COMBINED WIND AND PV RESIDENTIAL ENERGY SYSTEM WITH SINGLE DC-DC (CUK) CONVERTER AND 1-PHASE INVERTER TO POWER GRID

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Abstract: *A novel hybrid system using one and only modern DC-DC converter is being proposed. In this novel system, the gearless wind-driven permanent magnet synchronous generator (PMSG) and Photovoltaic (PV) sources are coupled to the grid with a support of single CUK converter and a single phase inverter. There are two controllers present in the system to individually trigger the CUK converter and a single phase current controlled inverter for pursuing the high power from both the renewable energy sources. When compared to previous systems, the proposed system has less switching loss, less voltage stress, more efficient, and reliable. This hybrid system has the advantages of high grid voltage and the current. It can be used for zero-net energy domestic erection applications in a smart grid scenario. The operations of controllers for different sources are obtained and the operations of novel distributed generators for steady state are successfully demonstrated through simulation*

Key Words: *Grid-connected hybrid system, Smart grid, Solar-PV, Wind-PMSG, Renewable Energy System, CUK Converter, Distributed Generations (DGs).*

Nomenclature

V_{pv}	Solar Output Voltage (V)
Vs	Source Voltage (V)
Vr	Output voltage of rectifier (V)
V_c	Output Voltage of CUK Converter (V)
V_{dc}	DC Link Voltage (V)
V_G	Grid Voltage (V)
I_{pv}	Output Current of Solar (A)
Iref	Reference Current (A)
V_{dc}	DC Link Voltage (V)
I_d	Scohtkey Diode Equation current (A)
Io	Reverse Saturation Current (A)
δ	Duty Cycle
Rs	Series Resistor (in ohms)
Rp	Parallel Resistor (in ohms)
Ns	Number of cells in series
K	Boltzmann Constant
T	Absolute Temperature (Kelvin)

I. INTRODUCTION

As a good solution to the energy crisis and global warming, combined PV and wind renewable energy sources are considered as feasible choices for the electricity generation. As the world's per-capita energy consumption is increasing drastically, life style of human beings is increasing, and also energy demand is increasing. Henceforth, it is important to consider alternative energy generating techniques to move from centralized power generation to distributed power generation with smart grid scenario. Generally, Renewable energy sources-based distributed generations is generated or stored by a variety of small grid- connected devices declared to as distributed energy resource systems. This combined PV and wind system need modern power electronic converters and controller methods towards an increase in the efficiency and power quality [1]. Because of the balancing nature of solar and wind energy resources, the combination of these two energy sources is analyzed using doubly excited Permanent-magnet brushless machine has been described in the literature[2].Hybrid renewable

Energy system is analyzed using a new remote DC/DC Bidirectional converter. With the help of this converter large voltage conversion ratio is achieved. For the easy switching two full bridge, insulated-gate bipolar transistors (IGBTs) are used. In this hybrid system, analysis and switching method have been detailed [3]. With the help of multi-synchronous reference frame, distributed generation system has been analyzed for grid voltage distortion. The renewable energy conversion systems are used to collect generated energy in DC bus bar and then converted to AC by a three-phase full-bridge inverter. This hybrid renewable energy system generation substructure deliveries to load with low total harmonic distortion [4].A hybrid renewable energy plant is designed and analyzed which is based on solar and wind energy conversion systems. Each separate energy conversion system is controlled using a regular PI controller along with an auxiliary controller containing perturb & observe MPPT algorithm [5]. Ackermann et al. defined the renewable energy based-distributed generation as a power-driven control source connected directly to the distribution system or on the client side of the meter. The distributed power generation systems like a solar-PV array, wind turbines, and micro turbines are continuing a fast development to meet the energy demand all around the world [6]. In the literature different potential arrangement of hybrid wind and solar-PV systems are explained. Previously, the buck-boost converter endeavored, where in pulsed input current, requires input filter, pulsed output current raises output voltage ripple and individual switches are used to equal the voltage of DC bus[7]. High step-up converters have been used in many applications such as photovoltaic systems, fuel cell power conversion systems, uninterruptible power supply and so on that require high-voltage transfer gain to meet load voltage [8]. A multi-input single-phase grid-connected inverter for hybrid PV/wind system developed using two separate boost converter for each source [9].Two individual converters are used for the hybrid system i.e., CUK converter is connected to solar –PV and SEPIC converter is connected to wind-driven PMSG are analyzed in [10]. Distributed generation systems have been analyzed for maximum power with single boost converter and an inverter connected to the grid. Grid voltage and the DC-link voltage and current are less and the final output voltage also less [11]. By using perturb and observe MPPT controller maximum power is extracted from sun's energy and converter output voltage various as expected [12], [13]. For the photovoltaic system, the functionality of filters is described in detail by using current source inverter for the system [14]. As environmental pollution is a global issue, energy saving has attracted more consideration, governments are making policies to motivate the distribution of energy saving system. on the other hand, due to the centralized system, the existing system has a drawback of scalability. An intelligent energy saving system is designed and implemented for zero-energy home [15].Comparison, advantages, and disadvantages of two different wind turbines are analyzed [16].In a grid-connected renewable energy system, to synchronize the voltage and frequency of a grid and to manage the load demand electric vehicle is plug-in as a load and this grid acts as a smart grid. The Smart grid is also known as future grid/intelligent grid [17].

