Chapter 6
Hybrid Energy Systems

Learning Objectives

On completion of this chapter, the reader will have knowledge on:

- Basic knowledge on Hybridizing solar PV module with wind energy system and diesel system.
- MATLAB/SIMULINK model of hybrid solar PV and wind energy conversion system.
- Converters used for hybrid solar PV and wind energy conversion system.
- Fuzzy logic controller for hybrid power systems.

6.1 Need for Hybrid Energy System

Instead of utilizing power from wind energy alone or solar energy alone, combining both wind and solar provides a better and reliable system. Both sources together can supply power and if any decrease in power occurs, in any one, the other source can compensate for the first. Also both system together can supply higher loads if required. Whenever the generated power is in excess, it can also be stored in a battery.

For reliable supply of power in remote locations or inaccessible rural areas, it is necessary to design and set up hybrid system, which combined the advantage of two different energy technologies. These could be either two renewable technologies or a renewable and a conventional energy or fossil fuel technology. A hybrid system would ensure that power supply can be maintained at an optimum level during cloudy days for a PV system and at low wind conditions for wind electric generators. According to many renewable energy experts, a small hybrid electric system that combines wind energy system and solar PV technology offers several advantages over either single system. In this chapter solar PV module is hybridized with

wind energy system and diesel system. The MATLAB/SIMULINK model is developed for the hybrid combination and the results are presented.

6.2 Hybrid Solar PV/Wind Energy System Using MATLAB/SIMULINK

This section presents the modeling of a solar-wind-hydroelectric hybrid system using MATLAB/SIMULINK. The application applicable for analysis and also simulation of a genuine hybrid solar-wind-hydroelectric system connected to a public grid. Application is built on modular architecture to facilitate quick study of each and every component module impact. Blocks like wind model, solar product, hydroelectric model, energy conversion and load are implemented. The simulation results of model are also discussed. As an exercise, one of the key studies is the behavior of hybrid process which allows employing renewable and adjustable in time powers while providing a continuous supply.

The custom modeling rendering, simulation and analysis of a prominent variety of techniques based on electrical power and to manage these systems, MATLAB was broadened with the RegenSim library. This library was made not only to implement the previously mentioned functions for crossbreed systems based on renewable energy options, but also to interface the components interfacing together with components from different libraries, particularly those of MATLAB SimPowerSystems library. Basic components of RegenSim library tend to be: Wind generators, PV generators, Hydro generation devices and Storage equipment. Each of these elements was basically sculptured on studies regarding mathematical models and possesses associated specific guidelines. The interfacing with MATLAB libraries parts was realized to make a thorough study of the modeled hybrid system by local automatic control systems to the centralized operational supervision system. Apart from the storage device component, each of the remaining three components has, input boundaries, the specific primary source of energy and, interconnection with different sorts of measurement blocks of MATLAB, voltages, currents, powers and energy flows from it, depending on the nature of the customer. The Storage product component was made with the primary, serving as a buffer to store the energy made by renewable sources, looking at the terminals being directly supplied to the DC consumers and the AC through this inverter blocks. On the batteries level can be monitored by making use of measure and present blocks from MATLAB, the shape and state regarding battery charge (SOC), the critical voltage or voltages absorbed by consumers. One of the major advantage of MATLAB software is the fact that libraries offer a variety of basic components intended for modeling according to the problem under consideration. Thus, it is usually modeled for both single phase and three phased consumers with some other powers, nature and also types (e.g.: resistive, capacitive or perhaps inductive consumers).
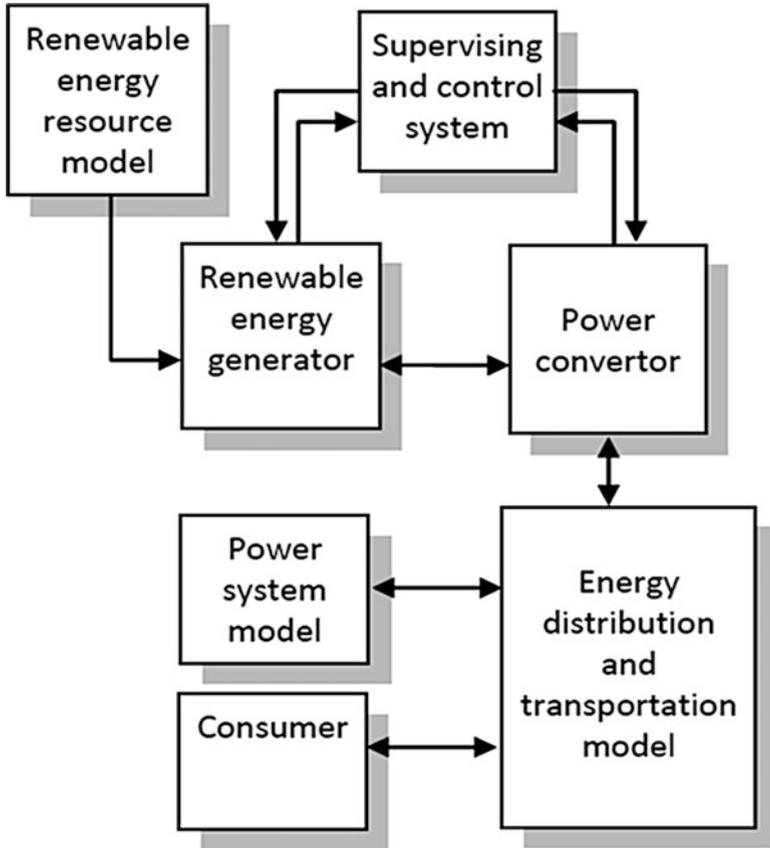
Fig. 6.1 Simulation model architecture based on RegenSim library

6.2.1   Architecture of Solar-Wind Hybrid System

The simulation model was implemented according to the system architecture presented in Fig. 6.1. Employing this architecture we could model any system determined by alternative energy. Several forms of primary sources with various parameters, different energy and power converters with specific parameters, different topologies from the local distribution system and as a final point a variety of consumers with linear or nonlinear characteristic is usually chosen within the simulation model, with respect to the version that is certainly intended as studied.

6.2.2   Implementation Using MATLAB/SIMULINK

With all the RegenSim library blocks an alternative energy hybrid system shown in Fig. 6.2 was developed. As shown, the simulation system contains power
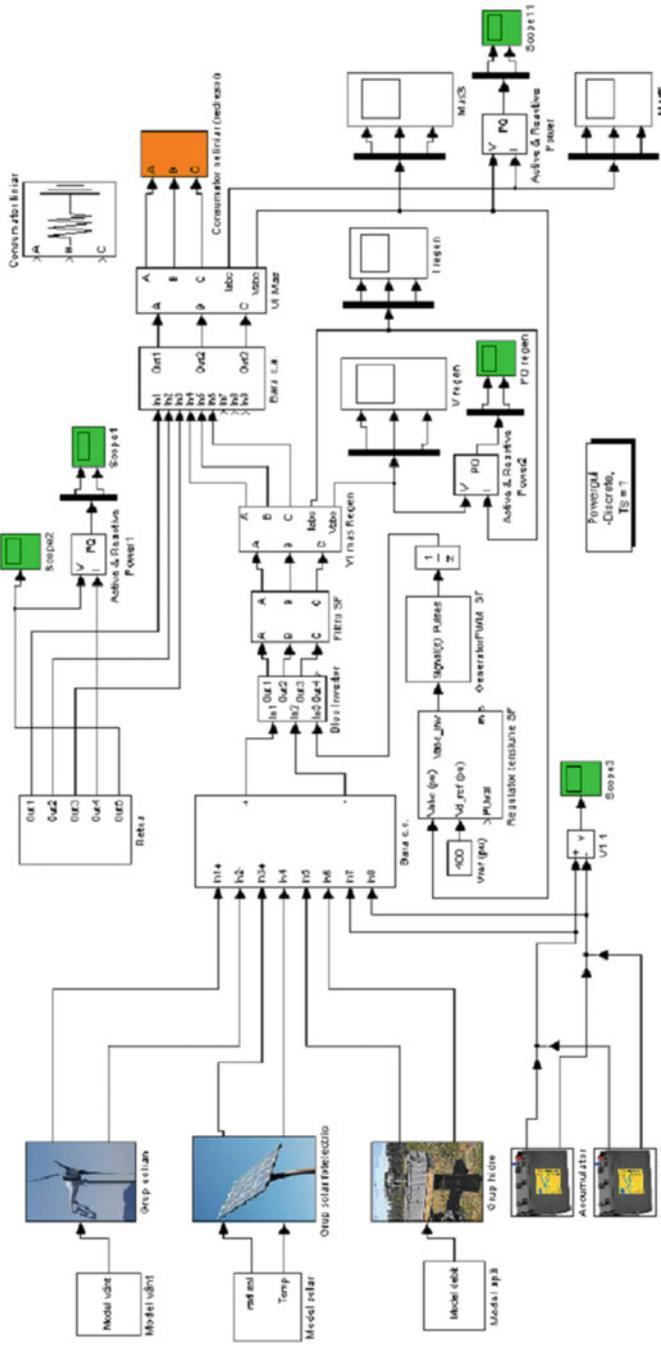
Fig. 6.2 MATLAB/SIMULINK simulation model of a hybrid system based on renewable energy

generation blocks from renewable energy sources including sun, wind or water, battery blocks (providing the energy storage), measurements blocks for electrical parameters (voltage, current, power), inverter blocks (for power generation in DC voltage), voltage regulator block, AC and DC voltage bus bars and AC and DC consumers blocks. It should also be specified that each with the power generation simulated blocks could be sized which enable it to operate independently providing energy within the system, but they might be also interconnected, a correct sizing of the batteries (dependant upon configuration) being mandatory.

The simulation model was primarily suitable for the means analysis of renewable energy resources usage, for its management in the design phase and for the study of issues that may occur as a result of the adopted solution. The adopted solution concerns the management solutions that could be adopted, but additionally the monitoring, control and command of renewable energy sources as well as the consumer. Beyond just the above functions, the model was created and developed to the study of real-time system operation and then for power quality analysis of the studied system. After running with the simulation, power flow graphs among hybrid system determined by renewable sources and the public power network and instantaneous voltages and currents graphics might be obtained.

Inside performed study were considered different configurations and situations of renewable energy sources availability for different sorts of consumers. Within this paper the alternative energy resource availability was taken within the choice of 0.8–3 kWh/m^2 for solar resource, a variable wind speed from 2 to 20 m/s along with a water flow and drainage between 30 and 100 l/s at 50 m level difference through the hydro resource. A linear plus a nonlinear consumer (Pi = 33 kW) were also considered.

6.2.3   Small Domestic Power Grid Based on Hybrid Electrical Power

In Fig. 6.3 is presented the active power variation in the power network. It might be noted that in case the force storage elements are loaded at given parameters from the sustainable energy availability, the device provides about two fifths of the electricity stated in utility network. If the energy storage elements are certainly not loaded at rated capacity it might be noted that, by the point of their fully recharge, energy is absorbed from the public network. In Fig. 6.4 is presented the reactive power variation in the local power network. It might be observed that the sustainable energy hybrid system can be used to produce reactive energy. The most favorable situation would be the use of all alternative energy in addition to all energy storage devices.

