

## PWM effect on MPPT for hybrid PV solar and wind turbine generating systems at various loading conditions

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### ABSTRACT

Hybrid systems employing different kinds of renewable energy sources, like wind and solar energy conversion systems, are used to reduce generation costs and the pollution of traditional fossil fuel-based electrical generation methods. The current paper presents the design of an off-grid hybrid connection of an 852 W photovoltaic (PV) panel with a 1 kW small-scale wind turbine. This work is based on a study of the effect of the changes in the pulse width modulation (PWM) of a DC/DC converter that was connected to each renewable energy source at various loads. The pulse width can be varied by changing its duty cycle value (D). In this paper, the D value is changed manually for each renewable energy source and automatically using an incremental conductance (IC) and Perturb and Observe (P&O) maximum power point tracking (MPPT) algorithms. The IC algorithm is used for the PV system whereas the P&O algorithm with a smaller step size is used for the PMSG wind turbine. The hybrid system is exposed to different environmental conditions to test the validity of the MPPT algorithm for both renewable energy sources. The results of manual and automatic changes of D values are compared for different loads. The AC output voltage is regulated to obtain a constant RMS voltage at different loads. The hybrid system is tested and simulated using MATLAB SIMULINK R2017a software.

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**Keywords:** DC/DC, Hybrid, MPPT, PWM, Solar, Wind turbine.

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### 1. Introduction

In the last decade, the rapid development of renewable energy conversion systems has lowered manufacturing expenditures. Very low electricity generation costs have led to increased demand for renewable energy applications in real-life electricity generation [1]. Renewable energy sources such as photovoltaic (PV) cells or panels and small-scale permanent magnet synchronous generator (PMSG) wind turbines can be connected to form hybrid renewable energy conversion systems [2]. These hybrid systems can be integrated with traditional electricity generation sources and connected to an electric grid or used for off-grid applications [3]. A PV system depends on the intensity of solar radiation to generate electricity, whereas a wind turbine depends on wind speed [4]. To generate electricity, those renewable energy sources should be connected to DC/DC circuits to extract and control the amount of electricity produced [5]. Normally DC/DC circuits can be operated by modulating the duty cycle (D) of their switching devices. Control of the duty cycle can be used by many algorithms and techniques to control the power flow and even reach the maximum power point tracking (MPPT) of a system

[6]. There are numerous researchers who designed PV and PMSG systems, as well as hybrid solar PV and PMSG wind turbine systems to generate electricity with a suitable MPPT algorithm or technique. D. Mahesh N. et al. [7] presented a paper on dynamic modeling and control for a hybrid wind/PV system connected to a grid. The study involved the performance of a hybrid system at different operation scenarios. These scenarios were changes in the environmental conditions and loads. Z. R. Labidi and A. Mami [8] did a simulation of a hybrid wind/PV system that was connected to a DC load. They used an MPPT algorithm, Perturb and Observe (P&O), for PV solar cells to generate suitable PWM signals to a DC/DC converter. However, for the wind turbine, voltage was regulated using a Proportional – Integral (PI) controller to generate the required PWM signals for its DC/DC converter. The hybrid system was examined at different environmental conditions. Also, in the same year, a modified carrier-based PWM technique was made for an H-bridge inverter for a stand-alone hybrid wind/PV system [9]. This modified PWM technique is based on a comparison between the modulation signal, which is a sine wave, and a semi-sinusoidal carrier. This technique was used to reduce the total harmonic distortion (THD) at the load side. In this system, no DC/DC converter is used and the MPPT technique was not implemented either. T. Maity et al. [10] effective controlled hybrid wind/PV systems for off-grid applications. A CUK-SEPIC DC/DC converter was used with the P&O algorithm. The system supplied three-phase loads via a three-phase 6-switch inverter. The system was designed such that if only solar energy is available, the DC/DC converter works in CUK mode. If only wind energy is available, the converter works in SEPIC mode. If both sources are available then the converter works in CUK-SEPIC mode. There is another hybrid wind/PV stand-alone system developed by [11]. The control strategy is to regulate power flow and to ensure battery charging at predefined limits. This system was tested at various loading conditions. B. Toual et al. [12] presented a modified MPPT technique for a hybrid wind/PV system. The aim of this technique was to track maximum power point as well as enhancing of power quality by decreasing its fluctuations. Di Wu et al. [13] constructed a grid tied a hybrid wind/PV system which was controlled by an improved strategy. The Radial Basis Function Sliding Mode (RBFMS) was used to regulate pitch angles of the wind turbine blades. Also, PID control with fuzzy logic was equipped to regulate the voltage at the terminals of a DC/DC converter connected to the PV panels. Both control techniques were used to get better system stability. The system was tested at various operating and environmental conditions. Alternatively, for off-grid applications, M. Pichan and H. Rastegar [14] developed a hybrid controller for a hybrid system at different loading conditions. The hybrid system was connected to a four-leg inverter where its hybrid controller was working in an abc frame. All of the aforementioned research involved studies of hybrid wind /PV systems with different designs, circuit topologies and control techniques. However, they did not show the effects of the PWM value at different loading conditions. Therefore, the current work is a study of the effect of pulse width modulation (PWM) change through varying D values. The study is made for hybrid solar PV panels and a small-scale PMSG wind turbine. The D value is changed both manually and automatically via a MPPT algorithm. This paper is organized as follows. An introduction is first presented. Then, operational principles of each solar PV panel and small-scale wind turbine are given along with connection of the proposed hybrid system, and an MPPT algorithm. The paper then gives simulation results, discussion and finally, conclusions.