This research work is aimed at reducing the number of power conversion stages with the high output voltage, high efficiency, less harmonics and with reduced cost of the system. If the switching losses are more, it should be recompensed by increasing the dimensions of the generator; otherwise, the cost of the hybrid system will be increased. The proposed grid-connected PV/Wind energy system for the application of residential energy system is shown in Fig.1.The proposed renewable energy system consists of a solar-PV and the wind as the two power sources, and grid. The proposed converter is simple and low cost used for power management between PV/wind hybrid systems. Using a suitable perturbation and observation MPPT controller at the converter side and Hysteresis current controller at the inverter end maximum power can be extracted from these two renewable energy sources. This technique is unique without a battery since it is connected to power grid.

In the above-mentioned existing hybrid wind and PV system, the system had either separate converter for each of the source used or a battery is used as a standby. In addition to it, for the extraction of maximum energy from the solar-wind

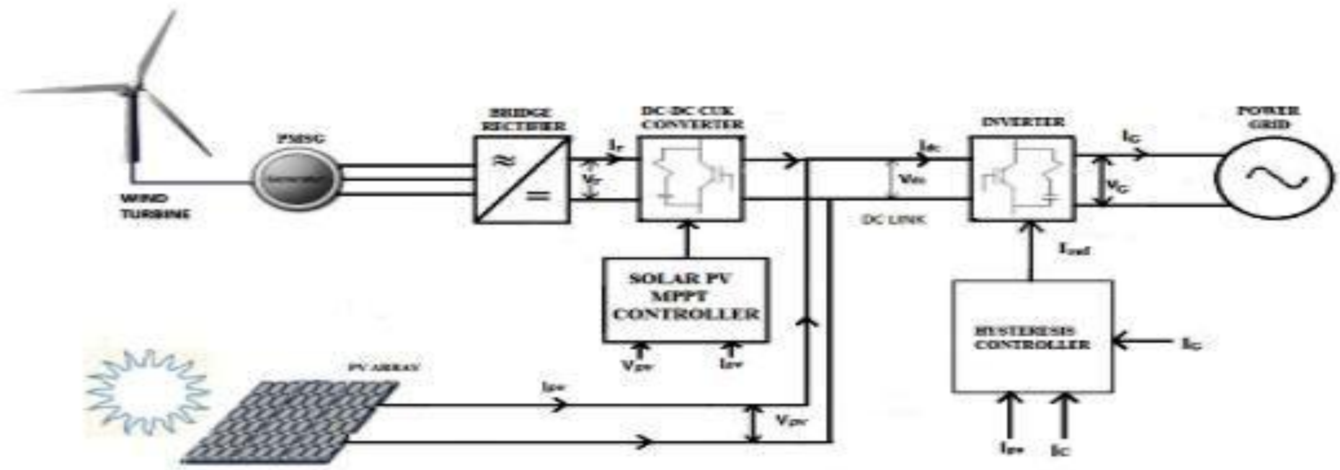


Fig.1. Proposed hybrid system with Wind-driven PMSG and Solar-PV using single DC-DC Cuk Converter

System, difficult algorithms are adapted to control each converter. Therefore to reduce switching and conduction losses of the devices, single Cuk converter is used for both the sources. The main benefits of this novel combined wind-PV system using a single Cuk converter are as follows

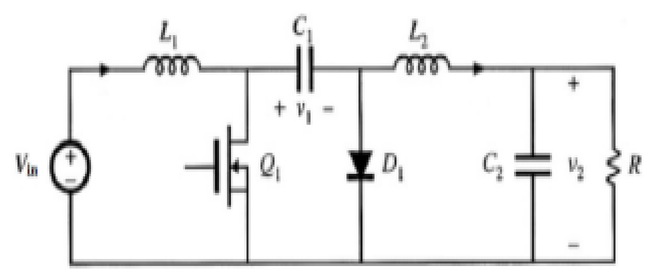
- Reduces the number of power conversion stages.
- Increases the reliability and efficiency of the system.
- It can act as boost/buck converter depending on the weather conditions.
- PV array is directly connected to the dc link.
- Additional filters are not required for the system.

Benefits of using a CUK converter, energy is transmitted when the switch opens and when the switch closes. It gives continuous input and output currents. The Cuk converter used in the proposed hybrid system acts as a current-voltage-current converter [18]. Hence, the proposed system acts as a smart grid.

The rest of this paper is organized as follows. SectionII.Proposed DC-DC Cuk converter configuration. Section III . The Mathematical model of the combined wind-PV energy system. Section IV Design and implementation of the control scheme for combined PV/wind energy system. Section V. Simulation results and discussion and Section VI Conclusion and future works.

II. PROPOSED DC-DC CUK CONVERTER CONFIGURATION

In the proposed system, a CUK converter is employed to harvest a constant voltage and deliver maximum power from the PV array and wind energy system to the power grid. A Cuk converter has the highest efficiency among all DC-DC converters. Thus, when compared to the other converters like a Buck, and Boost, in Cuk converter energy is transferred when the switch opens and also when it closes. But in Buck and Boost converter, energy only goes to the load, when the switch closes and the switch opens respectively.



