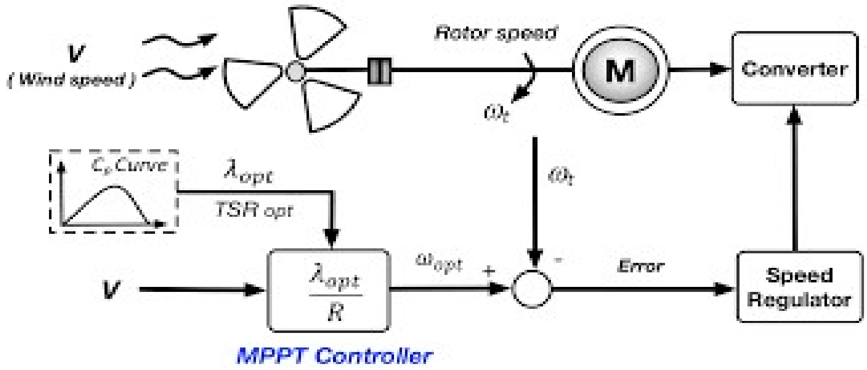

Fig. 7 Tip speed Ratio control

Table 2 Parameter specifications 500 W Wind system

Description	Rating
Power (P)	500 W
Impedance (Ra)	0.775 Ω
Inductance (Lqand Ld)	7.31 mH
Magnetizing flux (Øm)	0.37387 wb
Coefficient of friction (B)	0
Pair of Poles (PP)	2
Torque/Current (T/A)	1.1216 Nm/A
Cut-in wind speed (Vd)	4 m/s
Moment of inertia (J)	0.00126811 kg/m2
Rated wind speed (Vn)	12 m/s (26.8 mph)

MODELING OF BATTERY SYSTEM AND BI-DIRECTIONAL DC-DC CONVERTER:

4.1 Modelling of Battery Source

Battery is considered as a source and load based on the requirement. The power generated from wind and solar is not instantaneous in nature. Thus, an external source is required to support the load when there is demand. The battery is charged when the power generated is excess and discharged when the power generated from renewable energy is not sufficient. The lead acid battery is preferred than the conventional batteries for the simplicity, less initial cost and low maintenance. The model of battery source consists of voltage source in series with an internal resistance as shown in Fig. 8. The characteristic of charging and discharging of which is determined by the non-linear system is represented as follows in Eq. (1),

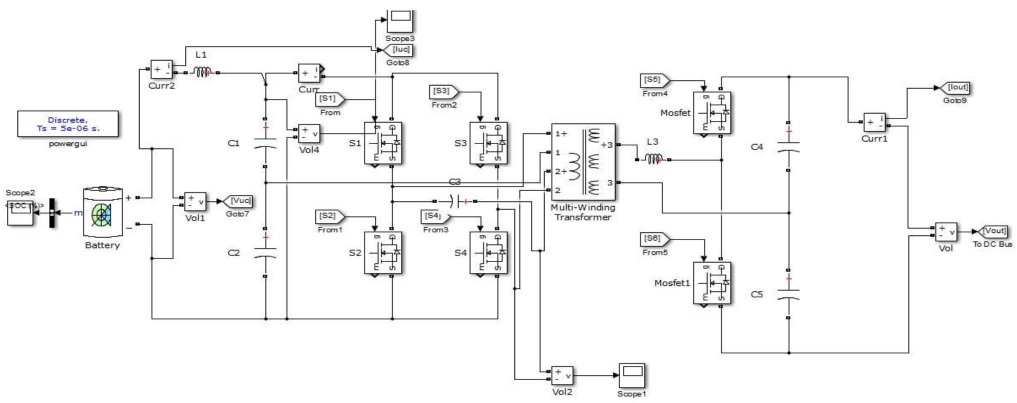

Fig.8 Output membership function of duty cycle

$$Exp(t) = B\,x\left|i(t)\,x\right|\left(-Exp(t) + A\,x\,u(t)\right) \quad (1)$$

The exponential voltage depends on its initial value Exp(t_o) and the mode of charge and discharge is considered as u(t)= 1 and 0 respectively as from Eq. (2) and Eq. (3).

$$E_{charge} = E_o - K.\frac{Q}{it-(0.1)Q}.i^* - K.\frac{Q}{Q-it}.it + Exp(t) \quad (2)$$

$$E_{discharge} = E_o - K.\frac{Q}{Q-it}.i^* - K.\frac{Q}{Q-it}.it + Exp(t)` \quad (3)$$

Where, E_o is the battery constant voltage (*V*), *K* the polarization constant *(V/Ah), Q* is the battery capacity (*Ah*), *it* is the actual battery and *i* is the battery current. *Exp(t)* or *A* represents the exponential time zone amplitude (V).