In Figs. 6.5 and 6.6 the active and reactive power created by renewable energy sources are presented. It might be noticed that the power generated from alternative energy is utilized for charging the vitality storage devices, with the consumers as well
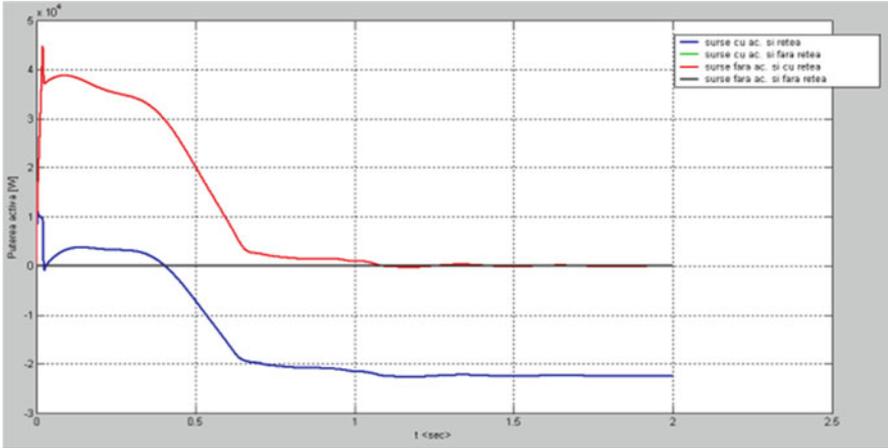
Fig. 6.3 Evolution of active power transit between the hybrid system based on renewable energy sources and the public network
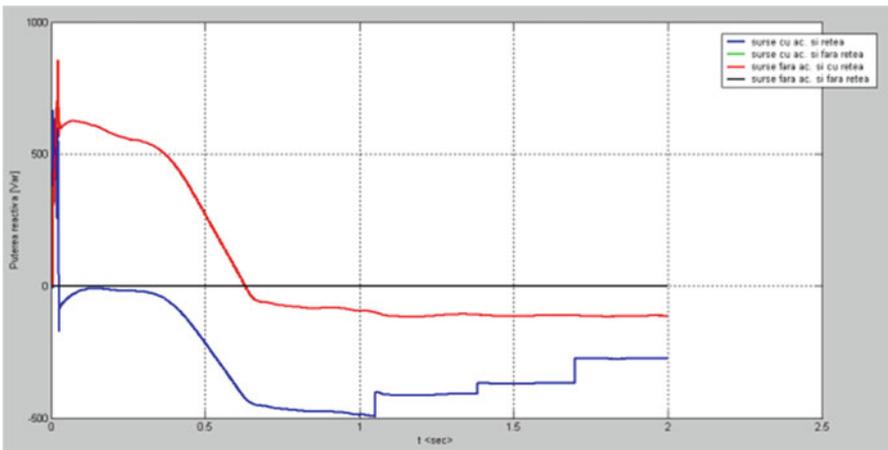
Fig. 6.4 Evolution of reactive power transit between the hybrid system based on renewable energy sources and the public network

as to cover losses plus the surplus is injected to the local public network. When the consumer is isolated power evolution is stabilized following an equivalent constant level in line with consumer power and losses. If consumer is isolated, the presence of reactive power is caused by nonlinear elements utilized in the simulation model: power transformers and power converters determined by electronic switching components. Confirmation for the above is shown in Figs. 6.7 and 6.8 that is definitely the active and reactive power at consumer terminals.
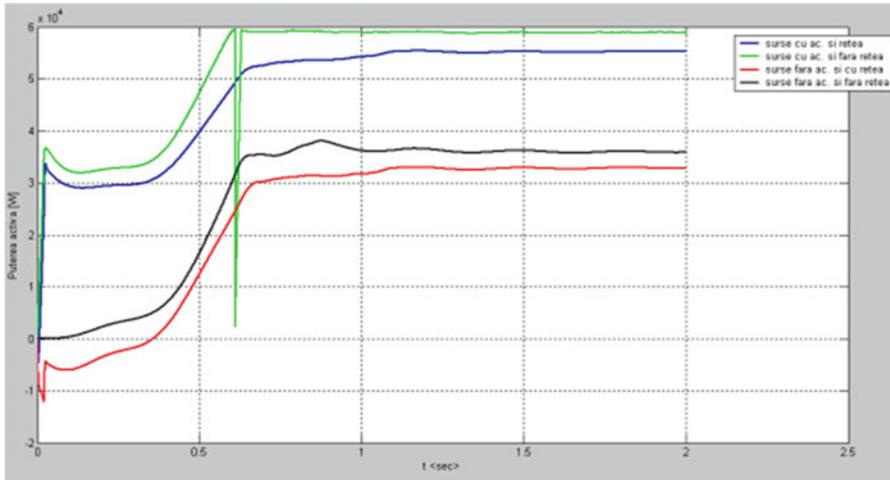
Fig. 6.5 Renewable energy sources active power variation
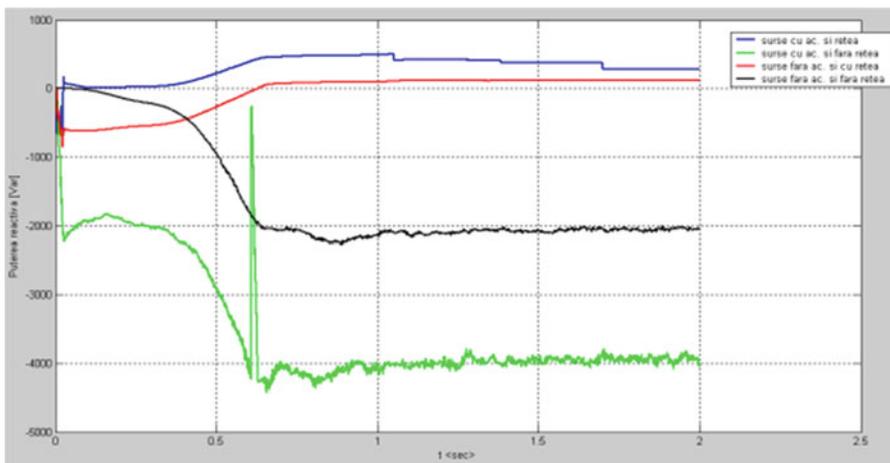

Fig. 6.6 Renewable energy sources reactive power variation

6.2.4   Small Industrial Power System Based on Hybrid Renewable Energy

In practice, individual drives are employed in variable speed drive applications. This drives consists of controlled rectifiers, whose speed varies according to the temperature, this has to modeled. In Fig. 6.9 is presented the active power variation in the local power network. It is usually noted that when the force storage elements are loaded at given parameters through the alternative energy availability, the
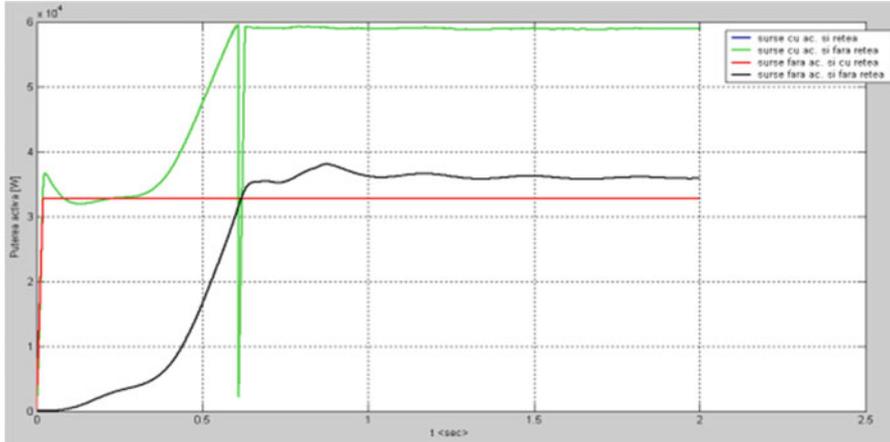
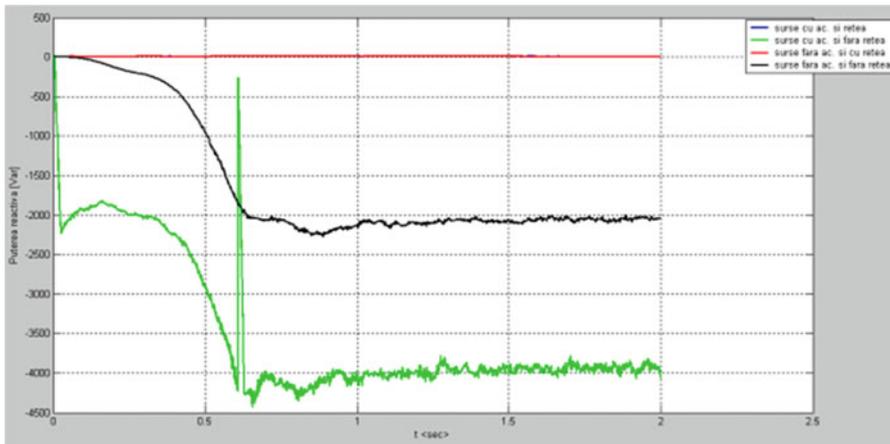**Fig. 6.7**   Consumer active power variation

Fig. 6.8   Consumer reactive power variation

machine provides produced energy in the public network. When the energy storage elements are certainly not loaded at rated capacity it might be noted that, at the point when they are fully recharge, energy is absorbed from the public network. In Fig. 6.9 can even be seen the highly nonlinear nature of the consumer. Dark and green characteristics correspond to situation the location where the consumer is isolated.

In Fig. 6.10 is presented the reactive power variation from the power network. It could be observed that the renewable power hybrid system enables to produce reactive energy in the considered cases. In Figs. 6.11 and 6.12 the active and reactive power produced by renewable energy sources are presented. It could be
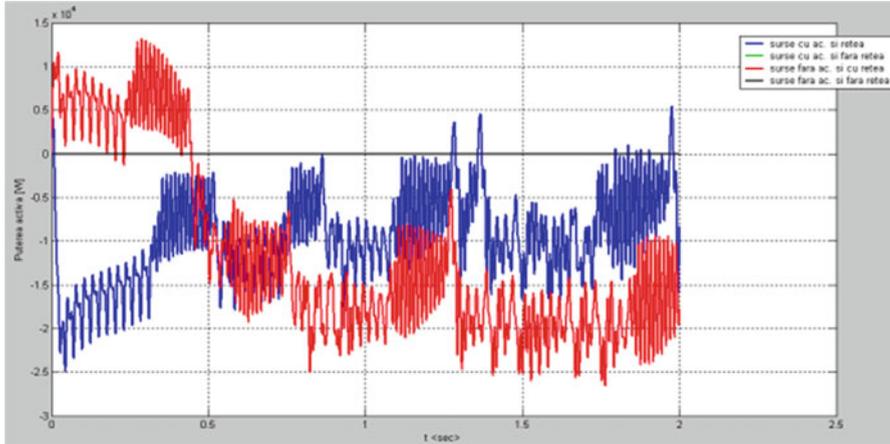
Fig. 6.9 Evolution of active power transit between the hybrid system based on renewable energy sources and the public network
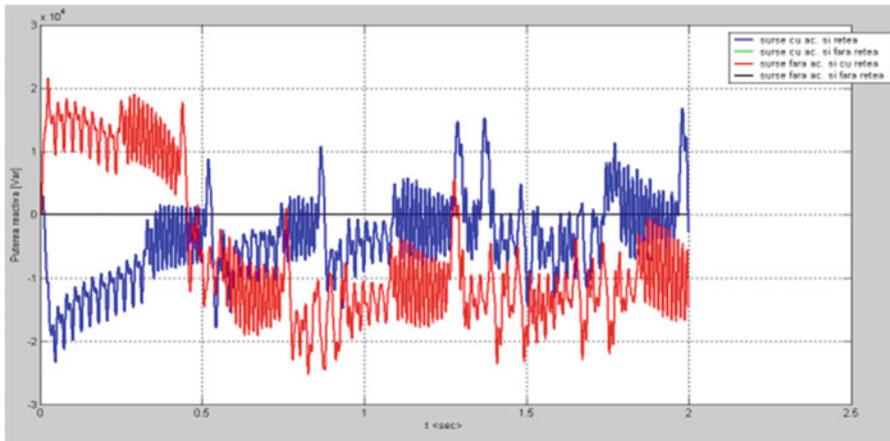
Fig. 6.10 Evolution of reactive power transit between the hybrid system based on renewable energy sources and the public network

seen that the power generated from renewable energy sources is employed for charging the force storage devices, for the consumers or to cover losses and also the surplus is injected to the local public network.