## 2. Operational principles of the solar PV panel and small-scale wind turbine

The operational principle of a photovoltaic (PV) solar panel is based on the following formula:

$$P_{PV} = A_{PV} I_s \eta_{PV} \quad (1)$$

This relationship is used to calculate the conversion of solar power to electrical power, where  $A_{PV}$  is the area of the solar panel in ( $m^2$ ),  $I_s$  solar irradiation in ( $W/m^2$ ), and  $\eta_{PV}$  is the efficiency of the panel [15]. The power of the panel is affected by several environmental conditions, including temperature and shading. Figure 1 represents the P-V curve of a single PV panel that is used in this paper. From this figure, it can be noted that when the temperature is increased, the power is decreased even at a constant solar irradiation. Thus, the DC voltage and power of the panel normally have different values with varying environmental conditions. To adjust to these changes, a suitable DC/DC converter and appropriate pulse width modulation (PWM) technique or algorithm can be used to reach the maximum power point (MPP) of the system P-V curve [16-17].

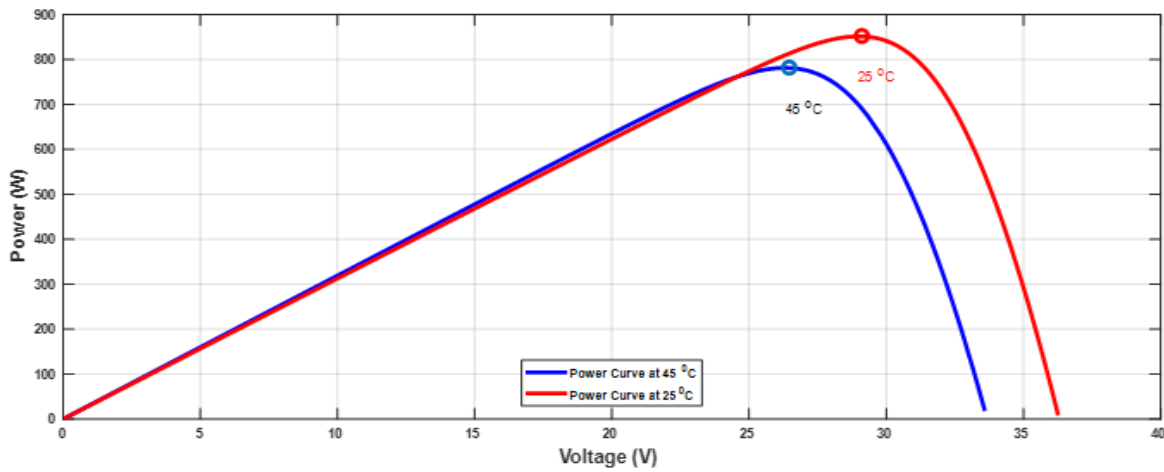


Figure 1. PV Solar Power Characteristics

A wind turbine is device that extracts energy from wind to generate electricity. The mechanical power that can be derived from a wind turbine is expressed by the following formula [18]:

$$P = \frac{1}{2} \rho \pi R^2 C_p V^3 \quad (2)$$

where  $\rho$  is the air density (1.225 kg/m<sup>3</sup>), R is the radius of the turbine’s rotor,  $C_p$  is the generator coefficient, and V is the wind speed in (m/s). The characteristics of a wind turbine are shown schematically in Figure 2. At each wind speed, there is a particular power curve. The type of electrical generator attached to the wind turbine in the current work is a three-phase small scale permanent magnet synchronous generator (PMSG). The three-phase model in the (d-q frame) is expressed by the following equations [19]:

$$\frac{d}{dt} id = \frac{1}{Ld} Vd - \frac{R}{Ld} id + \frac{Lq}{Ld} P \omega_m iq \quad (3)$$

$$\frac{d}{dt} iq = \frac{1}{Lq} Vq - \frac{R}{Lq} iq - \frac{Ld}{Lq} P \omega_m id - \frac{\lambda P \omega_m}{Lq} \quad (4)$$

where  $Ld$  &  $Lq$  are the inductance along the d and q axes, respectively, P is the number of pole pairs, R is the resistance of the stator windings,  $\lambda$  is the amplitude of the flux induced by the permanent magnets of the rotor,  $Vd$  and  $Vq$  are the voltage along d & q axes, respectively, and  $\omega_m$  is the angular rotational speed of the rotor. Electrical torque is expressed as:

$$Te = 1.5 P [\lambda iq + (Ld - Lq) id iq] \quad (5)$$

As shown in Figure 2, the turbine mechanical output power is express in terms of its nominal mechanical power. In MATLAB software, some component quantities can be defined on a per unit (pu) basis. So, it is necessary to convert these quantities from or to a pu system. The pu quantity is determined as follows [20]:

$$pu (quantity) = \frac{Actual Value}{Base Value} \quad (6)$$

The base frequency of a PMSG is calculated as:

$$\omega = 2\pi f \quad (7)$$

The base rotational speed of the PMSG is:

$$Base \ rotational \ speed = \frac{(Rated \ speed \ in \ RPM) 2\pi}{60} \quad (8)$$

and the base torque is calculated as follows:

$$Base \ torque = \frac{3 (Base \ rated \ power \ in \ W)}{Base \ rotational \ Speed} \quad (9)$$