(a)

The circuit diagram of Cuk converter is as shown in Fig. 2(a).This DC-DC Converter always works in the continuous conduction mode. The output voltage magnitude of DC-DC Cuk converter is either greater than or less than the input voltage magnitude. With respect to the common terminal output polarity of the DC-DC converter is negative. This converter operates through capacitive energy transfer. When switch Q_1 is turned ON, the diode D_1 is reverse biased, the inductors ($L_1$and L_2) current increases, the power is delivered to the load. When Q_1 is turned OFF, diode D_1 becomes forward biased and the capacitor C_1 is recharged. Design parameters of Cuk converter are represented in Table I and Cuk converter output voltage is given by

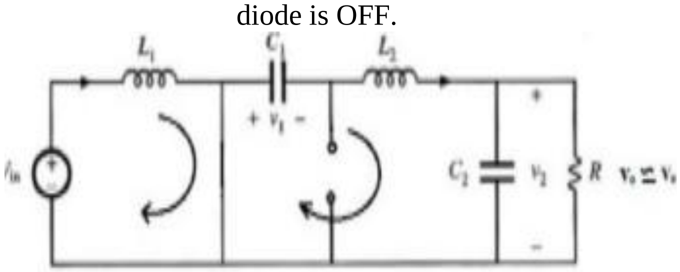
$$V_O = V_{in} \quad \frac{\delta}{1-\delta}$$

TABLE I
SIMULATION PARAMETERS FOR CUK CONVERTER

Parameter name	Value	Unit
Inductor L_1	10	mH
Capacitor C_1	120	µF
Inductor L_2	05	µH
Capacitor C_2	500	µF
Switching frequency	20	kHz
MOSFET switch is used.		

There are two modes of operations:

A.MODE I OPERATION: When the switch is ON, a diode is OFF.



(b)

When the switch (MOSFET) is ON at t=0, the current through the inductor (L_1) rises and at the same time voltage of the capacitor (C_1) reverse biases diode D_1 and turn it off. The capacitor C_1 discharges its energy to the circuit C_1-C_2-LOAD-L_2. Circuit diagram for mode I operation is shown in Fig.2 (b).

$V_{L1} = V_{in}$

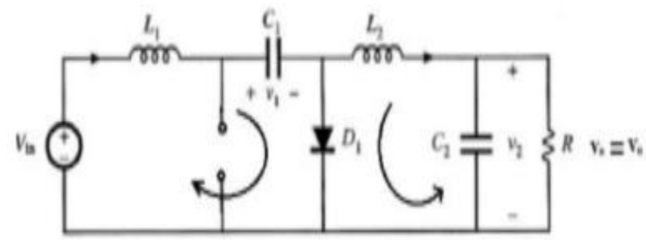
$V_{L2} = -v_1-v_2$

Where v_1 and v_2 are voltage across capacitor C_1 and C_2.

$i_{c1} = i_2$

$i_{c2} = i_2 - v_2 / R$

B.MODE II OPERATION: When the switch is OFF, a diode is ON.



(c)

Fig.2. Operating modes of Proposed Cuk DC-DC Converter (a) CUK Converter configuration (b) Operation when the switch is turned ON. (c) Operation when the switch is turned OFF.

When the MOSFET switch is turned OFF at $t=t_1$, the capacitor will start to charge from input supply V_{in} and the energy stored in the inductor transferred to the load. The capacitor C_1 is the medium for transferring energy from source to load. Mode II operation circuit diagram is shown in Fig. 2. (c)

$V_{L1} = V_{in} - v_1$

$V_{L2} = -v_2$

$i_{c1} = i_1$

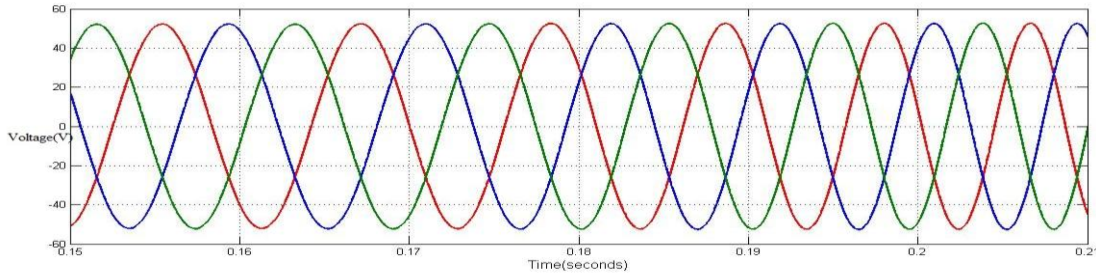
$i_{c2} = i_2 - v_2 / R$

When the Cuk converter operates in a steady state conditions, the periodic average inductor voltage and capacitor current waveforms are zero. The comparative output and input currents and voltages are given by the following equations:

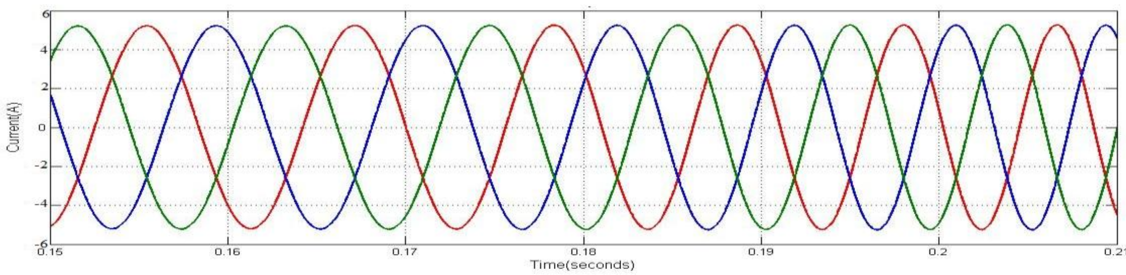
$$\frac{Vo}{Vin} = - \frac{\delta}{1-\delta}$$

$$\frac{Iin}{Io} = - \frac{\delta}{1-\delta}$$

III. MATHEMATICAL MODEL OF THE COMBINED WIND-PV ENERGY SYSTEM



(a)