If the consumer is isolated, the presence of reactive power is due to nonlinear elements employed in the simulation model: power transformers and power converters based on electronic switching components, but is usually attributable to the highly nonlinear nature of the consumer as mentioned in Fig. 6.12. Confirmation in
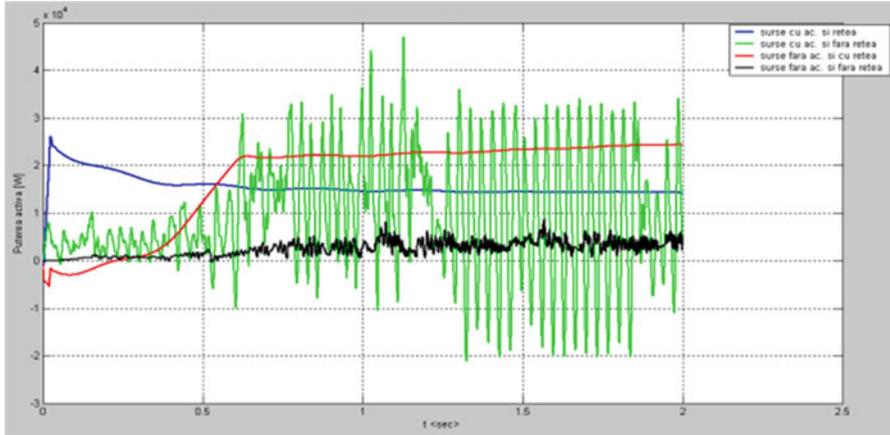
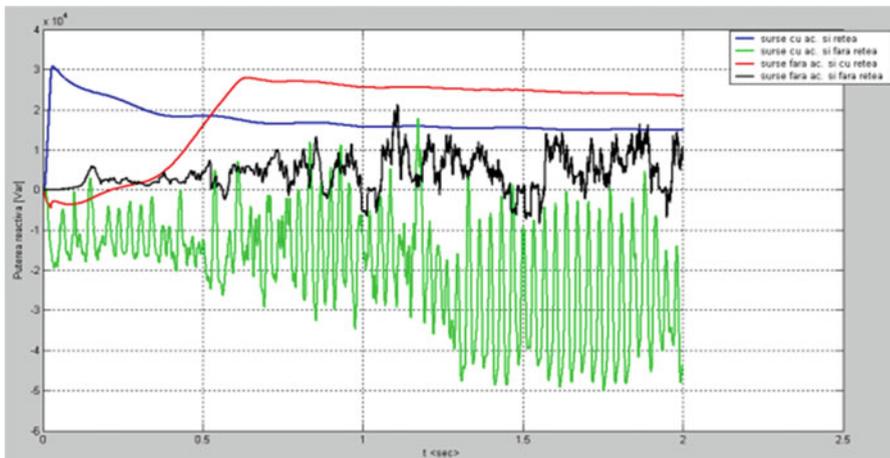**Fig. 6.11** Renewable energy sources active power variation

Fig. 6.12 Renewable energy sources reactive power variation

the above is shown in Figs. 6.13 and 6.14 that presents the active and reactive power
at consumer terminals.

This section presents a pretense model helpful for the study of small power
programs dependant on sustainable energy. To the simulation model advancement
an accumulation objects organized in a very new MATLAB/SIMULINK library
named RegenSim was created. The realized simulated model in line with the new
RegenSim selection is compatible and may be interconnected along with aspects of
the dedicated SimPowerSystems library that is used for power techniques function-
ing, simulation, acting and analysis. The particular simulation model in this partic-
ular section is quite useful in the present circumstances allowing research
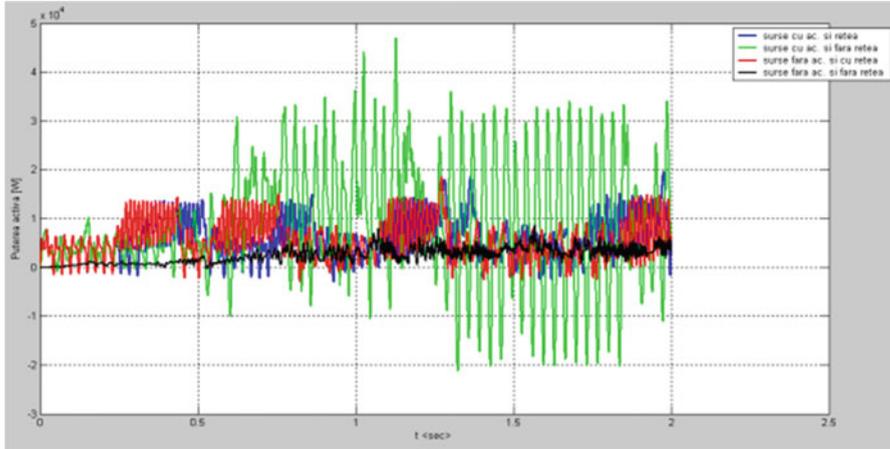
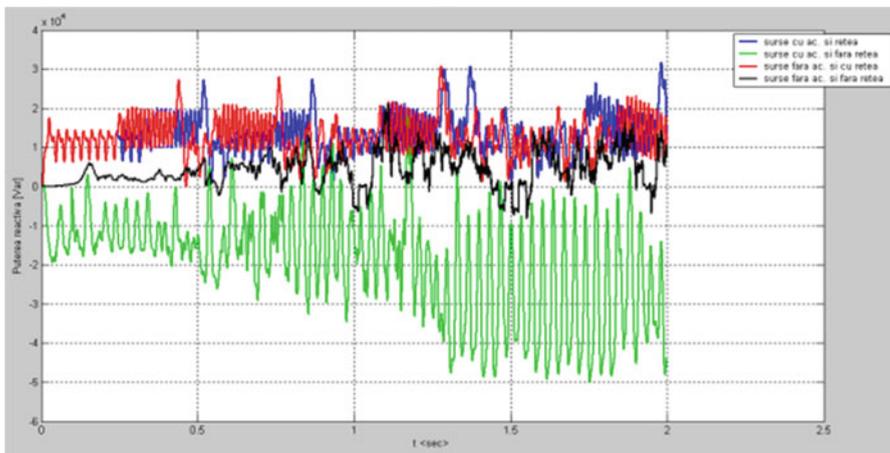**Fig. 6.13**   Consumer active power variation

Fig. 6.14   Consumer reactive power variation

considering the identification, any type of usage opportunity as well as the imple-
mentation for might systems dependant on renewable energies available within a
certain area. In order to exemplify this attribute the Mureş State area was thought to
be and performed a work with the appropriateness employing solar, wind along
with hydro resources available here. Other significant studies allowed because of
the developed simulation product consider steady or passing regimes, using the
potential for active and responsive power flowing progress.

6.3   Hybrid Model of Solar PV and Wind Energy System Using Cuk-Sepic Converter

Power supply system all over the world is facing challenging situations where they have to be extremely flexible, reliable and expandable. Existing grids have to be modified due to the growing proportion of distributed and renewable energy sources. Power electronic inverters are the key components to couple different energy conversion systems and to manage their operation. To fulfill the changing demands of the growing smart grid needs, new concepts for inverter design are needed. In this section an innovative concept for future oriented power systems – the modular inverter design – is detailed. A modular inverter design is presented for a modern power system which inputs power from both AC and DC Renewable resources. The Converter is the combination of Cuk-Sepic converters, the input from the source can be either buck or boosted or stabilized at the particular value, the inductor in circuit further provides the function of filter reducing Harmonics. The Inverter is the combination of two kinds of Inverters and it supports both symmetric and asymmetric loads. System works on the presence of both or any one of the Renewable resources, Furthermore; existing systems can be changed, rescaled and expanded easily. The system senses the load (symmetric or asymmetric) and switches between the Inverters (Three leg inverter or three leg inverter with Neutral point) according to the loads.

Due to the increasing awareness about climate change and global warming, the research in the electrical energy sector is geared towards making use of renewable energy sources (RES) for electricity generation. The renewable energy system can be constructed as a stand-alone system for the domestic applications or grid-connected system to supply the AC power to utility system. Both Solar and wind energy sources have great potential for power generation. The Photovoltaic (PV) and fuel cell systems generate DC power which needs to be converted to single- or three-phase AC for utility connection. The wind, micro-turbine systems generate variable frequency AC output which needs to be converted into 50/60 Hz AC for the utility connection.

The Wind and Solar energy systems are highly unreliable due to their unpredictable nature. None of these are available round the clock. Thus hybridizing solar and wind power sources provide a more reliable source of power generation. When any of the two sources is unavailable or insufficient in meeting the load demands, the other energy source can compensate for the difference. The main requirement of power electronic interfaces for the PV systems is to convert the generated DC voltage into a suitable AC for consumer use and utility connection.

6.3.1   Objectives

Several hybrid Wind/PV power systems with Maximum Power Point Tracking (MPPT) control have been proposed earlier. A separate DC/DC buck and buck boost converter connected in fusion with the rectifier stage has been used to perform the MPPT control for each of the renewable energy power sources. Most of the systems uses boost converter for this purpose. In this project, a Cuk-SEPIC converter for grid connected PV/Wind hybrid system has been used. MPPT control of PV source is implemented on Cuk converter. The Cuk-SEPIC fused converters have the capability to eliminate the high frequency current harmonics. So no additional input filters are needed. Fusion of Cuk-SEPIC converter works well for individual as well as for simultaneous operation.

6.3.2   Hybrid Power System

Hybrid Power System (HPS) is to provide an economical and sustainable power for the rural electrification. HPS use a combination of non renewable energy sources like fossil fuel, nuclear energy or a combination of renewable energy sources like solar and wind energy. This is clean and abundantly available in nature. The advantages over non renewable fossil fuel based power generation systems, such as low pollution, high efficiency. The Hybrid power system is classified as follows:

 (i) Stand alone/off-grid/islanding HPS (Fig. 6.15).
(ii) Grid connected HPS.

   The power units commonly used for PV panels (dc source), Wind Power (WP) and Diesel Generators (ac sources). Batteries are used for storage and backup. The control system for HPS configurations should minimize fuel consumption by maximising power by the variability of the renewable energy, which cause disturbances that can affect the quality of the power delivered to the load. The major constraint in the synchronization of the inverters and ac sources to maintain the voltage and frequency of the system. The undesired harmonics introduced into the system by the use of inverters increases the level of power quality problems. Both buses are connected through a bidirectional converter that permits power flow between two buses. This arrangement increases the system power reliability and supply continuity.