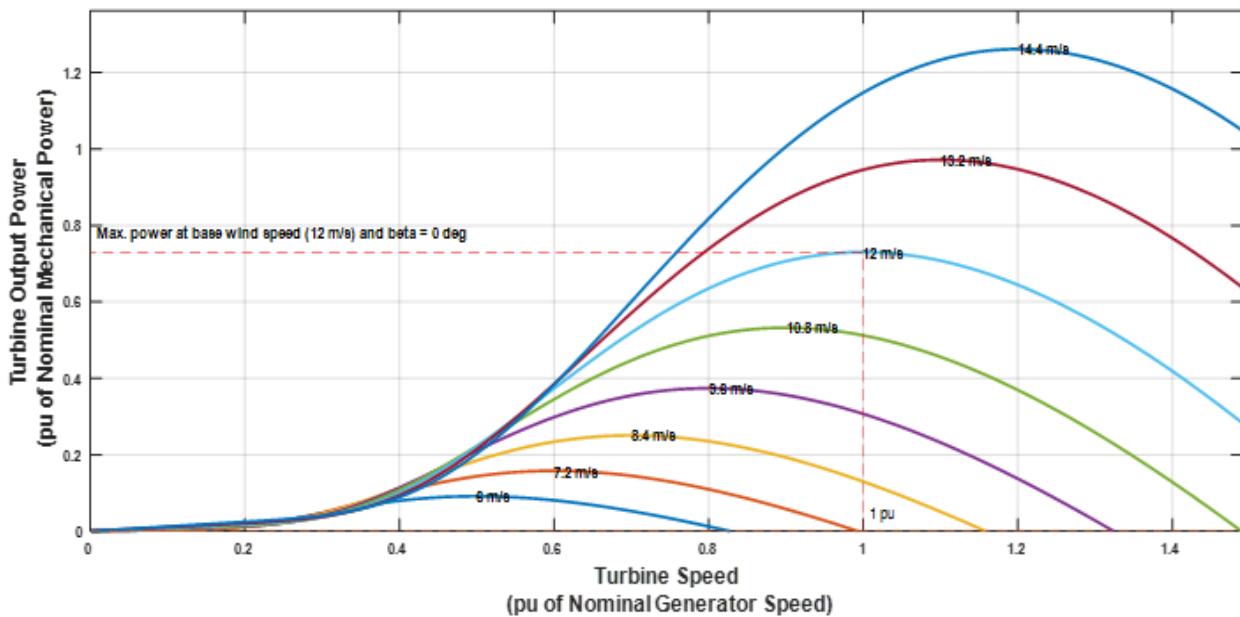


Figure 2. Wind Turbine Power Characteristics

### 3. Connection of the proposed hybrid system

The proposed system is shown in Figure 3. This system includes a hybrid wind and solar system consisting of four PV panels connected in parallel. The output power of each panel is 213 W. The four panels can deliver a total power of 852 W. The system also has a 1 kW small scale permanent magnet synchronous generator (PMSG) wind turbine. Each power source is connected to a DC/DC boost converter. The design specifications of each boost converter rely on selection of appropriate inductance and capacitance values, which can be determined using equations 10 and 11, respectively [21].

$$L = \frac{D \times V_{dc}}{F_s \times \Delta i_{in}} \quad (10)$$

$$C_{is} = \frac{2 \times D \times I_o}{F_s \times \Delta V_o} \quad (11)$$

In these equations,  $D$  is the duty cycle,  $V_{dc}$  is the DC voltage from each source,  $F_s$  is the switching frequency,  $\Delta i_{in}$  is the ripple value of the boost converter input current,  $\Delta V_o$  is the boost converter output voltage ripple, and  $I_o$  is the boost converter output current that is fed to the DC link bus. The capacitance of each boost converter is connected at the DC link bus. This DC link represents a common coupling point between the source DC and the load AC sides. The voltage of this bus is supplied to a single-phase H-bridge inverter. The output side of the inverter is connected to a LC filter and then to a single-phase transformer. The transformer is used to step up the inverter voltage to reach a level of 230 V RMS at its secondary side, which is then normally connected to a load.

### 4. MPPT algorithm

There are many types of MPPT algorithms, including perturb & observe (P&O), incremental conductance (IC), ripple correlation control (RCC) and some artificially intelligent methods that are normally based on P&O and IC algorithms [22]. In this paper, for the hybrid system, different MPPT algorithms are selected for each source. The IC algorithm is selected as the MPPT algorithm for PV system due to its simplicity and superior steady state performance to a P&O algorithm [23]. This algorithm considers that at the MPP, the slope ( $\Delta P/\Delta V$ ) is zero. With operations to the left of MPP, the slope has positive value, while to the right, the slope has negative value. Whereas the MPPT algorithm for wind turbine is P&O with very small step size. For small scale wind turbines, the P&O algorithm is more preferred [24]. The IC and P&O algorithms are illustrated in Figure 4. The algorithms are programmed in MATLAB.