(b)

Fig. 4.Steady state PMSG (a) Output voltage (b) Output current

In today's world, the best combination of hybrid renewable energy sources available is grid connected direct driven wind turbines and solar PV cells, which can compensates each other. In addition, photovoltaic (PV) generate electricity during sun light is available during the day time, while the wind energy compensate during the power needed in the night time. Single diode model is used for the solar-PV and its corresponding circuit is presented in Fig.3.The I-V characteristics of solar are presented in Fig.5 & its equations are given in (1), (2) & (3). The output voltage and output current of the rectifier in terms of the source voltage and source current are specified in equations (4), (5). V_s changes with wind speed, and consequently output voltage of the rectifier V_r is a variable DC. This variable DC is fed to the CUK converter. The equation for the CUK converter output voltage is specified in equation (6). The DC-link current equation is given by (7). Presuming CUK converter will not give any power loss, the rectifier output voltage and current will be equal to output voltage and output current of converter which is given in equation (8).

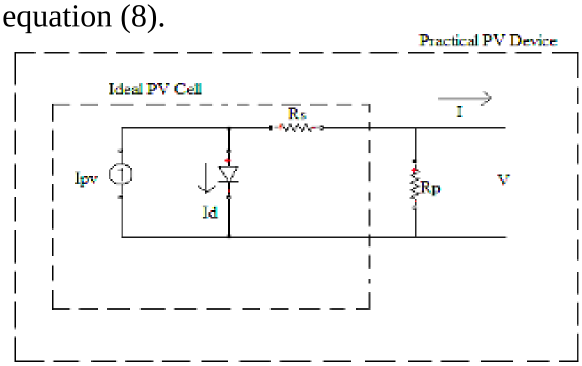


Fig.3. Equivalent circuit of single diode model of PV Cell

The output current equation is given by

$$I = i_{pvcell} - i_d \quad (1)$$

The diode current equation is given by

$$I_d = i_{o,cell}[\exp \frac{qv}{\alpha kT} - 1] \quad (2)$$

The total output current of a single diode model is given

$$I = i_{pv} - i_o[\exp(v + \frac{Rsi}{v_t\alpha})-1] - \frac{(v+R_s i)}{R_p} \quad (3)$$

The rectifier output voltage and current are given as [19], [20].

$$Vr = \frac{3\sqrt{6}}{\pi} Vs \quad (4)$$

$$Ir = \frac{\pi}{\sqrt{6}} Is \quad (5)$$

The CUK converter output voltage is

$$Vc = Vdc = Vr\ \frac{\delta}{1-\delta} \qquad (6)$$

The Direct Current-link is

$$I_{dc} = I_c + I_{pv} \qquad (7)$$

Presuming no power loss in CUK converter

$$V_r I_r = V_c I_c \qquad (8)$$

$$Idc = Ic + Ipv = \ (1 - \delta/\delta)\frac{\pi}{6}Is + Ipv \ (9)$$

$$I_{ref} = \ \sqrt{2}\ \frac{(V_{pv}I_{pv}+V_rI_r)}{I_G} \qquad (10)$$

Of all the generators that are used in wind turbines, the PMSGs are stable, secure, small in dimension, functional without DC supply, works at low speed and without gearbox. The CUK converter output voltage is given in equation (6).

In the proposed hybrid system, duty cycle (δ) and the reference current (Iref) are varied to extract the peak Idc at any particular time. By means of equations (1)-(10) the projected hybrid system has been simulated using MATLAB in this paper. Using wind-driven PMSG the following are the benefits of Wind –driven PMSG by permanent magnet synchronous generators make a solution as a variable-speed generator. PMSG are suitable for use in wind turbines as compared to wound rotor synchronous generators (WRSGs) and PMSG does not require an additional DC supply for excitation circuit or winding.

Steady state three phase output voltage and current waveforms of PMSG are depicted in Fig.4.From this, it is clear that both(voltage and current) have uniform amplitute and frequency. At a wind speed of 12 m/s voltage obtained is 50V and current at 5amperes as depicted in Fig.4.For the lower wind speed, the rotor injection power is higher.

IV. DESIGN AND IMPLEMENTATION OF CONTROL SCHEME FOR COMBINED PV/WIND ENERGY SYSTEM

There are two important goals in designing the control strategy for the power system with renewable energy sources.

- One important issue is extracting maximum power from the PV /WIND energy sources.
- The other issue is regulating the output voltage.