   In centralized ac bus Fig. 6.16a, the sources and battery are all installed in one place and are connected to a main bus bar before connecting to the grid. This system is centralized in the sense that the power delivered by all the energy conversion systems and battery is fed to the grid through a single point. In distributed ac-bus Fig. 6.16b, the power sources do need not be installed close to each other, and they do need not be connected to main bus. The sources are connected to the grid
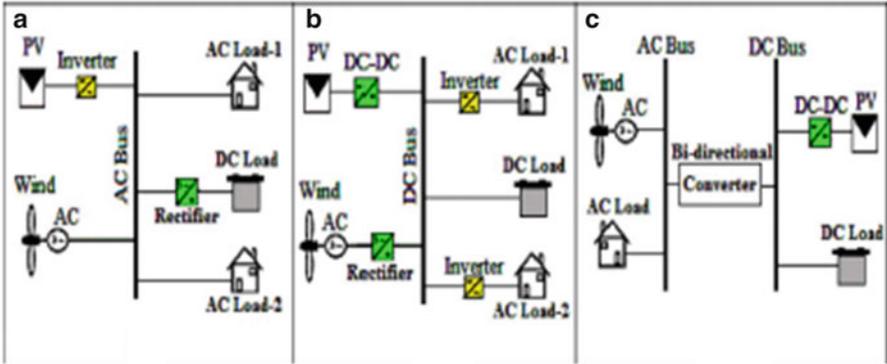
Fig. 6.15 Standalone HPS (**a**) DC sources needed to have an inverters to convert dc to ac before connecting to ac bus. (**b**)AC sources needed to have rectifiers to convert ac to dc before connecting to dc bus. (**c**)The ac and dc sources and loads are connected to ac and dc bus
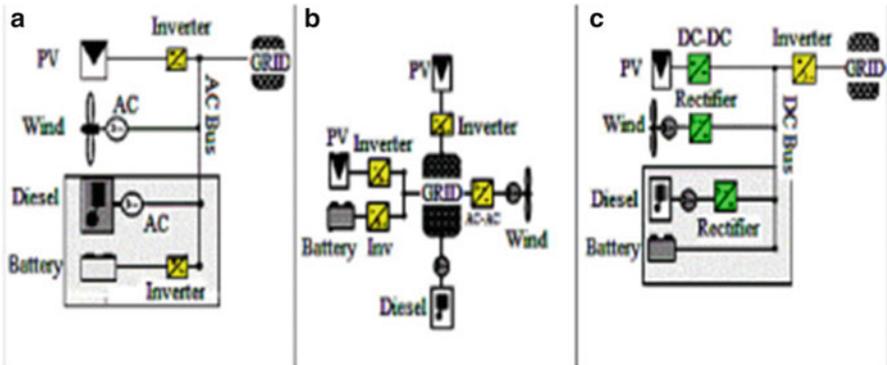
Fig. 6.16 GRID connected HPS

separately. The main drawback of this arrangement is the difficulty of controlling the system. The centralized ac-dc bus Fig. 6.16c utilizes a main centralized dc bus bar. So the energy conversion system that produce ac power, deliver to rectifiers to be converted into dc before connecting to the main dc bus bar. A main inverter takes the responsibility of feeding the ac grid from this dc bus.

6.3.3   Cuk: SEPIC Based Converter on Source Side

Hybridising solar and wind power sources provides a realistic form of power generation. A modular inverter is designed for a modern power system which inputs power from both AC (wind) and DC (solar) Renewable resources. The Inverter is the

combination of two kinds of Inverters and it supports both symmetric and asymmetric loads. System works on the presence of both or any one of the Renewable resources. The features of the presented topology are: (1) the inherent nature of these two converters eliminates the need for separate input filters for PFC (2) it can support step up/down operations for each renewable source (can support wide ranges of PV and wind input); (3) System works on the presence of both or any one of the Renewable resources; (4) individual and simultaneous operation is supported.

One of the inputs is connected to the output of the PV array and the other input connected to the output of a generator. The fusion of the two converters is achieved by reconfiguring the two existing diodes from each converter and the shared utilization of the cuk output inductor by the SEPIC converter. This configuration shown in Fig. 6.17 allows each converter to operate normally individually in the event that one source is unavailable. Figure 6.18 illustrates the case when only the wind source is available. In this case, $D1$ turns off and $D2$ turns on; the proposed circuit becomes a SEPIC converter. On the other hand, if only the PV source is available, then $D2$ turns off and $D1$ will always be on and the circuit becomes a Cuk converter as shown in Fig. 6.19.

In both cases, both converters have step-up/down capability, which provide more design flexibility in the system if duty ratio control is utilized to perform MPPT control. If the turn on duration of M1 is longer than M2, then the switching states will be state I, III. Similarly, the switching states will be state I, II, III if the switch conduction periods are vice versa. To provide a better explanation, the inductor current waveforms of each switching state are given as follows assuming that $d2 > d1$; hence only states I, II, III are discussed in this example. In the following, Ii, PV is the average input current from the PV source; Ii, W is the RMS input current after the rectifier (wind case); and Idc is the average system output current.
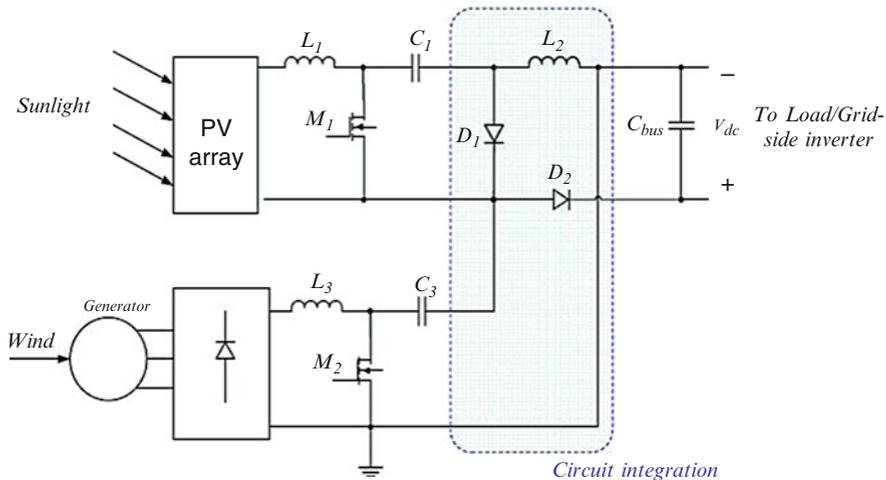

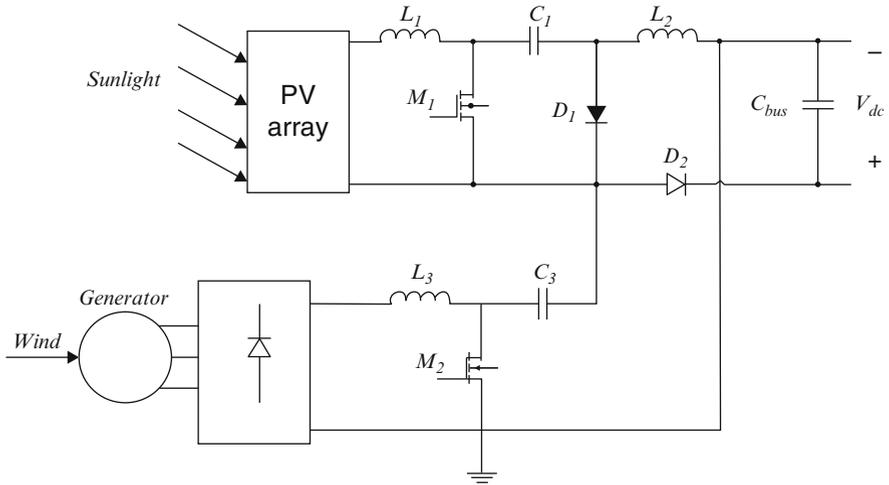Fig. 6.17   A system diagram of the proposed rectifier stage of hybrid energy system
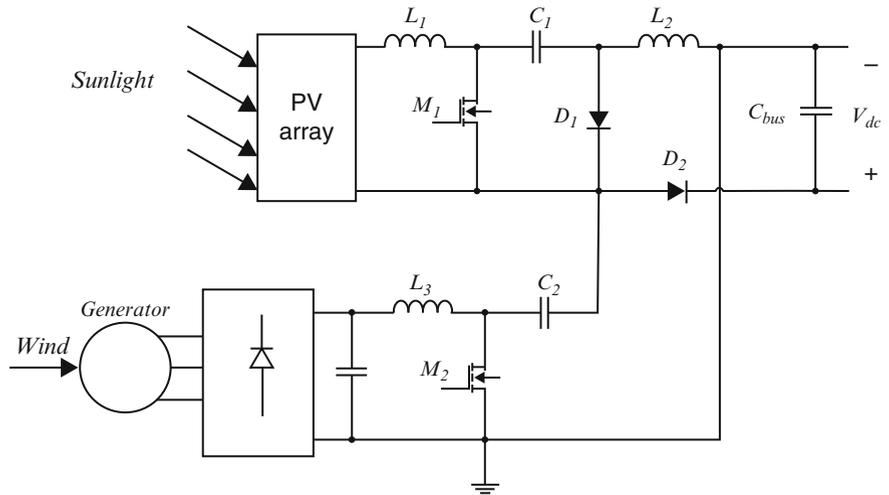
Fig. 6.18 SEPIC converter (wind source available)

Fig. 6.19 CUK converter (PV source available)

State I (M_1 on, M_2 on)

$$i_{L1} = I_{i,PV} + \frac{V_{PV}}{L_1}t \qquad 0 < t < d_1 T_s$$

$$i_{L2} = I_{dc} + \left(\frac{v_{c1} + v_{c2}}{L_2}\right)t \qquad 0 < t < d_1 T_s$$

$$i_{L3} = I_{i,W} + \frac{V_W}{L_3}t \qquad 0 < t < d_1 T_s$$

State II (M$_1$ off, M$_2$ on)

$$i_{L1} = I_{i,PV} + \left(\frac{V_{PV} - v_{c1}}{L_1}\right)t \qquad d_1 T_s < t < d_2 T_s$$

$$i_{L2} = I_{dc} + \frac{v_{c2}}{L_2}t \qquad d_1 T_s < t < d_2 T_s$$

$$i_{L3} = I_{i,W} + \frac{V_W}{L_3}t \qquad d_1 T_s < t < d_2 T_s$$

State III (M$_1$ off, M$_2$ off)

$$i_{L1} = I_{i,PV} + \left(\frac{V_{PV} - v_{c1}}{L_1}\right)t \qquad d_2 T_s < t < T_s$$

$$i_{L2} = I_{dc} - \frac{V_{dc}}{L_2}t \qquad d_2 T_s < t < T_s$$

$$i_{L3} = I_{i,W} + \left(\frac{V_W - v_{c2} - V_{dc}}{L_3}\right)t \qquad d_2 T_s < t < T_s$$

6.3.4   Model for Hybrid Wind and Solar Power Plant

The model of a hybrid wind and solar power plant is shown in Fig. 6.20.

6.3.5   Three Phase Uncontrolled AC-DC Bridge Rectifier

The three-phase AC-DC rectifier using six diodes is shown in Fig. 6.21. The diodes are arranged in three legs. Each leg has two series connected diodes. Upper diodes D1, D3, D5 are the positive group of diodes. The lower diodes D2, D4, D6 are the negative group of diodes. The positive group of diodes are conducted when the supply voltage is most positive anode. The negative group of diodes are conducted when the voltage is most negative anode. The output waveforms for the AC-DC bridge rectifier are shown in Figs. 6.22 to 6.24.