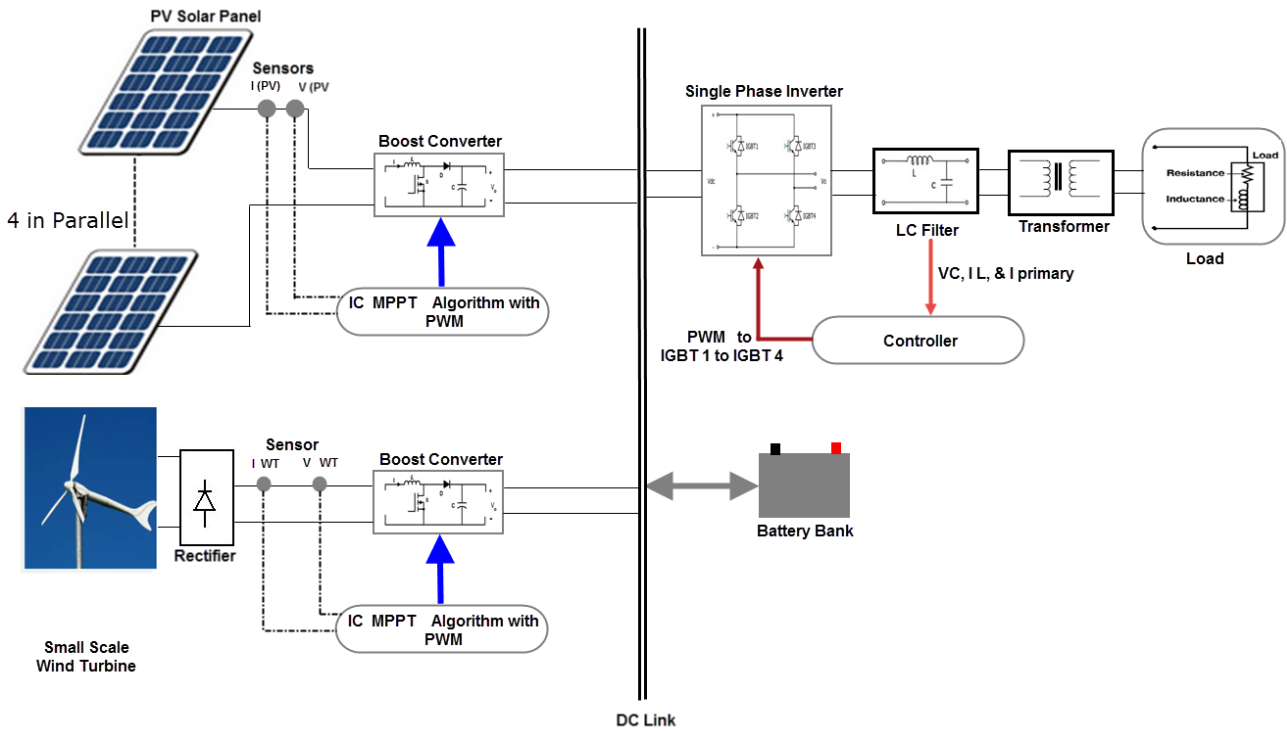


Figure 3. Connection of the proposed hybrid system

### 5. Simulation results and discussion

The proposed hybrid system is simulated via MATLAB Simulink R2017a and is illustrated in Figure 5. In this simulation, the battery is neglected. The specifications of the proposed PV solar and PMSG wind turbine are shown in Table 1.