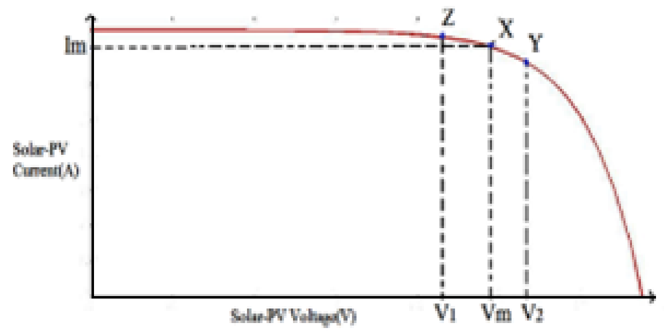


Fig.5. I-V Curve

When the wind speed changes, the rotor speed and the frequency of the induced voltage changes. However in variable speed applications, with PMSG, the generator is connected to the grid through a converter that will adapt the frequency of the induced voltage to grid frequency. When both the solar-PV and wind-driven PMSG sources are generating power together, the duty cycle variation of the CUK converter will ultimately disturb the solar-PV terminal voltage (V_{dc}=V_{pv}).The rectifier voltage differs with the speed of the wind, and the DC-DC converter duty cycle should be balanced consequently such that V_{dc} is equivalent to the maximum voltage (V_m), the solar- PV delivers maximum current (I_m) which is simultaneously drawn by the single phase inverter. Fig.5. Describes MPPT controller operation. As appeared in Fig.5.

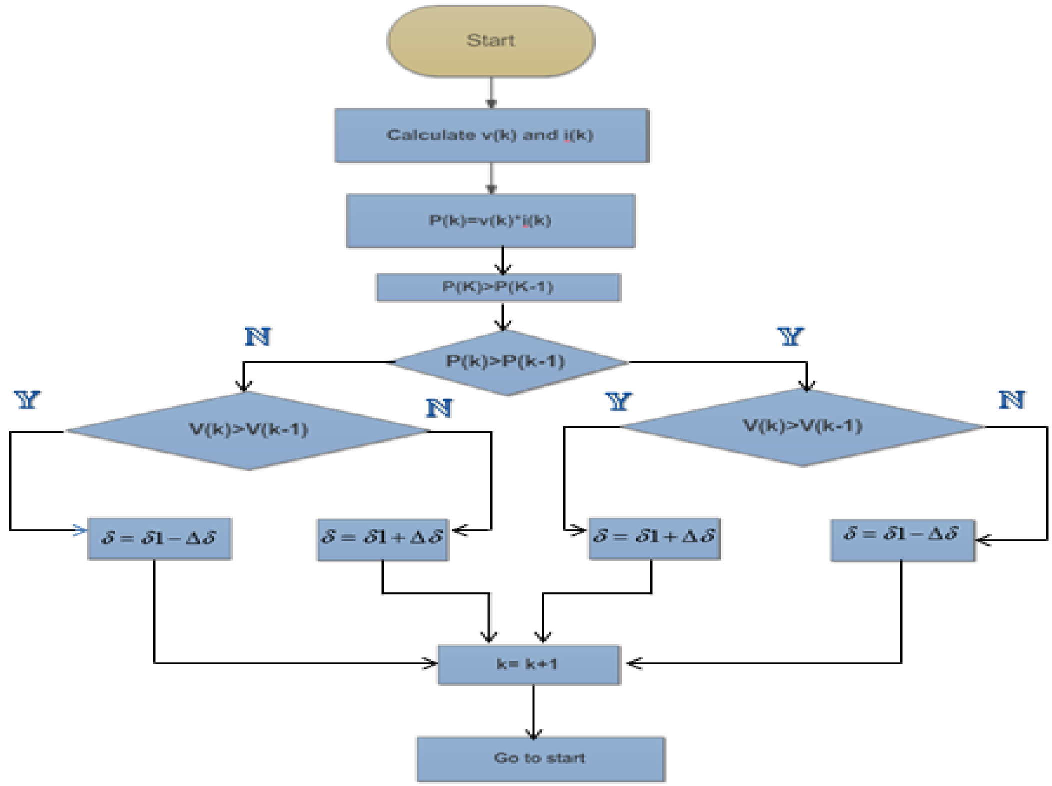


Fig.6. Basic Flow Chart of P & O Algorithm

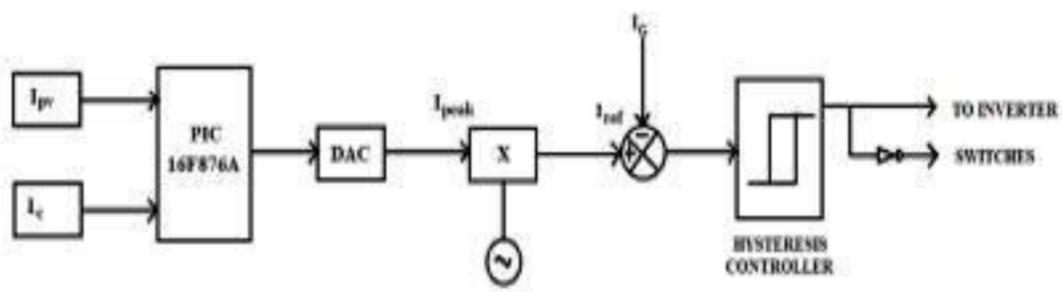


Fig.7. Block diagram of hysteresis controller

The voltage of DC-link might be V_1 (Z) or V_2(Y) subject to the CUK Converter existing duty cycle. To reach the maximum point(X) of the solar-PV array the output of the converter is adjusted to V_m by altering the converter duty cycle. The steady-state operation of grid output voltage and current, when both the sources are working is shown in Fig.10.The reference current at steady state for a specific solar insolation and speed of wind is given in equation (7). In the proposed combined PV and wind energy system controller developed must adapt to the weather variations. Perturbation and observation