Conduction of Positive Group Diodes

Diode D1 conducts during the interval $\omega t = 30°$ to $150°$.
Va is more positive than the voltages Vb,Vc
Diode D3 conducts during the interval $\omega t = 150°$ to $270°$.
Vb is more positive than compared to Va,Vc
Diode D5 conducts during the interval $\omega t = 270°$ to $390°$.
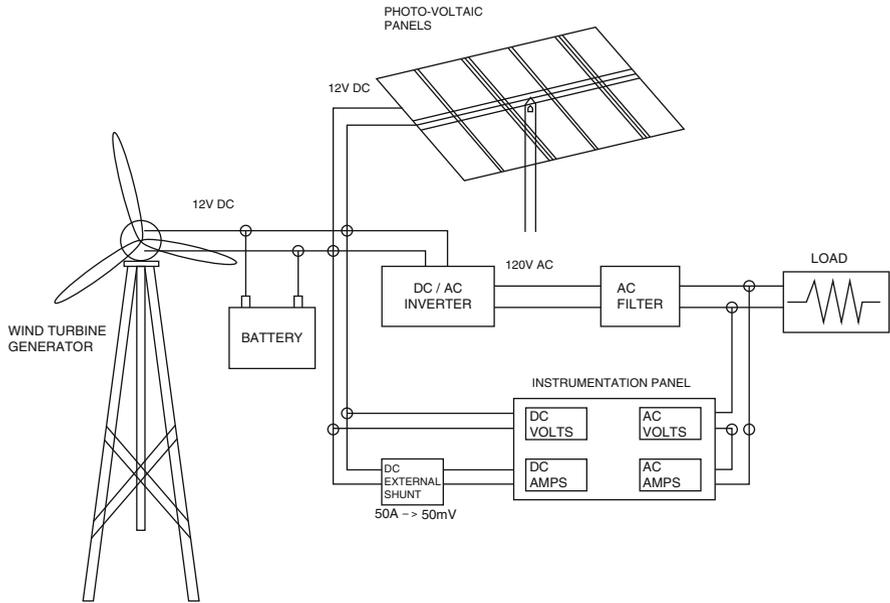Vc is more positive than the voltages Va,Vb

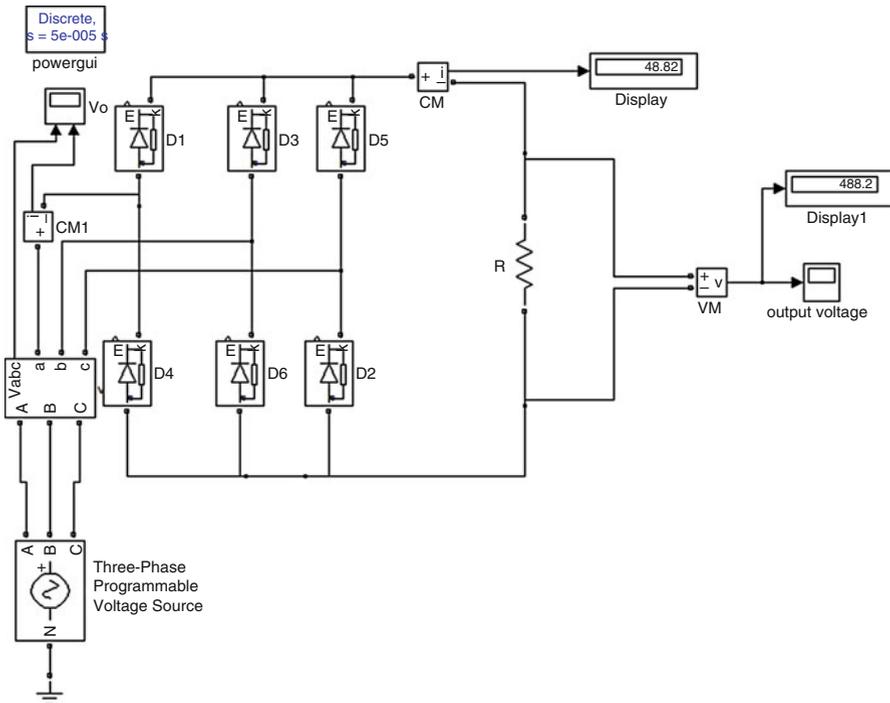**Fig. 6.20** Model representation of hybrid wind and solar power system

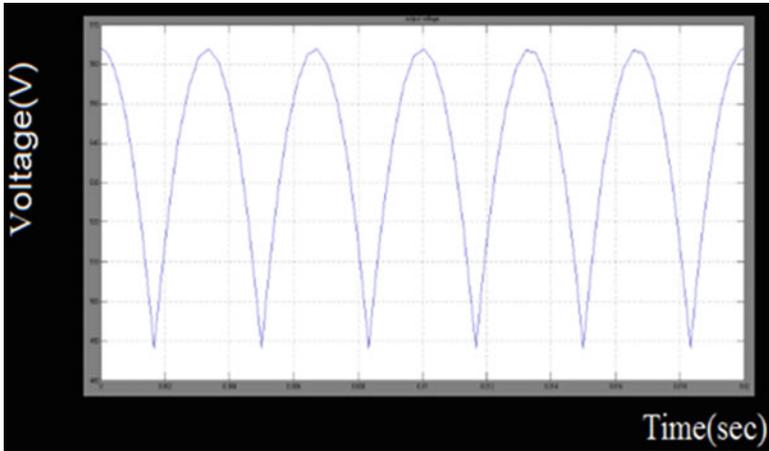**Fig. 6.21** Three phase uncontrolled AC-DC rectifier using MATLAB

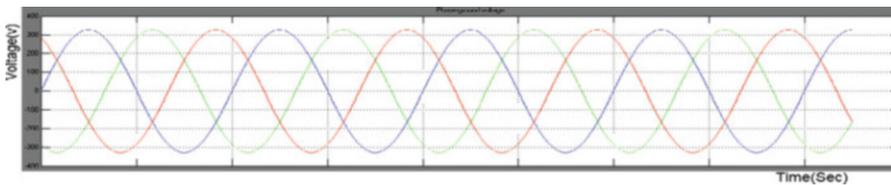**Fig. 6.22** Output voltage waveform for AC-DC bridge rectifier

Fig. 6.23 Phase to ground voltage waveform for AC-DC bridge rectifier
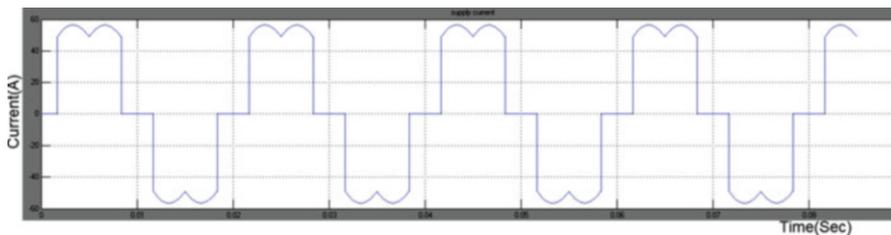

Fig. 6.24 Supply current waveform for AC-DC bridge rectifier

Conduction of Negative Group Diodes

Diode D2 conducts during the interval $\omega t = 90°$ to $210°$.
Vc is most negative than the voltages Vb,Va
Diode D4 conducts during the interval $\omega t = 210°$ to $330°$.
Va is more negative than compared to Vb,Vc
Diode D6 conducts during the interval $\omega t = 330°$ to $450°$.
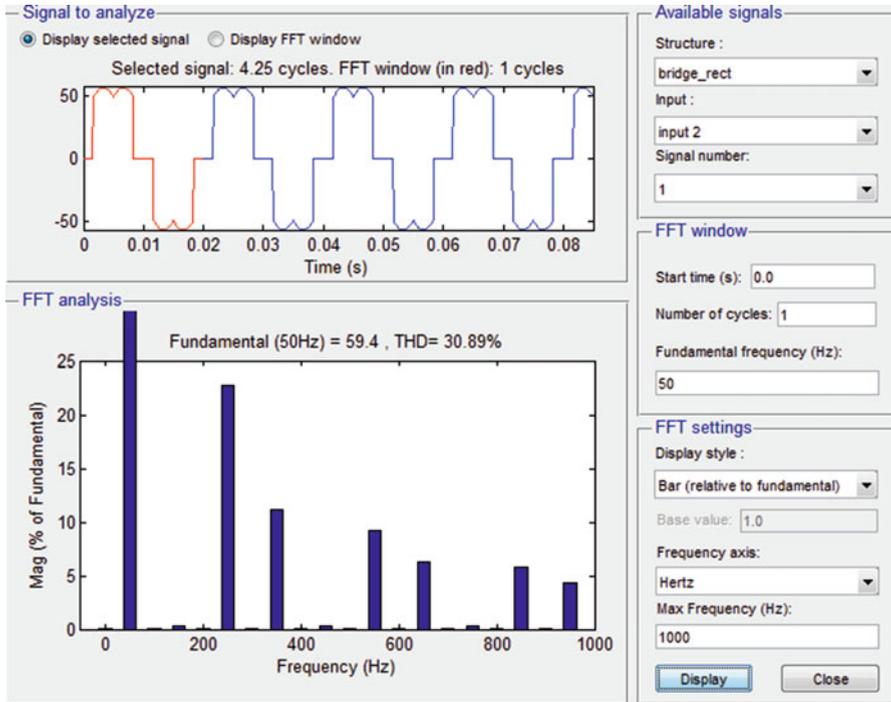Vb is more negative than the voltages Va,Vc

Fig. 6.25 THD analysis for AC-DC bridge rectifier

6.3.6   Total Harmonic Distortion

The first and foremost power quality parameter is the Total Harmonic Distortion (THD). The as the ratio of the sum of the squared individual harmonic amplitudes to the fundamental frequency (or) the root mean square (RMS) value of the total harmonics of the signal, divided by the RMS value of its fundamental signal. The signal can be a measured voltage or current as shown in Fig. 6.25.