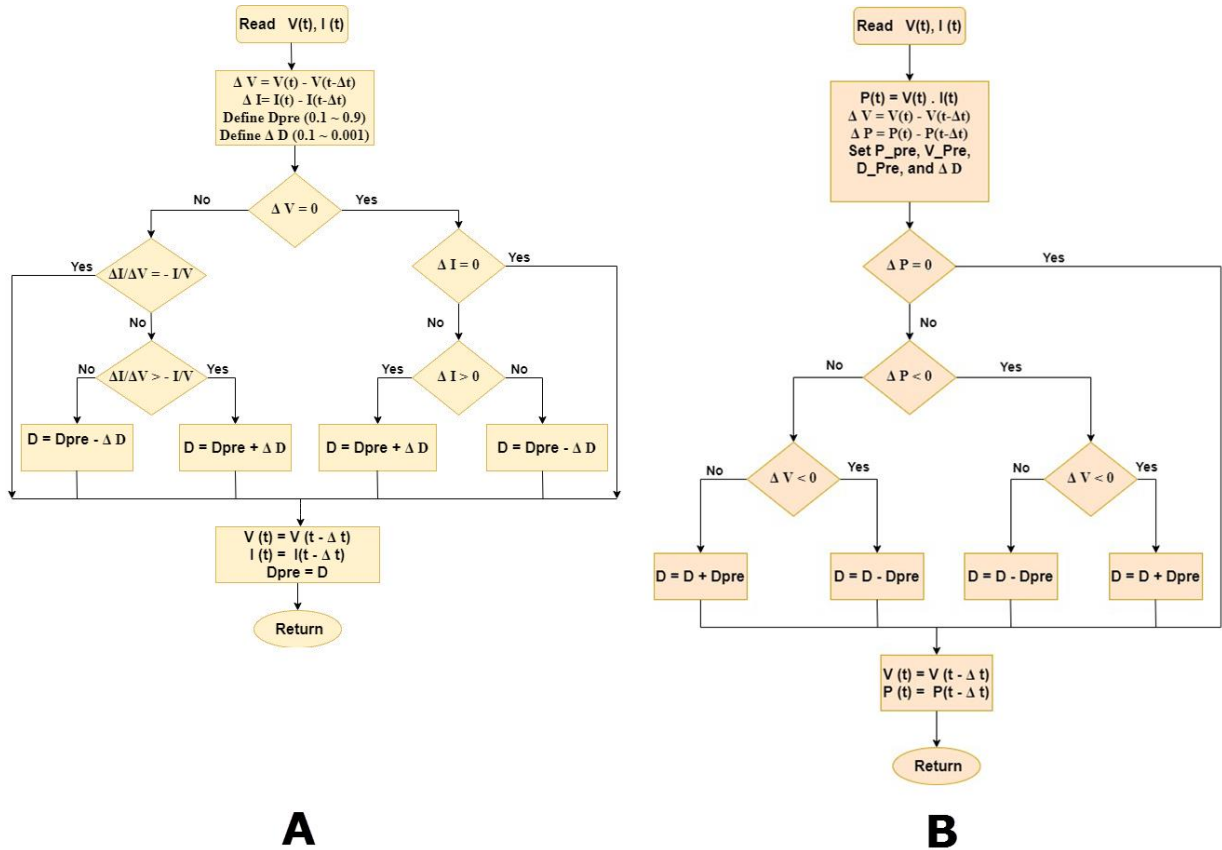


Figure 4. MPPT algorithms: A- P&O, B- IC

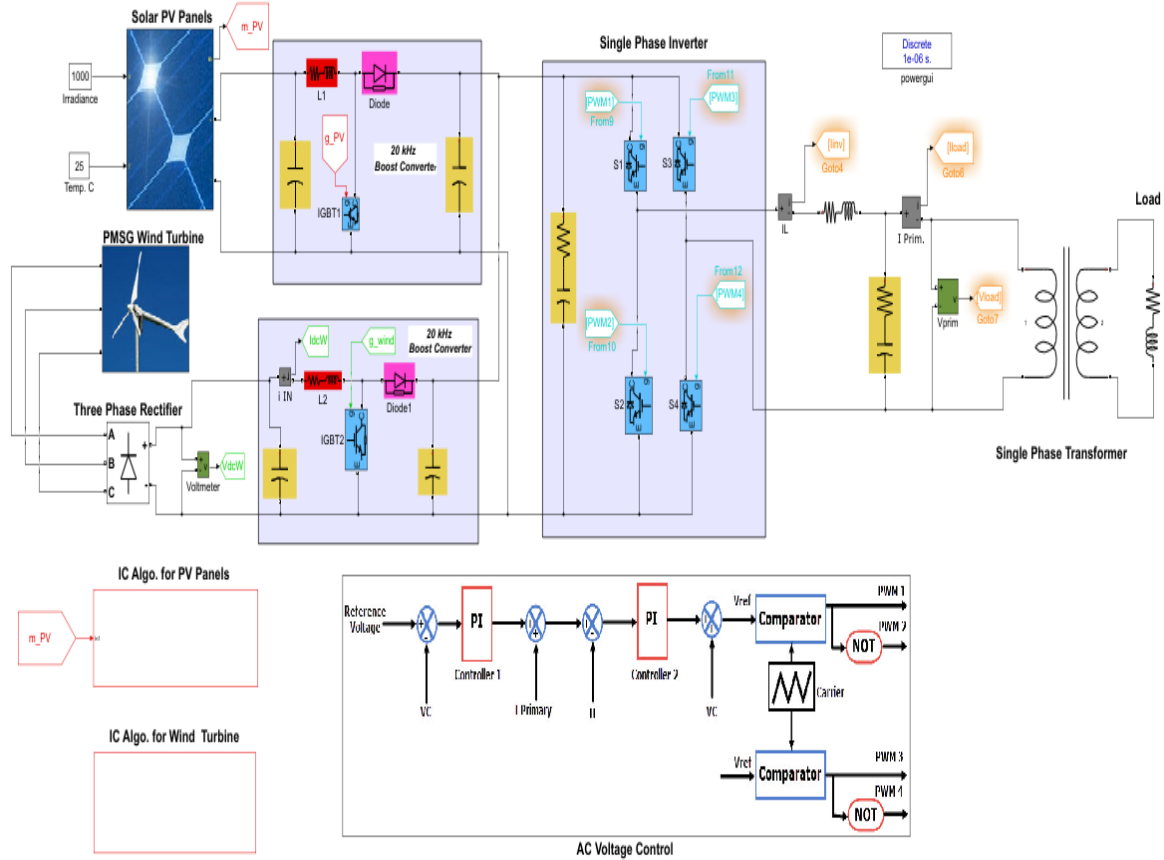


Figure 5. MATLAB Simulink of the proposed hybrid system

Table 1. Specifications of the proposed PV solar and small scale PMSG wind turbine

Renewable Energy Source	Specifications	
PV panel (1×4 in parallel)  The specification of a single panel	Maximum Power	213.5 W
	Open Circuit Voltage	36.3 V
	Voltage at MPP	29 V
	Short Circuit Current	7.84 A
	Rated Solar Irradiation and Temperature	1000 W/m <sup>2</sup> at 25 °C
Small Scale PMSG Wind Turbine	Mechanical Nominal Power	1000 W
	Base Power of The Electric Generator	1000/0.9 W
	Number of Phases	3
	Maximum Power at Base Wind Speed (pu of Nominal Mechanical Power)	0.73 pu
	Pitch Angle	0
	Base Wind Speed	12 m/s
	Stator Resistance	1.95 Ω
	Armature Inductance	1.9 mH
	Voltage Constant (V peak L.L. / Krpm)	200
	Inertia	0.1 J(kg.m <sup>2</sup> )
	Viscous Damping	0.0024 F(N.m.s)
Number of Pole Pairs	8	
Rated Rotor Speed	400 RPM	

In the beginning, the simulation is done without using the IC algorithm. Instead, a manual change of duty cycle D is made over the range of 10% to 80%. Various loads, (100, 80, 60, 40, 20, 10, and 5) Ω, are selected

and simulated with each D value. Table 2 represents the manual duty cycle change for the PV system only. Data in this table shows the input power measured at each D value and load change.

Table 2: Manual duty cycle change for the PV system

	Duty cycle 10%	Duty cycle 20%	Duty cycle 30%	Duty cycle 40%	Duty cycle 50%	Duty cycle 60%	Duty cycle 70%	Duty cycle 80%
Load ( $\Omega$ )	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)
100	16.2	20.8	27.3	38.1	53.4	83.8	145.9	314.2
80	20.2	25.8	33.4	46.5	65.1	104.3	180.2	380.2
60	26.8	34.9	44.7	61	87.9	135.5	233.4	440.9
40	39.7	50.8	66.5	90	129.3	198.2	338.9	682.9
20	78.5	99.4	129.4	174.7	247.6	373.9	610	769.1
10	154	193.8	250	333.1	461.9	664.1	836.8	397.2
5	296.2	368.1	466.8	603.6	780.7	775.9	445.7	202.9

At low loads, the drawn power is increasing with the increase in the duty cycle. At some high loads, such a 10 to 5  $\Omega$ , increasing the duty cycle to more than 60% or 70% may result in decreased drawn power. This occurs since the increase of duty cycle at high loads may move the drawn power point the right of the MPP depicted in Figure 1, which leads to decreased power drawn from the PV panels.

Table 3 represents the input power measured at each D value with various loads for the small scale PMSG wind turbine. In this table, it can be noted that at light loads, when the D value is increased, the input power also increases. At medium or high loads, when the D value is more than 40% or higher, the input power will decrease since it may move to the right of the MPP of Figure 2. Comparing Tables 2 and 3, it can be noted that at low D values, the drawn power from the PMSG wind turbine is higher than for the PV panels. This is due to the characteristics of wind turbines. They supply more power than PV panels, even if their rated power is the same at a rated wind speed or solar irradiation and temperature, respectively. In Table 4, the IC and P&O MPPT algorithms are applied to PV panels and a PMSG wind turbine, respectively, where their input voltage and current are the inputs their MPPT algorithm. The output of the algorithm is the regulated duty cycle, D, that is fed to each DC/DC boost converter. The selected loads are the same as in Tables 2 and 3.