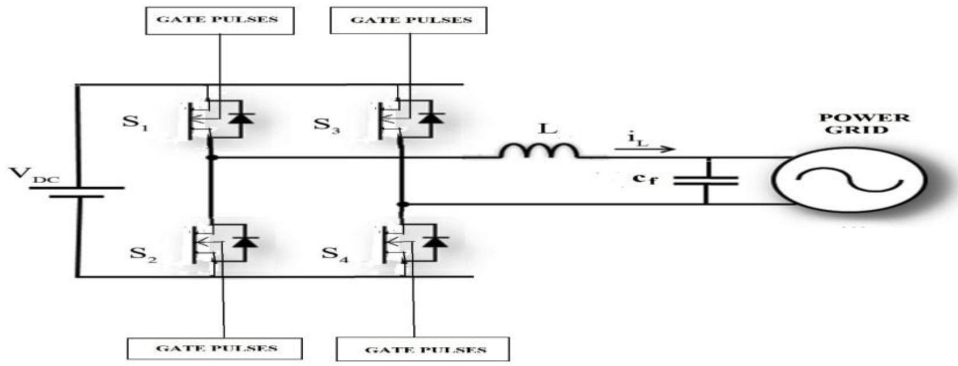
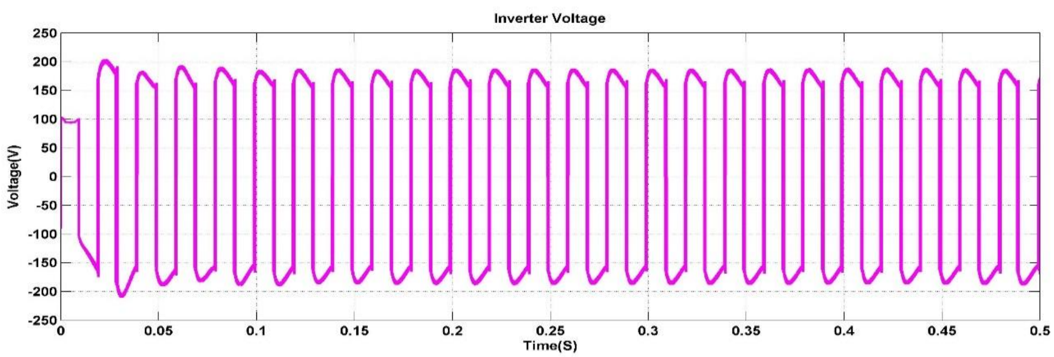
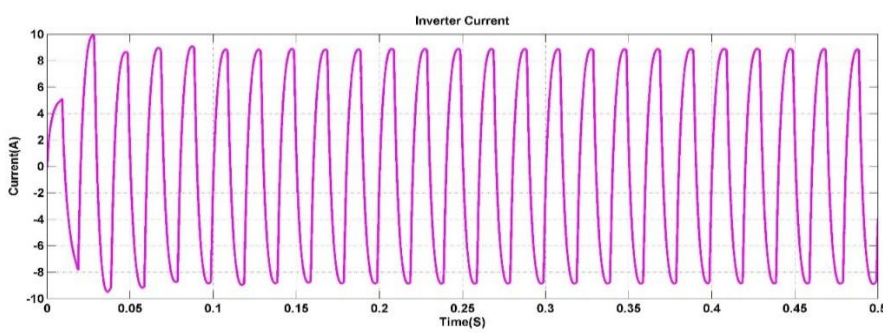


Fig.8.Control of single phase inverter



(a)



(b)

Fig.9. Steady state inverter (a)Voltage and (b)current waveforms

(P&O) maximum power point (MPP) control method is explained with the flow chart in Fig.6.The system voltage is periodically increased or decreased by a small constant increment and the resulting change is power P is observed. If P is positive, the operating point is closer to the maximum power point (MPP). The operating point moved away from MPP, if P is negative and the direction of perturbation should be reversed. The operating voltage is sampled by comparing power quantities between a present and the previous instants as shown in the flow chart. If the power in the existing instant is increased than the earlier value, the perturbation is continued in the same direction; otherwise, the perturbation direction is reversed in the next perturbation cycle. The voltage never reaches an exact value but perturbs around the maximum power point. The duty cycle variation in the system is opposite to the MPPT controller duty cycle. Where solar-PV leads a Cuk converter. Cuk converter output voltage is adjusted to the maximum by varying the converter duty cycle.

This method is very simple and uses less number of sensors. The drawback of this P & O algorithm is as the solar irradiation reaches certain limit control efficiency reduces.

The block diagram of hysteresis current controller is shown in Fig.7.The main purpose of hysteresis controller is to vary output current of inverter fed to the power grid. Due to the fast response and inherently current limiting factor hysteresis current controllers is popularly used in full bridge inverter. These controllers continuously provide maximum power either from one source or from both sources to the grid by changing I_{ref}. By using current transducers, two currents Photovoltaic current Ipv and Cuk converter current Ic are sensed and converted to digital with the help of ADC to reduce the error. From the microcontroller output obtained is peak value Iref. This value is multiplied by a multiplier IC along with sinusoidal wave reference from the grid voltage fed to the current controller (Hysteresis) as the reference current signal. The proposed inverter control procedure uses suitable hysteresis controllers and pulse width modulation (PWM) method to generate proper pulses for driving the switches of inverter. Economical microcontrollers and analog circuits are used for the controllers which are applied for the residential energy system. Hence the system becomes reliable and maintenance free operation.