6.3.7   Test Simulation and Results

The MATLAB/SIMULINK model of the wind power system using a permanent magnet synchronous machine is shown in Fig. 6.26. The parameters such as generator speed, pitch angle, wind speed, and the solar power system are set according to Table 6.1. Figure 6.27 represents the voltage waveform of the wind power model. The MATLAB/SIMULINK model of the solar power system, the parameters and their settings and the output voltage waveform are shown in Fig. 6.28, Table 6.2 and Fig. 6.29 respectively. In this hybrid model a cuk-sepic converter is used and its MATLAB/SIMULINK model is provided in Fig. 6.30. Table 6.3 provides the parameters and their settings for the cuk-sepic converter.
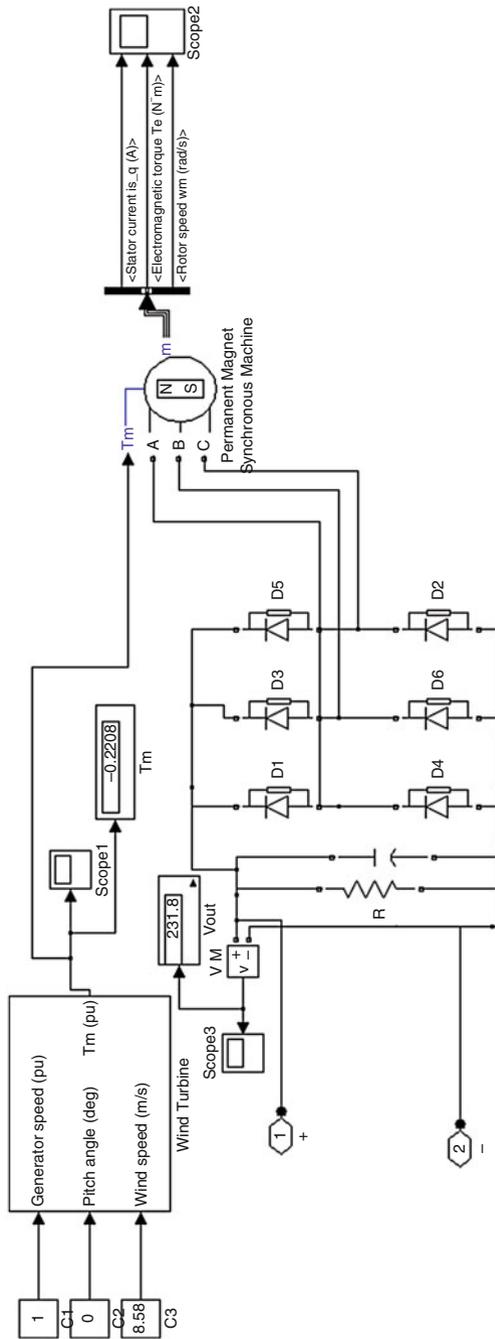
Fig. 6.26 Wind power system using MATLAB

Table 6.1 Parameters used in wind power system

Sl. No.	Parameters	Description
1	No. of bridge arms	3
2	Generator speed	1 (pu)
3	Pitch angle	0
4	Wind speed	8.58 (m/s)
5	Resistor	1k (Ω)
6	Capacitor	1000e-6 (F)
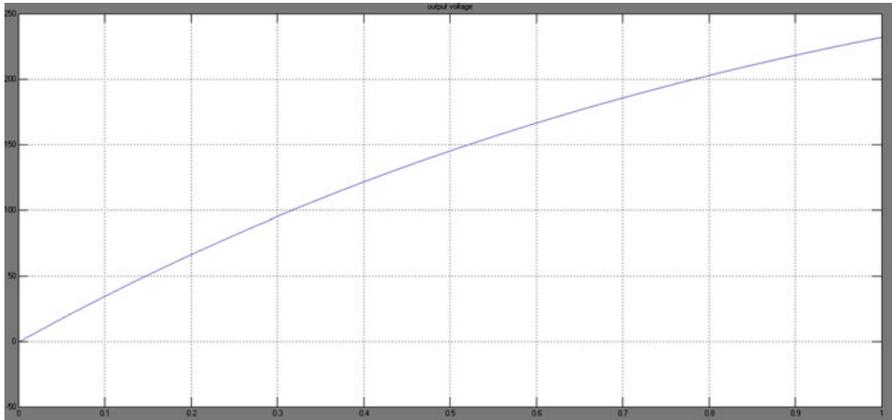
Fig. 6.27   Output voltage waveform for wind power system
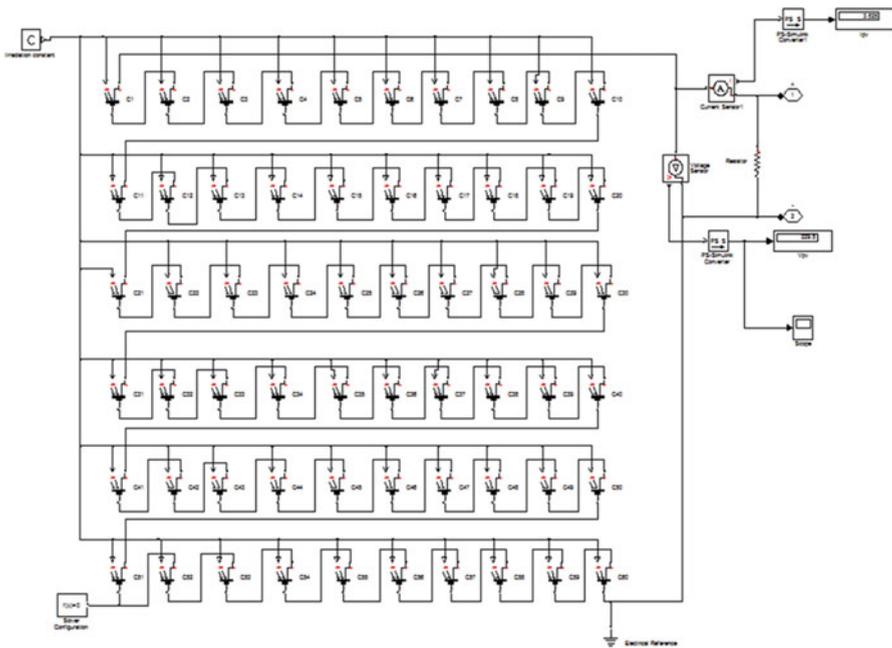
Fig. 6.28   Solar power system using MATLAB

Table 6.2 Parameters used in solar cell

| Sl. No.	Parameters	Description
1	Short circuit current (Isc)	7.65 (A)
2	Open circuit voltage (Voc)	3.86 (V)
3	Irradiance (Iro)	1,000
4	Quality factor (N)	7.5
5	Resistor (R)	60 (Ω)
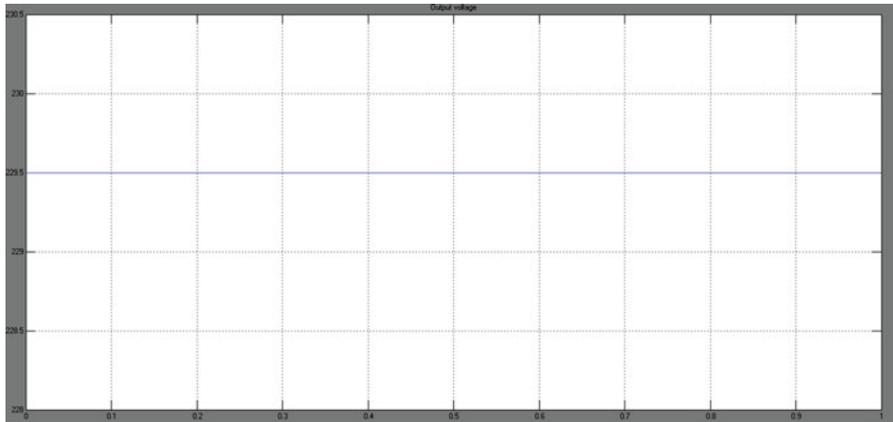
Fig. 6.29 Output voltage waveform for solar power system
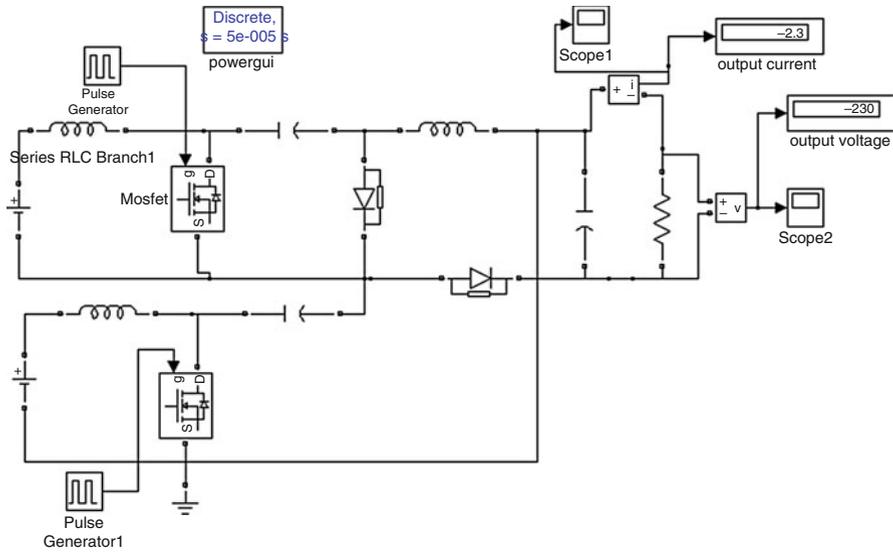
Fig. 6.30 Cuk-SEPIC converter

Table 6.3 Parameters used for cuk-SEPIC converter

Sl. No.	Parameters	Description
1	Pulse generator	–
2	Power electronic device	MOSFET, DIODE
3	Inductor	218e-6 (H)
4	Capacitor	1000e-6 (F)
5	Resistor	100 (Ω)
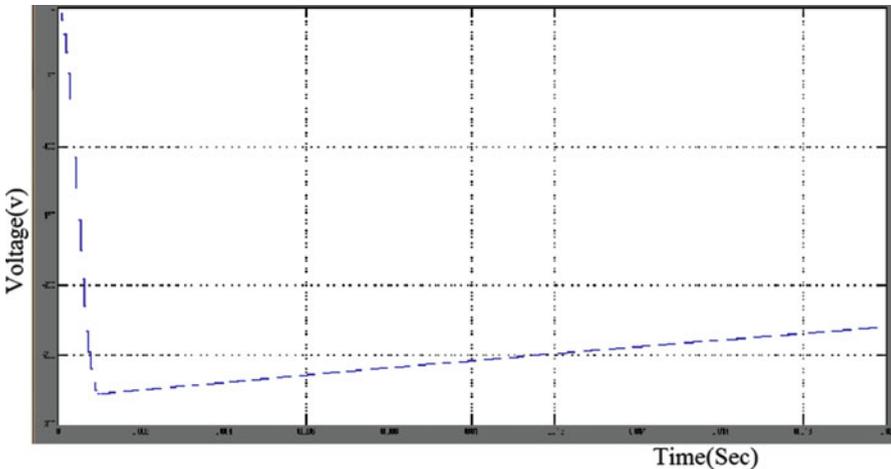
Fig. 6.31 Output voltage waveform for cuk-SEPIC converter

Here the two inputs are shown as taken from a dc source of 230 V each, but in practical condition they are the outputs from the wind and the solar which is shown in Figs. 6.31 and 6.32. In order to get the harmonics free output various carrier modulation techniques such as multiple pulse width modulation and single pulse width modulation is used in the inverter in the power system.

Thus the hybrid wind and solar power system is successfully done and the outputs are verified. The topology allows the two sources to supply the load separately or simultaneously depending on the availability of the energy sources. The output voltage obtained from the hybrid system is the sum of the inputs of the Cuk and SEPIC converters. Two PV arrays each of 5 kW is simulated in MATLAB/SIMULINK. PV 1 is the input to the Cuk converter and PV 2 is the input to the SEPIC converter. The converters are fused together by reconfiguring the two existing diodes from each converter and the sharing the Cuk output inductor by the SEPIC converter. This configuration allows each converter to operate individually in the event that one source is unavailable. MPPT has been realized to extract maximum power from PV source using perturb and observe (P&O) method.
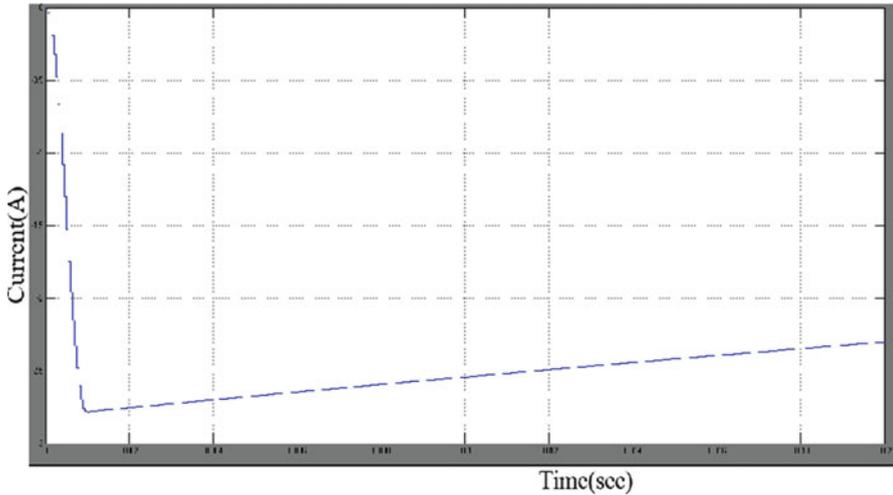
Fig. 6.32   Output current waveform for cuk-SEPIC converter

6.4   Hybrid Model of Solar PV and Diesel Energy System

6.4.1   Need for Solar PV Diesel Hybrid System

Over several areas of the world, power grids are either inadequate or non-existent. Due to this, industrial consumers usually ensure the availability of power all time using diesel gensets. Worldwide statistics have shown that 500 GW of power are generated from diesel gensets for electricity in industrial companies. In addition, fuel costs for the gensets continue to increase rapidly, due to the rising price of diesel. Moreover, if fuel has to be transported to remote regions, then the effective costs increase even more as a result of the necessary storage. In contrast, the cost for PV system has decreased more than 50 % during the last 5 years, hence proving to be the most economical alternate energy for remote regions throughout the world. Thus is it sensible to combine PV and diesel systems so that solar irradiation – which is both abundant and free – can profitably be used as an energy source in industrial applications. Besides, nearly 450,000 l of diesel can be saved per year and significantly reduce CO_2 emissions while using hybrid combination.