4.2 Modeling of Bi-directional Converter:
In this paper, a bi-directional DC-DC converter is utilized to raise the terminal voltage to achieve the flexible control of the battery energy storage system (BESS). To overcome the drawback of low voltage of battery system, a phase shifted full bridge DC-DC converter is used to connect the battery source to AC grid. The bidirectional converter consists of high frequency transformer which is required to match the AC grid and battery voltage level. The bidirectional converter consists of leakage inductance and output filter inductance. When BESS is charging state, bidirectional converter acts as the buck converter by controlling the switches $I_1 - I_4$. When the BESS is in discharging state, the bidirectional converter acts as a boost converter by controlling the switches $C_1 - C_4$.

The converter topology chosen for the proposed work is depicted in Figure 9. During the standalone operation of renewable energy source like PV, smooth and continuous power flow is affected by its intermittent nature. The possible solution was to permit energy exchange between the converter to the storage system and the converter to the load. The evolution of bidirectional DC-DC converters could find its way classified in the literature as isolated and non-isolated. The isolated bidirectional DC-DC converters gained prominence due to its voltage matching and galvanic isolation provided by means of a transformer. The bidirectional converter proposed in the research work [20] features series resonance and boost capability with simple PWM. The isolated bidirectional converter proves to be much better when assessed based on attributes like high efficiency, high gain, and the number of switches [21]. The PV integration improves the utilization of the converter through its voltage boosting capability, which is enhanced further by the transformer [22].

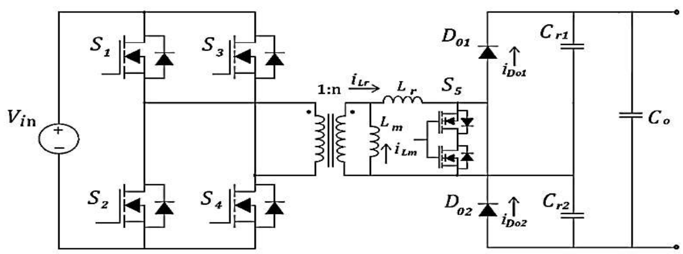

Fig. 9. Isolated Bidirectional DC-DC Converter

The hybrid converter resembles an isolated resonant converter of [18], except for the active bidirectional switch (S_5) at the secondary side of the galvanic isolation transformer. The design of transformer, resonant inductor Lr, resonant capacitors Cr_1, Cr_2, and the gating scheme is adapted from the literature [20]. The design procedure involves selection of transformer turns ratio and the design of the resonant tank. Turns ratio of transformer is given by Eq. (4)

$$n = \frac{V_o}{2V_{in}} \quad (4)$$

In the resonant tank design, the resonant inductor Lr is independent of the conversion ratio since it acts as boost inductor. A large enough inductor was chosen based on the longer switching state of PWM boost mode and the resonant mode. The length of switching time is less than switching periods Ts of all operating ranges. The Lr, Cr, Lm should be chosen such that they satisfy the equations from Eq. (5) to Eq. (7).

$$C_r > \frac{P_o T_s}{V_o^2} \quad (5)$$

$$L_r > \frac{V_o^2}{2\omega_r^2 P_o T_s} \quad (6)$$

$$L_m \le \frac{n^2 T_{DT}}{4C_o f_s} \quad (7)$$

The resonant capacitance can also be chosen based on the resonant frequency ω_r , from Eq. (8)

$$\omega_r = 2\pi f_r = \frac{1}{\sqrt{Lr\left(C_{r1} + C_{r2}\right)}} \quad (8)$$

SIMULATION RESULTS OF HYBRID SYSTEM PERFORMANCE WITH REAL-TIME DATA

The performance of the proposed hybrid PV and wind energy system is analyzed with the available real-time input Sources data of PV Irradiance (W/m^2) and Wind Speed (m/s) data are shown in Figure 10 and Figure 11. from the literature both solar and wind energy sources are alternative to each other, same has been proven in the available solar and wind data.