Control of single phase inverter is depicted in Fig.8.It consists of four MOSFET switches connected to a single phase grid. The proposed combined PV-Wind system controls the active and reactive power injected into the grid. The Proposed control system has the following advantages

1. Power from the solar-PV / the wind can be delivered to the grid independently or concurrently.

2. Variation in the input voltage caused by different irradiation and wind speed is acceptable.

Steady state inverter wave forms are depicted in Fig. 9. Inverter voltage 195 volts and current at 9A are obtained. Initially, inverter voltage and current are less gradually voltage reaches maximum value and stable with the help of hysteresis current controller.

V.SIMULATION RESULTS AND DISCUSSION

For the simulation work in MATLAB, the design parameters of a direct driven gearless permanent magnet synchronous generator and PV array details are mentioned in table II and table III respectively. A single-phase inverter with MOSFET is used for the proposed hybrid system. For the investigations, CUK converter is used with MOSFET are chosen. The following are the base values: Base power =1KVA, BASE Voltage= 100V, Base current = 10A and Base speed= 300rpm.

TABLEII
SPECIFICATIONS OF SOLAR PV POWER

Parameter name	**Value**	**Unit**
Open circuit voltage	0.28	p.u
Short circuit current	0.62	p.u
Peak power for each panel	0.085	p.u
PV array consists of six panels in series		

TABLE III
SPECIFICATIONS OF PMSG MODEL

Parameter name	**Value**	**Unit**
Rated power	0.85	p.u
Poles	10	
Rate mechanical speed	280	rpm
Stator inductance	6.5	mH
stator resistance	0.25	Ω
Pitch angle	0	
Star-connected		

A. Steady-State waveforms

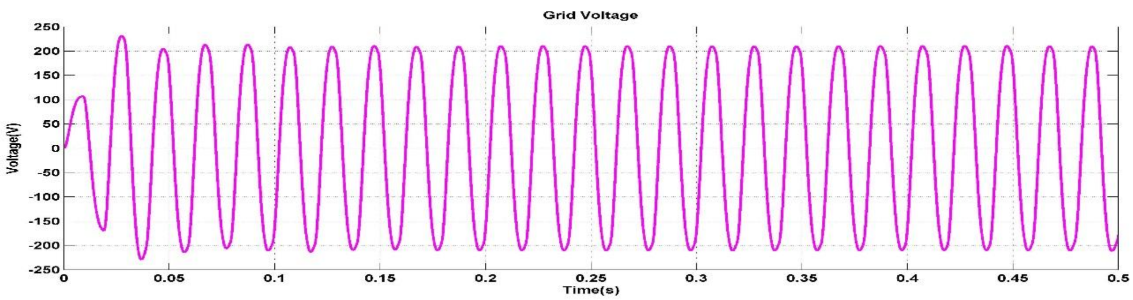
For the steady -state investigations solar irradiation is considered at 750 W/m^2 and shaft speed PMSG is 0.65 p.u and proposed system was connected to a grid through a step-up transformer simulated wave forms of grid voltage and grid current are shown in

Fig.10.which are in phase and at unity power factor.

B. Transient condition waveforms

To simulate wind turbine DC motor is used to drive gear-less PMSG and motor speed is increased to 0.75 p.u. and solar irradiation is at 900W/m^2 and to maintain constant DC-link voltage as depicted in Fig. 12, the duty cycle of Cuk Converter decreases from 0.7 to 0.5. At starting, DC link voltage increase and stabilizes at maximum constant voltage with the help of duty cycle of converter. It is clear from Figs.11 & 12 DC-link voltage levels are same and the system stability & reliability is maintained. However, hysteresis controller react to the step change in PMSG shaft speed and regulates the grid voltage and increases grid current as depicted in Fig.13. But with the help of MPPT controller maximum power is extracted from PV to maintain same level of DC-link voltage.

To evaluate the performance of the proposed system comprehensive simulation analysis is carried out under different conditions. From the simulation results it is clear current delivered to the grid by the inverter at peak power factor. At 900W/m^2 rid voltage at 150V and grid current at 6A.



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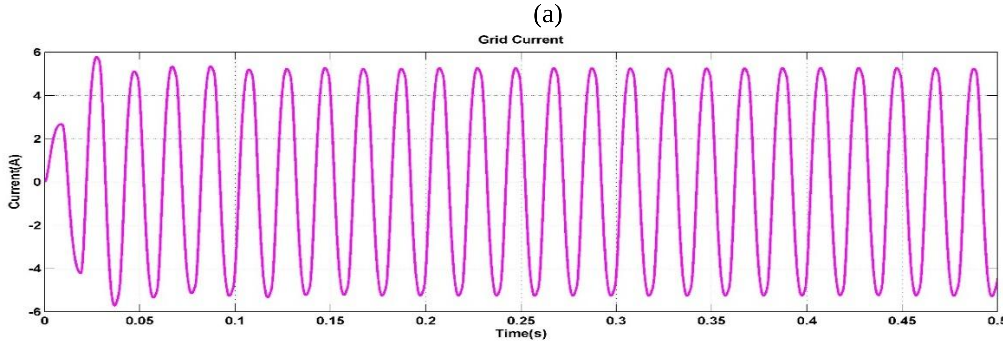


(b)

Fig.10 .Wave forms of Combined PV-Wind system steady- state (a) Output Grid voltage (b) Output Grid Current.