Table 3. Manual duty cycle change for a PMSG wind turbine system

	Duty cycle 10%	Duty cycle 20%	Duty cycle 30%	Duty cycle 40%	Duty cycle 50%	Duty cycle 60%	Duty cycle 70%	Duty cycle 80%
Load ( $\Omega$ )	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)	Input Power (W)
100	244.6	245.6	382.1	385	605.1	610	750.3	752
80	284.9	290	437.3	446	650.1	658	720.1	722
60	355	361	517.7	522	710.6	720	656.1	660.4
40	462.1	463	625	632	756.4	761	550.3	546
20	650.3	664.9	750.7	751	720.7	718.5	360.2	355
10	762.5	763	743.1	744	561	553	200.5	195
5	725	726.3	598.1	600.2	360.6	354	115.5	105

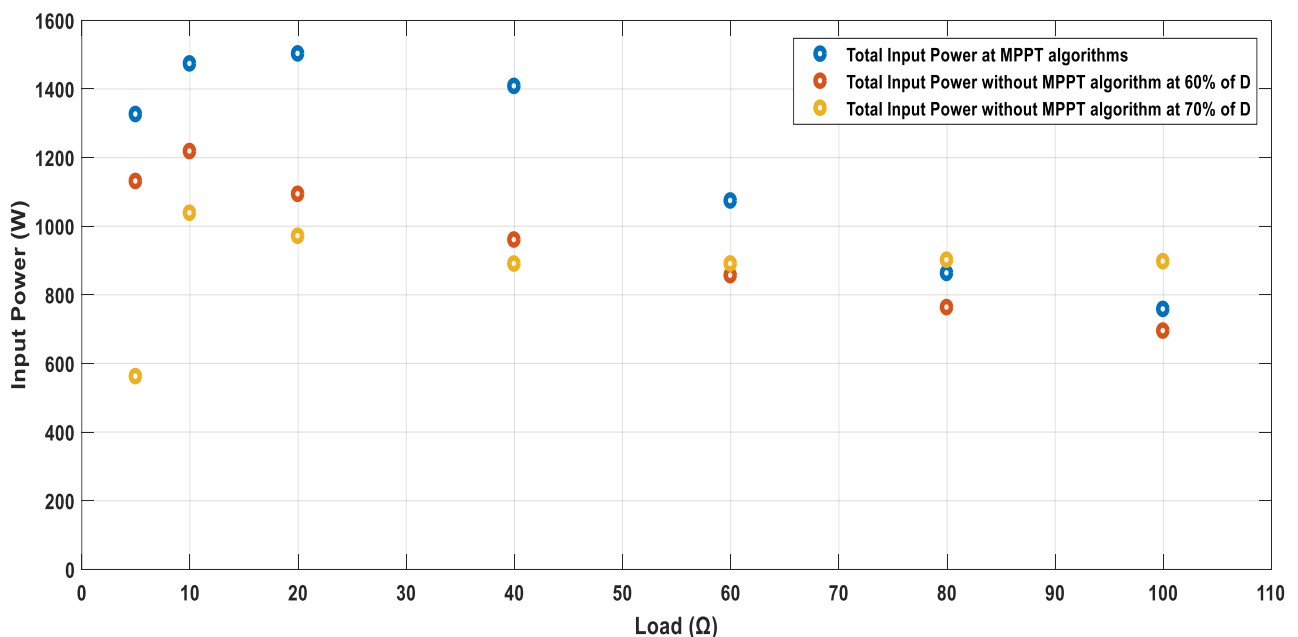


Table 4. Input and output power, as well as efficiency for the hybrid system with an IC MPPT algorithm at various loads

Load ( $\Omega$ )	Input Power for PV Solar System (W)	Input Power for PMSG Wind Turbine system (W)	Total Input Power (W)	Load Power (W)	System Efficiency %
100	42	715	757	694.3	91.7
80	132	730	862	809.6	93.9
60	333	740	1073	1022.5	95.2
40	652	755	1407	1360.7	96.7
20	749.2	752.5	1501.7	1468.8	97.8
10	815	675.5	1472.5	1456.8	98.9
5	825	500	1325	1321.9	99.7

In Table 4, it can be seen that when the load is increased, the drawn power from each source, the output power, and the system efficiency, increase as well. At light loads, the power values supplied from the PV panels are lower than the power from the PMSG wind turbine. At medium or high loads, the wind turbine system can reach its MPP or at least approach it. The power from the PV system can reach a point near its MPP at high loads. Figure 6 presents a comparison between the total input power when the IC and P&O MPPT algorithms are used and when both algorithms are not used at 60% and 70% of D. In this figure, it can be noted that at medium or high loads, using an MPPT algorithm is more effective than at low loads.

The response of the hybrid renewable sources is simulated and shown in Figure 7. In this figure, it can be seen that the generated power from the PV panels more quickly reaches its steady state than does the PMSG wind turbine. This difference in response is due to the inertia of the wind turbine that slows its start and movement of the turbine rotor.

Figure 6. Input Power at various loads with and without an IC MPPT algorithm at 12 m/s wind speed and 1000 W/m<sup>2</sup> solar irradiation at 25 °C