6.4.2   Photovoltaic Diesel Hybrid System

A "hybrid" is one approach that is modeled by combining two different components that develop the same or maybe similar results. A photovoltaic diesel hybrid system a mix of both system ordinarily is made up of PV system, diesel gensets and intense

management to be sure that the amount of solar energy fed into the technique exactly matches the demand at that instant.

6.4.2.1   Working

Fundamentally, the Photo voltaic system complements the diesel gensets. It might supply additional strength when loads are high or minimize the genset to minimize its fuel use. From the potential, excess energy may optionally be kept in batteries, making this practical for the actual hybrid system to utilize more solar might even at night time. Intelligent management of various system components guarantees optimal fuel economic climate and minimizes CO_2 emissions.

6.4.2.2   Advantages

In contrast to power supply systems using diesel gensets, and despite their higher initial cost, PV systems can be amortized in as little as 4–5 years, depending on the site and system size, and they have low operating costs.

In addition, PV systems are flexible and can be expanded on a modular basis as the energy demand grows. Compared to pure genset systems, a photovoltaic diesel hybrid system provides numerous advantages:

- Lower fuel costs.
- Reduced risk of fuel price increases and supply shortages, thanks to optimized planning.
- Minimal CO_2 emissions (protects the environment and facilitates CO_2 certificate trading).

6.4.3   Components of the Photovoltaic Diesel Hybrid System

6.4.3.1   PV Inverters

Inverters would be the central components and are designed specifically for use in weak utility grids, they may be well suited for high profile and frequency fluctuations. In addition they remain extremely productive in harsh ambient conditions, including heat, moisture and salty air, a few. A centralized PV system contains one string right into a central point, where DC is converted to alternating electric current. In a decentralized PV system, the PV power is put into many strings, which can be converted to AC by a few inverters. The selection between a centralized or decentralized system is dependent upon many factors. Both system installation costs and operating costs have to be considered. One example is, maintenance work on a decentralized strategy is not complicated, even in

inaccessible areas. If service is needed, local electricians can replace individual inverters. However, remote monitoring is very simple for just a centralized system structure.

6.4.3.2 PV Array

The solar energy is generated inside PV modules, which can be placed on the soil or on the roof, dependant upon local conditions. Inverters chosen must work with all PV module types and technologies available in the marketplace.

6.4.3.3 Diesel Genset

In grid-remote regions, pure diesel systems often provide the energy for industrial applications. They constitute the local grid, ensuring a constant power supply to all connected users. Because the gensets require a constant fuel supply, they are often the system's highest operating cost. In regions with weak utility grids, diesel gensets often serve as a backup during grid power outages.

6.4.3.4 Genset System House

The Genset consists of the monitoring and control systems required for the working of the diesel gensets. The genset system home is the central terminal and point of common coupling.

6.4.3.5 Optional Storage Batteries

In order to increase the efficiency of the entire energy supply system, it is necessary to include a storage battery. During darkness, when solar irradiation is insufficient, the storage battery supplies the required energy, ensuring optimal hybrid system operation.

6.4.3.6 Industrial Loads

Application-specific load profiles, such as heavy-duty industrial loads for mining or processing raw materials as well as for agricultural use, are generally characterized by loads with high starting currents and widely fluctuating load curves. Intelligent system management ensures that generation and load are perfectly matched. It achieves constant system stability by reacting quickly to generation and load performance spikes, such as when a conveyor belt is turned on.

For industrial, large-scale loads in remote regions, complementing diesel gensets with photovoltaics is the ideal solution under the following conditions:

1. When the effective cost of diesel increases.
2. When intelligent communication between the genset and PV systems facilitates demand-oriented use of PV power.
3. When local solar irradiation conditions allow the use of PV.

6.4.4   MATLAB/SIMULINK Model of Solar PV/Diesel Hybrid System

The hybrid model of solar PV and Diesel generator system is implemented using MATLAB/SIMULINK as shown in Fig. 6.33. The subsystem of the diesel generator and diesel engine are shown in Figs. 6.34 and 6.35. The user can simulate the model and analyze the results in terms of output voltage Va.

Photovoltaic diesel hybrid systems (MATLAB model is shown in Fig. 6.36) can be amortized especially quickly in sunny regions, with little or no grid access. For industries such as mining, raw material processing, agriculture (such as flower farms and water desalinization systems), and tourism (facilities with a high energy demand), low power generation costs, quick operational readiness, maximum reliability and availability are fundamental. The environmental benefits are also convincing: CO_2 emissions and noise pollution are significantly reduced, minimizing the environmental impact.

6.5   Fuzzy Logic Controller for Hybrid Power System

The wind and solar among the renewable resources are the most preferred option as they are readily available at all places and anyone can utilize it easily. Combining both the wind and solar forms a better option. This is because, if even one resource
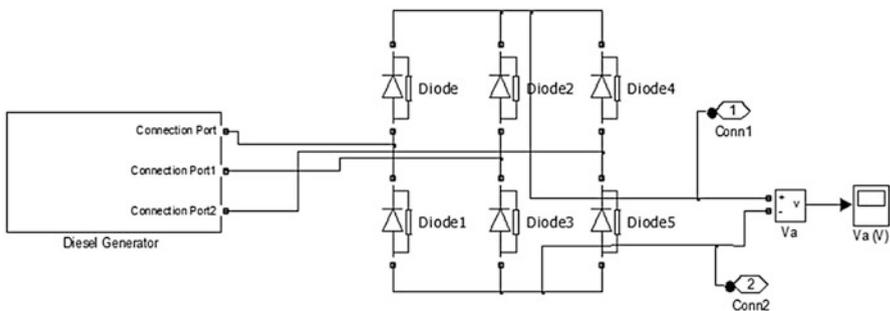

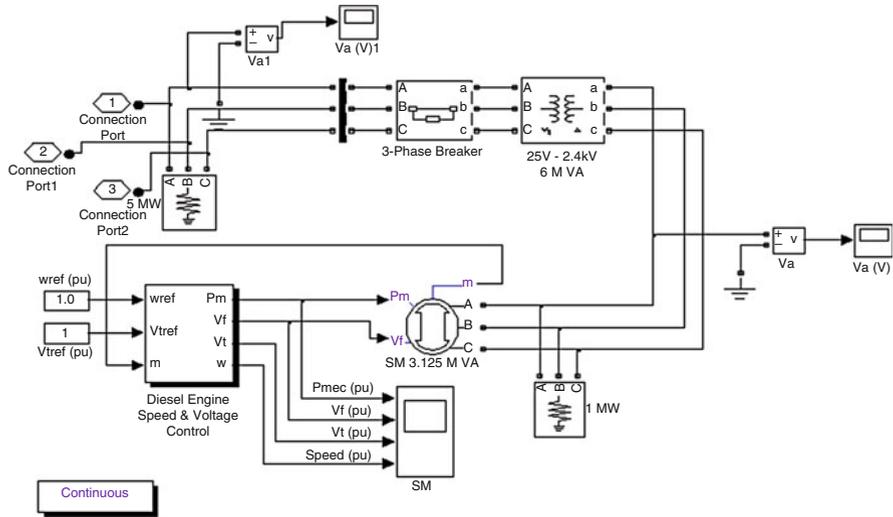**Fig. 6.33** MATLAB/SIMULINK model of diesel generator

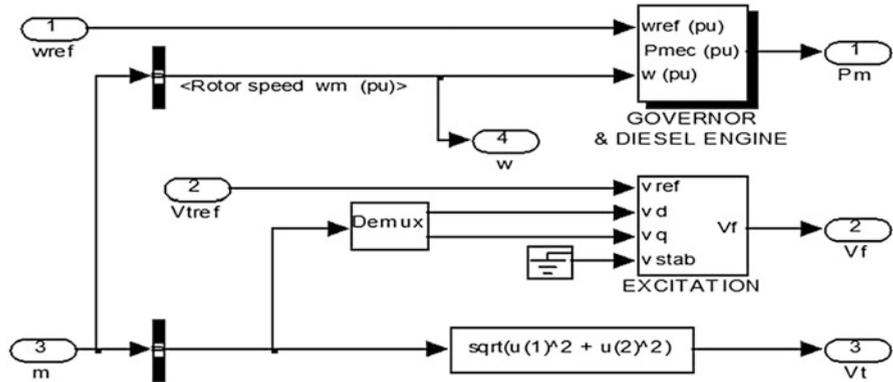**Fig. 6.34** Subsystem of diesel generator

Fig. 6.35 Subsystem of diesel engine

becomes less, we can manage the system with the other resource. But still the hybrid wind and solar energy system also requires a backup, as decrease in both the resources at the same time may happen. Usually a constant reliable source of supply is required with the renewable energy sources. The system can operate well on wind and solar energy and when there is a insufficient supply of wind and solar power, the batteries can provide power to the system.