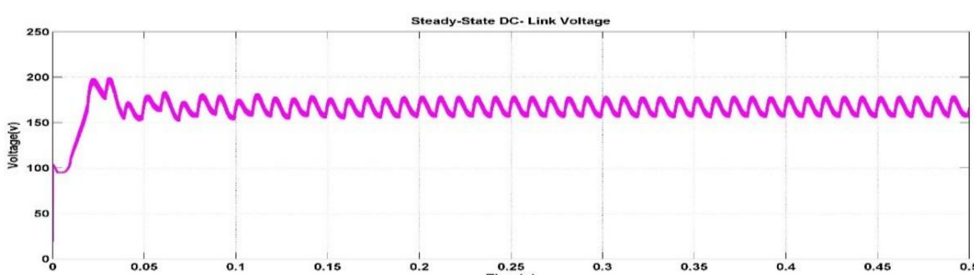


Fig.11. Combined PV-Wind Steady-state DC-link Voltage

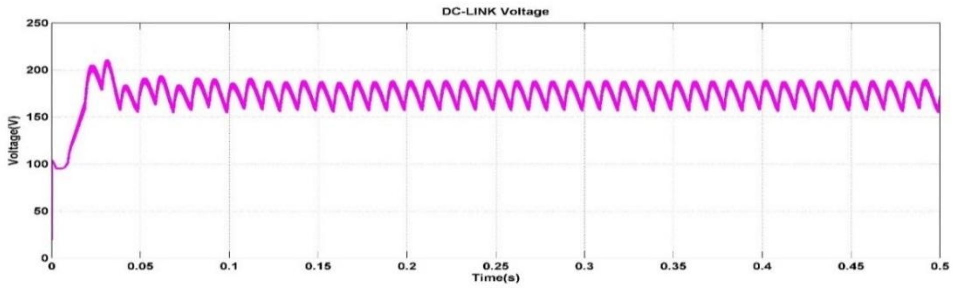
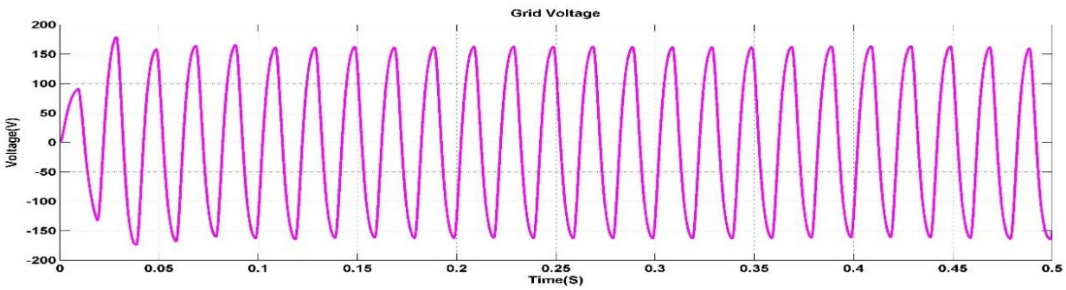


Fig.12.PV-Wind system transient DC-link voltage.



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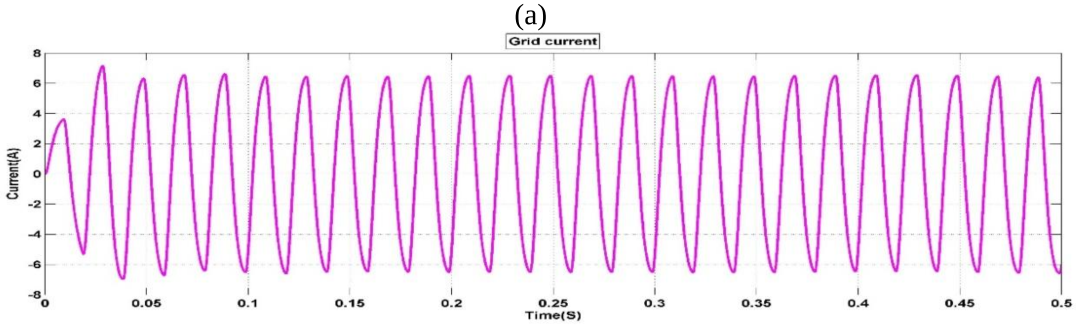

(b)

Fig.13. Transient (a) Output Grid Voltage (b) Output Grid current

VI. CONCLUSION

The proposed converter has been applied for simultaneous power management of a combined wind/PV system. This system is developed by the mathematical model to study the scheme presentation in MATLAB. The studies carried out for different insolation and wind shaft speeds confirm the projected scheme can be used in residential buildings. From the simulation results conclude that scheme delivers maximum power at unity power factor is fed to the grid. The advantage of the proposed system of the scheme is Generation cost is less, maintenance-free operation is required for the smart grid operation. A new reliable and efficient system is proposed. Hysteresis controller is essential to track maximum power at the inverter end

The Future scope of the proposed system can be extended by adding an additional source as a fuel cell to this hybrid system.

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