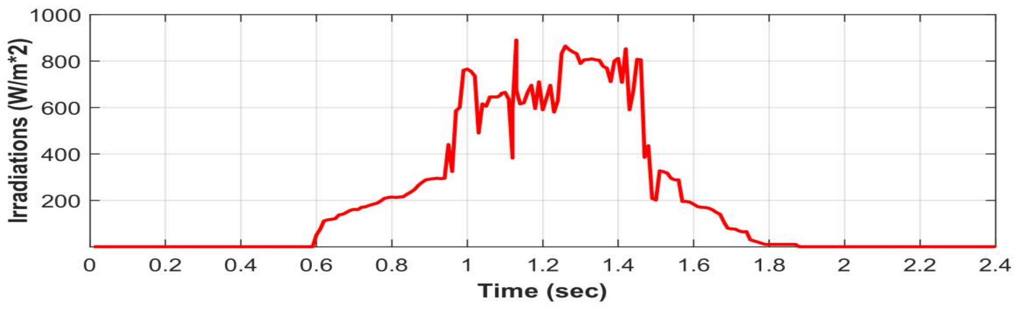

Fig.10 PV System real-time Input Irradiance (W/m^2)

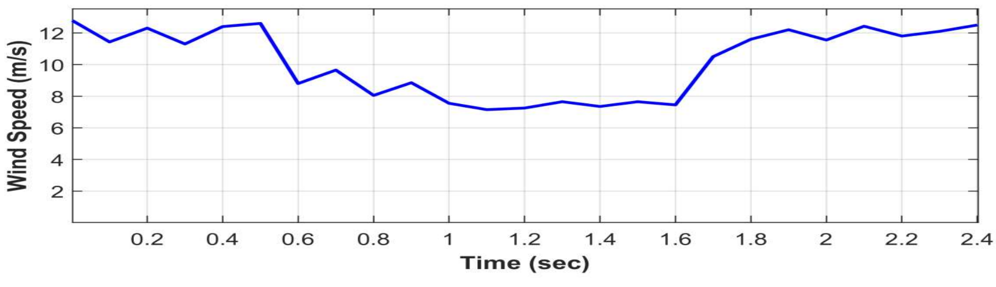

Fig.11 Wind System real-time Input Speed (m/s)

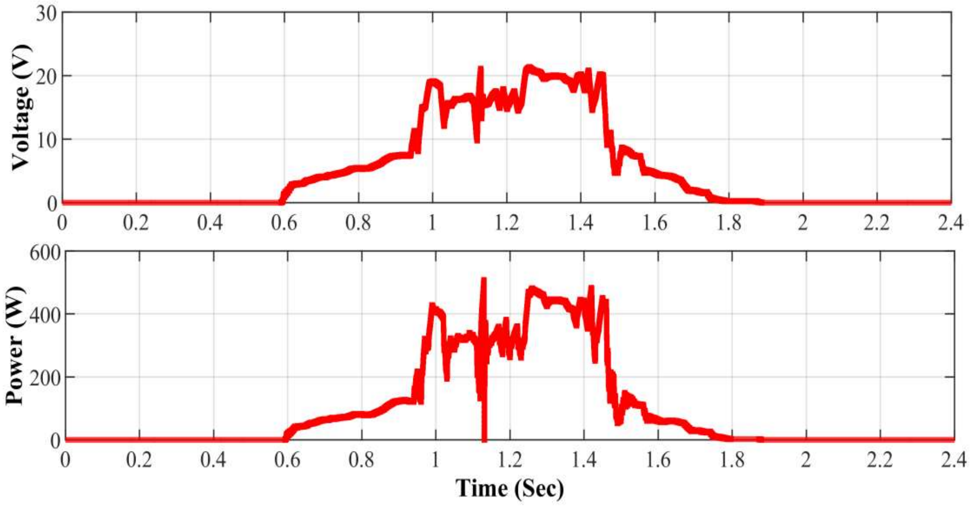

Fig. 12 PV System Output Voltage and Power

Fig. 12 and Fig. 13 shows the voltage and power obtained at the PV and wind system outputs corresponds to the availability of real-time solar irradiation data and wind speed as represented in the Figure 10 and Figure 11.