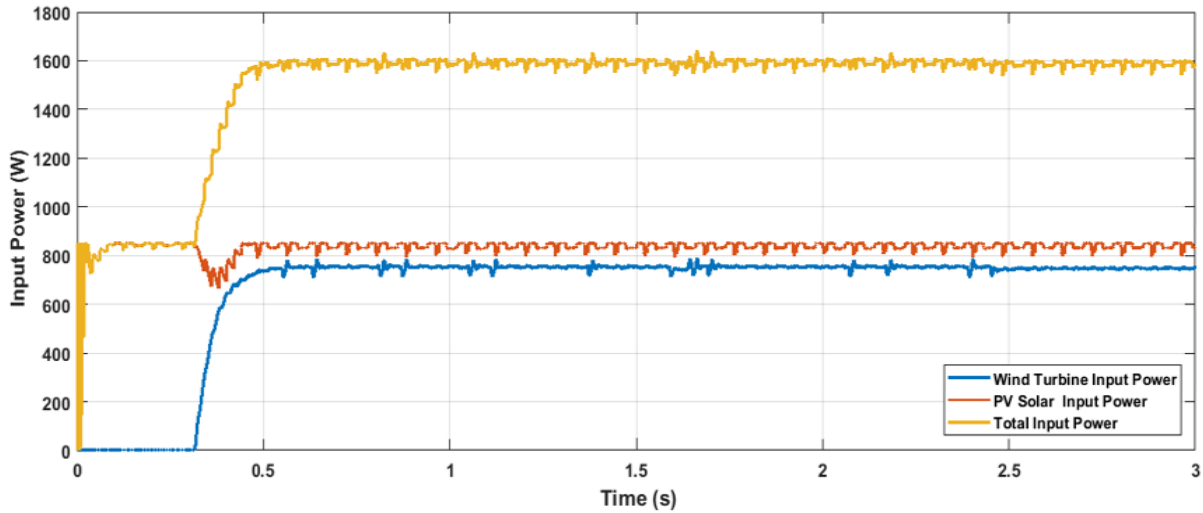


Figure 7. Input Power during  $5 \Omega$  load at IC MPPT algorithm at 12 m/s wind speed and  $1000 \text{ W/m}^2$  solar irradiation at  $25^\circ\text{C}$

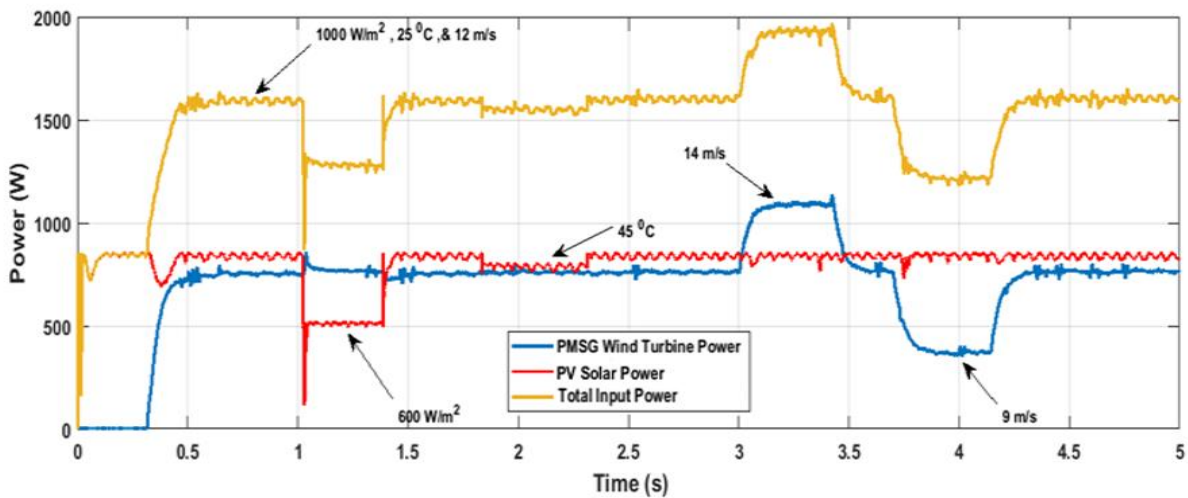


Figure 8. Effect of changes in wind speed, temperature, and solar irradiation under an IC MPPT algorithm with a  $5 \Omega$  load

Figure 8 shows the effect of changes in wind speed for the wind turbine as well as temperature and solar radiation for the solar PV panels upon the total input power at full load. In this figure, the IC MPPT algorithm is applied to both renewable energy resources. Normally, for a PMSG wind turbine, a greater wind speed results in increased generated voltage and power. The increase of wind speed also results in a new range of MPPs, which can be reached to achieve greater power. This is limited by the design of the wind turbine at high rotational speeds. For solar PV panels, an increase in temperature and/or decrease of solar irradiation from the rated designed values will result in decreased generated power from the PV panels and vice versa.

The role of an MPPT algorithm is to reach the MPP to supply the maximum possible power from renewable energy resources. At various loads, the voltage at the DC link between the boost converter side and the inverter side varies with the load. It increases when the load is decreased and vice versa. The role of the inverter is to supply a constant voltage under different loads. In this work, since the power range is less than 2 kW, a single-phase inverter is more suitable. The modulation technique employed is sinusoidal pulse width modulation (SPWM). This is done through a comparison of the sine of a reference signal and that of a high frequency carrier. The reference signal ( $V_{ref}$ ) is generated via the controller depicted in Figure 9. This controller takes three measurements of signals from the output side of the inverter. These three signals are the voltage at the capacitor  $C$  of the LC filter, the primary current of the transformer primary winding, and the current to the inductance  $L$ .

of the LC filter. In this figure, the reference voltage is a sine wave signal at 50 Hz. Its amplitude is the same as the magnitude of the transformer primary side voltage.

In the same figure, it can be observed that two proportional integral (PI) controllers are used. The first controller is employed to regulate the output voltage, where its proportional  $K_P$  and integral  $K_I$  gains are 0.031 and 21, respectively. The second PI controller is used to regulate the output current. Its  $K_P$  and  $K_I$  gains are 27.06 and 6.67, respectively. The regulated output AC voltage is shown in Figure 10. It can be observed that when the load is changed, the output voltage is constant at 230 V RMS and only the output current varies. In this system, the percentage of total harmonic distortion is measured as well. This is shown in Figure 11.