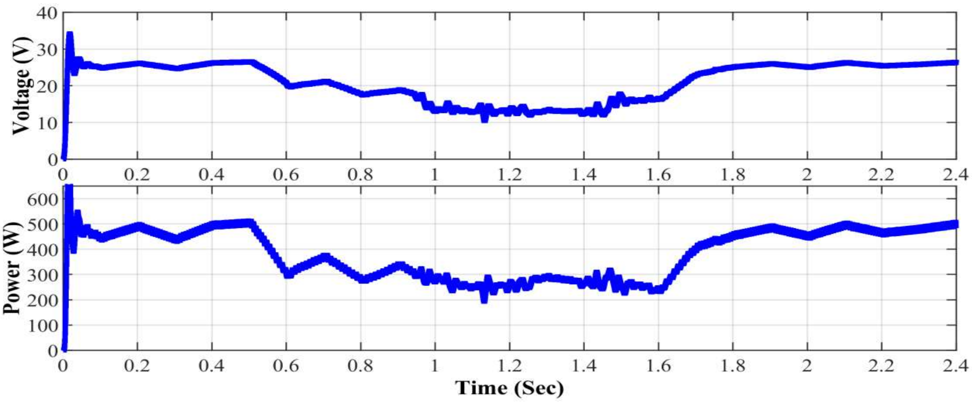

Fig. 13 Wind System Output Voltage and Power

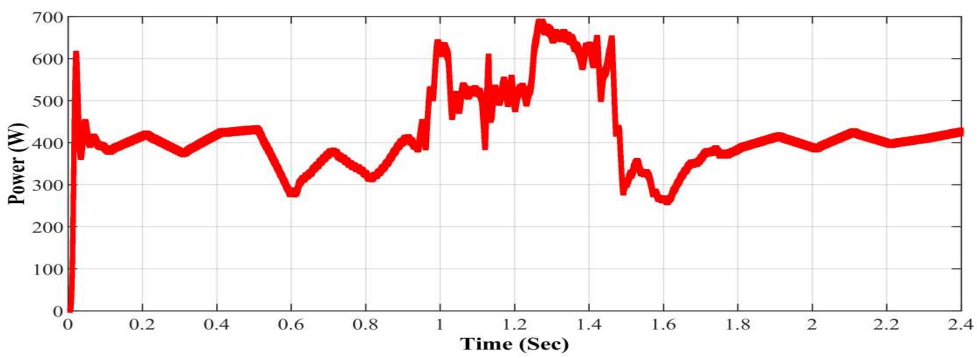

Fig. 14 DC Link Power

The Fig. 14 shows the DC link power of hybrid system under real-time solar irradiation and wind speed data.

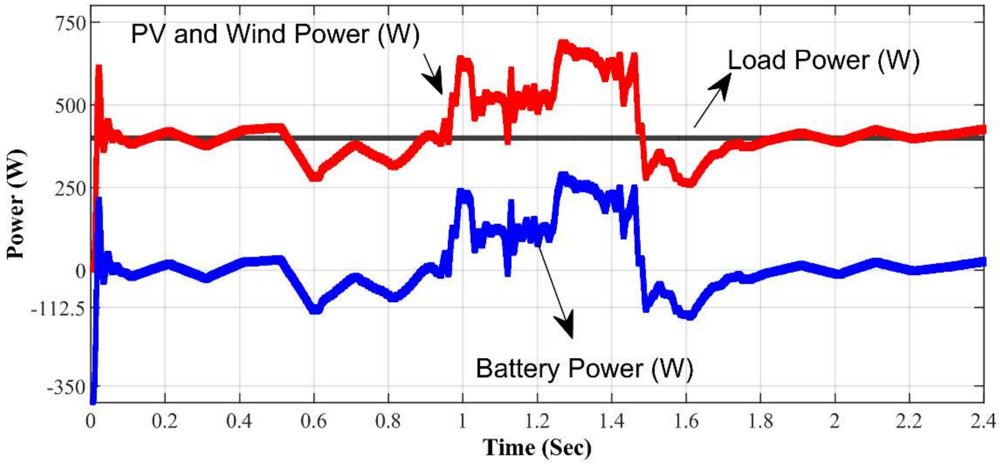

Fig. 15 Hybrid system output with Power Sharing

The battery source is connected to the DC bus using bi-directional DC/DC converter. The battery is charged when the load demand is low and there is excess power whereas, the battery supports the DC bus system when the load demand is high. The load demand of 400W is considered for this real-time study. The Fig. 15 shows the power sharing between the renewable energy sources and battery energy system to meet the load demand of 400 W throughout the time period from 0 to 2.4 sec as per the consideration of renewable energy sources input.

CONCLUSION

The developed 1kW hybrid System with battery storage unit is designed in MATLAB/Simulink environment. Maximum output power is obtained from both PV and Wind units with efficient operation of Boost converters with ANFIS Controllers. The performance of the outlined system is validated in consideration of different solar and wind input under different time durations with the constant 400 W load demand. Similarly, with real-time input data ANFIS based battery management system is implemented in the system to charge and discharge battery through Bi-directional DC-DC Converter controlled by ANFIS controller on the availability of solar and wind power. The effectiveness of load shared between renewable energy sources and battery are presented.

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