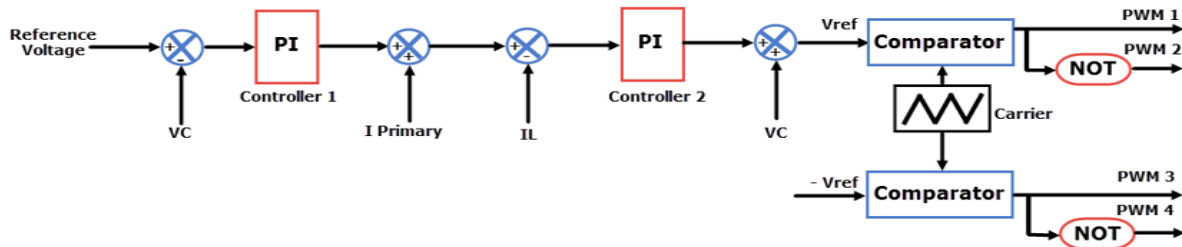


Figure 9. AC side voltage controller

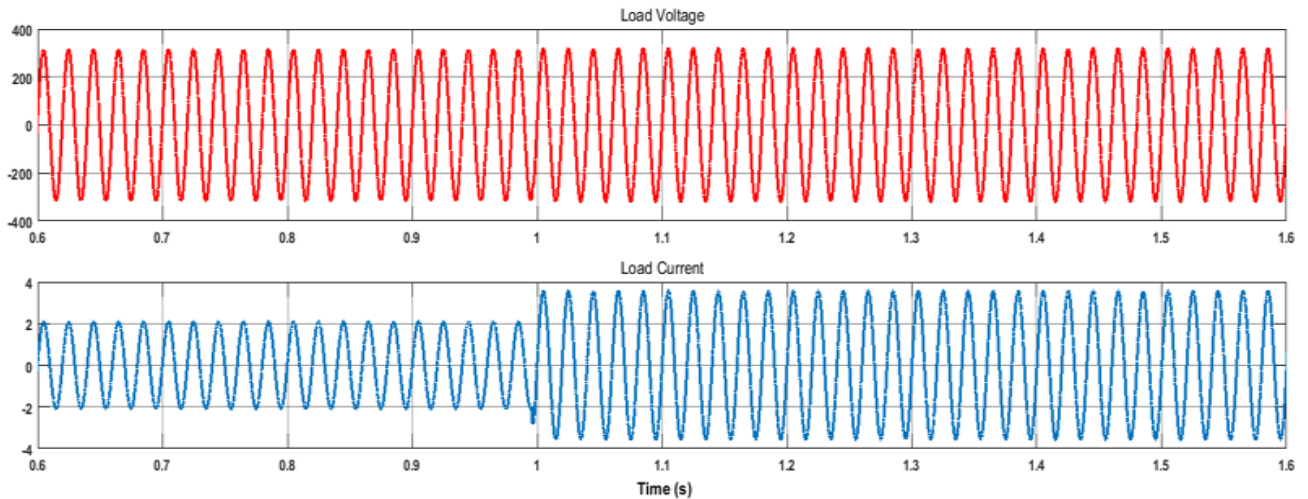


Figure 10. Output voltage and current at various loads

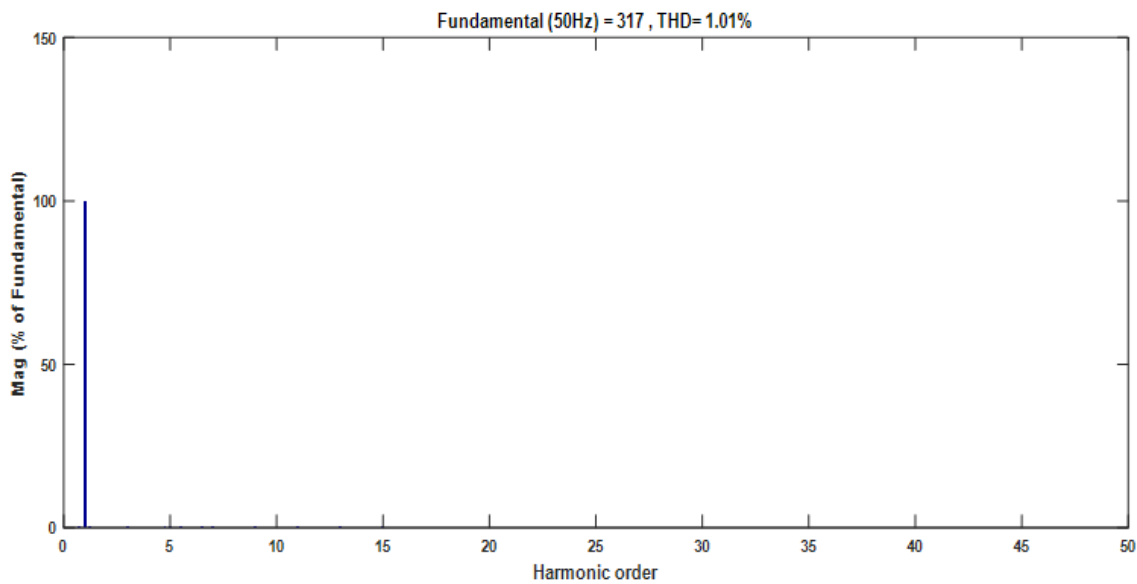


Figure 11. THD (%) of the load voltage

## 6. Conclusions

In this work, the effects of manual pulse width change,  $D$ , for each PMSG wind turbine and solar PV panel are studied. The study is done at various loads and by applying an IC MPPT algorithm for a PV system and a P&O algorithm for a PMSG wind turbine. It is concluded that at light loads, the MPPT algorithm is less effective. Also, the PMSG wind turbine can generate more power than the PV panels by applying its MPPT algorithm. In the case of medium or high loads, the MPPT algorithm is more effective for both sources. Due to mechanical inertia, the response of the PMSG wind turbine is slower than the PV system. Also, a small change in the wind speed results in a great change in the total power of the system. However, this is limited by the ability of the manufactured wind turbine to work at high wind speeds. In the hybrid system, each power source can generate power at the same output DC link voltage. The common connection of their boost converters at the DC link forces them to attain the same voltage value, which is normally unregulated. Voltage regulation is the role of an inverter that employs an appropriate control technique to achieve a constant AC voltage to supply various loads. The role of the DC/DC boost converter is to manage the MPPT algorithm. The inverter's role is to supply regulated AC voltage for various loads. Yet, the voltage level of the DC link is low thus, a transformer at the inverter output terminals is mandatory. Normally the transformer generates losses. In future work, it is required to design such a system but with no transformer.

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