Multi-source HPS with proper control has a higher potential for providing better quality and more reliable power to utilities than a system based on a single resource.
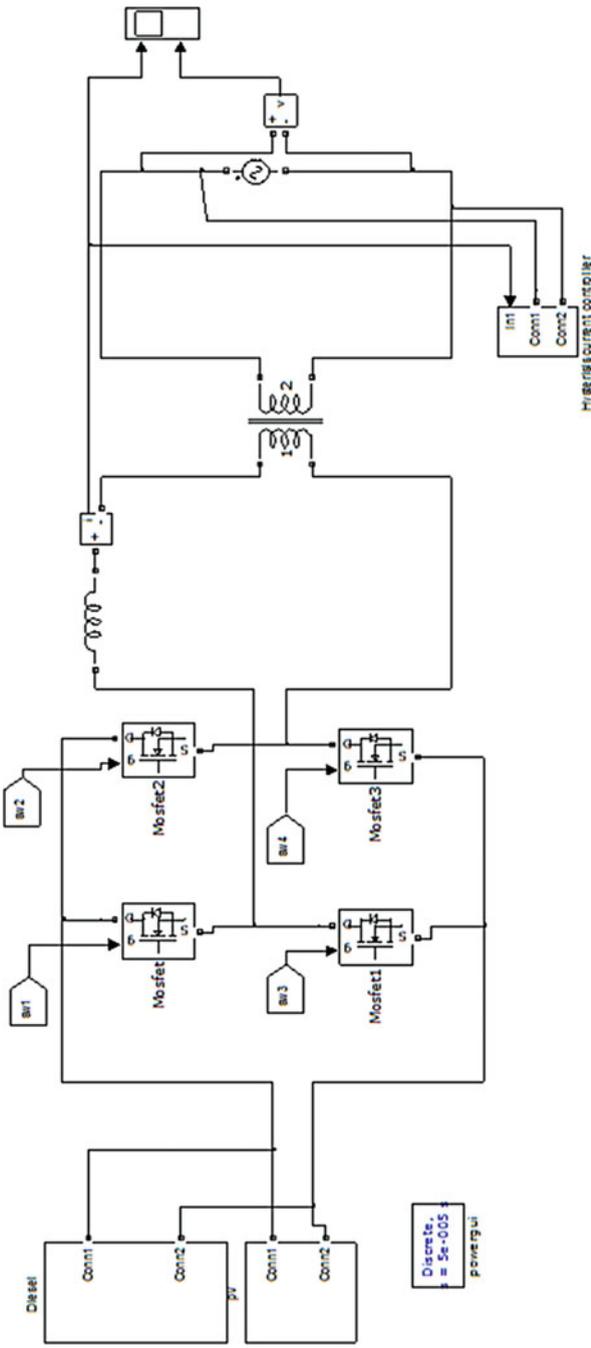
Fig. 6.36 Solar PV and diesel hybrid system

The hybrid system can be utilised to power individual domestic loads and the industries that require more power could be supplied from power stations. The wind generates an AC and a solar generates a DC. Therefore we need to convert any one power to the other so as to interconnect them. Here wind generated AC power is converted to DC with the help of rectifier and paralleled with solar energy system. Converting AC to DC is more preferred when boosting the voltage.

For any system there is a need of a controller. Controller is required so that the system becomes more reliable and stable. There is always a possibility that the voltage in the system may be fluctuating. Hence maintaining a constant voltage and frequency is required and hence a controller is required. The most commonly used controller is the Proportional Integral Derivative (PID) controller or a Proportional Integral (PI) control. But after the advent of fuzzy logic, FLC is preferred nowadays. FLC is compared to the conventional controllers are cheaper to develop and also cover a wider range of operating conditions. FLC allows for rapid prototyping because the system designer doesn't need to know everything about the system before starting and it can achieve steady state in a shorter time interval. A fuzzy controller can automatically refine an initial approximate set of fuzzy rules and hence a FLC is more preferred.

As both the wind and solar power are of fluctuating type, employing a FLC makes the system more reliable. Thus a constant DC voltage is obtained from the system. This DC power can be used to charge a battery or can be used to supply a DC load. The same can be inverted and can be supplied to an AC load also. Thus a hybrid wind and solar energy system which a load of 200 kW can be designed and implemented.

The objective of this section is designing a hybrid wind and solar energy system and controlling it by means of a FLC for domestic loads of about 100–200 kW. The main goal is to develop a new simple, cost-effective grid connected hybrid wind and solar power system. The developed system should also enable further enlargements with a less or no modification. A future expansion of the system should not put any constraints on the existing system. By doing so, a flexible design with high efficiency, and low cost is achieved. In more detail, the objective of this work is as follows:

1. Development of hybrid wind and solar power generating system.
2. Development of a controller for the overall system.

6.5.1 FLC for HPS

The modelling of Solar PV, Wind Turbine (WT), Fuzzy logic Controller (FLC), Inverter and the overall modelling of the system work done is explained in this section.
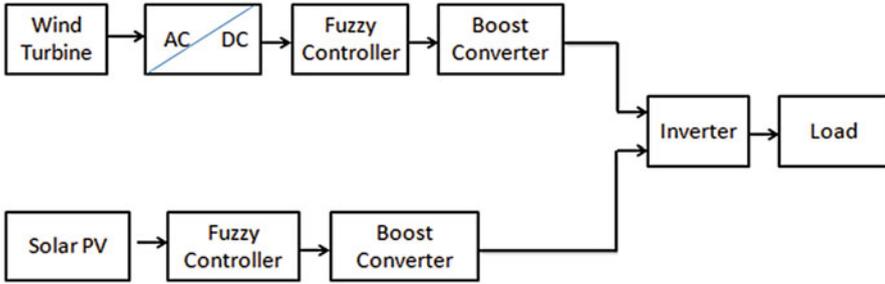
Fig. 6.37   Hybrid wind and solar power generation system

The overall system shown in Fig. 6.37 consists of a solar PV panel, Wind Turbine (WT), rectifier (AC-DC), battery, charge controller, Fuzzy logic controller (FLC), Inverter and loads. Individually the solar PV system and Wind energy system are controlled and their outputs are connected in parallel.

The output of the solar PV module is DC and the output of wind turbine is AC, before combining these two output of sources converted into any one of the source. Hence the output of wind turbine is AC is converted into DC by using rectifier. The fuzzy logic controller is introduced between rectifier, solar PV output and boost converter. FLC is used to maintain constant voltage and power throughout the system. The output of FLC is duty cycle which is given to the gate pulse of MOSFET switch which is used in boost converter.

6.5.2   Description of the Model

Initially a Solar PV is designed and is simulated in MATLAB/SIMULINK and analyzed. The Solar PV is then connected to a boost converter for getting the required output voltage. Then the Solar PV along with boost converter is connected to the FLC for getting a constant output voltage.

Similarly a Wind Turbine system is taken and analyzed. The Output from the WT is AC and hence is rectified and then boosted to the required level by means of a boost converter. Then this system is also connected to a FLC to get a constant output voltage.

Then both the Solar PV and the Wind Turbine system are connected together in parallel and the combined output is taken.

6.5.2.1   Equivalent Circuit of Solar PV Module

A solar cell (also called a photovoltaic cell) is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of photoelectric cells in that its electrical characteristics. e.g. current, voltage, or

Fig. 6.38 Equivalent circuit of solar cell
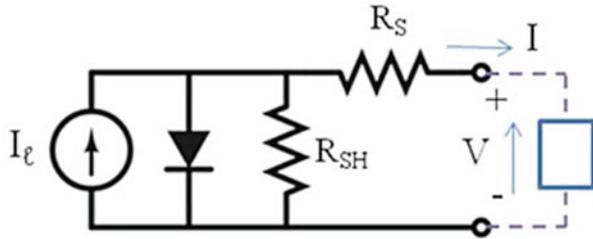
resistance vary when sunlight is falls on solar cell its generated charge carriers that produces electrical current without being attached to any external voltage source. The group of solar cell is called solar PV module. The amount of power generated by solar cell is very small. So, the cells are to be arranged in series and parallel to produce useful range of electrical power. The efficiency of solar PV depends on environmental and operating conditions such as irradiation and temperature.

A solar cell as a parallel combination of a current source, exponential diode and parallel resistor R_P, that are connected in series with a resistance R_S. The equivalent circuit of solar cell is shown Fig. 6.38. The solar PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array. The value of series resistance is very low and the shunt resistance value is infinity.

The output current of solar cell is given by,

$$\mathbf{I = Iph - Is * e\hat{\ }[(V + I * Rs)/(N * Vt) - 1]}$$

where

Iph – is the actual photon generated current (A)
Is – diode saturation current (A)
Rs – series resistance (Ω)
N – quality factor
Vt – thermal voltage (V)

The short circuit current I_{SC} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage is 0.

$$I \,(\text{at } V = 0) \;=\; I_{SC}$$

$$I_{sc} = \left\{ I_s \left[\exp\left(\frac{qV}{KT}\right) - 1 \right] - I_{ph} \right\} \text{ at } V = 0$$

The open circuit voltage (V_{OC}) occurs when there is no current passing through the solar cell, V (at I = 0) = V_{OC}

$$V_{oc} = \frac{K_B T}{q} \ln\left[\frac{I_{ph}}{I_s} + 1\right] \cong \frac{K_B T}{q} \ln\left[\frac{I_{ph}}{I_s}\right]$$

where

q – is the electron charge [$1.60217646 \times 0^{-19}$ C]
k – is the Boltzmann constant [$1.3806503 \times 10^{-23}$ J/K]
T – is the temperature of the p-n junction [K]

$$P_{MAX} = V_{MP} \times I_{MP}$$

P_{MAX} is the maximum power (W)
V_{MP} is the Array voltage at maximum power point (V)
I_{MP} is the Array Current at maximum power point (A)

6.5.2.2   WECS

The Inputs to the wind turbine are,

1. The generator speed in per units is 1.p.u.
2. The pitch angle is chosen to be zero.
3. The wind speed is chosen to be 12 m/s.

The pitch angle is the angle at which the wind turbine blade surface contacts the wind. It's chosen to be zero for our convenience. The output of Wind Turbine is mechanical torque (Tm).

The output power of wind turbine is given by the following equation,

$$P_m = \frac{C_p(\lambda, \beta).\rho.A.v^3}{2}$$

where

P_m – mechanical output power of the turbine (W)
C_p – performance coefficient of the turbine
ρ – Air density (kg/m^3)
A – turbine swept area (m^2)
β – blade pitch angle
λ – tip speed ratio of the rotor blade tip speed to the wind speed

The output waveform from the PMSG is an Alternating Current (AC) output waveform. The Alternating output is rectified using a rectifier. A high value of resistor is connected between the PMSG and the rectifier circuit. The rectifier used is a basic diode bridge rectifier. The rectified voltage is again boosted and controlled by means of a FLC.

Fig. 6.39 Schematic diagram of boost converter
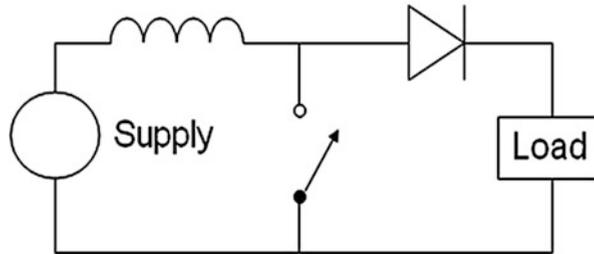
The output of wind power is ac, which is given to the input of the uncontrolled bridge rectifier. The wind turbine output is given to the permanent magnet synchronous machine. The rectifier is used to convert ac into dc. The Permanent Magnet Synchronous Machine operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque (positive for motor mode, negative for generator mode).

6.5.2.3   Three Phase Uncontrolled AC-DC Rectifier

The three-phase AC-DC rectifier using six diodes. The diodes are arranged in three legs. Each leg has two series connected diodes. The upper diodes are the positive group of diodes. The lower diodes are the negative group of diodes. The positive group of diodes are conducted when the supply voltage is most positive anode. The negative group of diodes are conducted when the voltage is most negative anode.

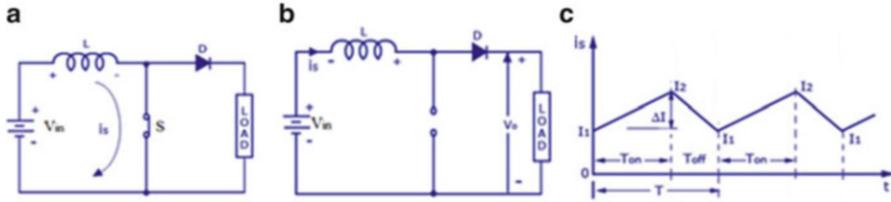### 6.5.2.4   Boost Converter

A boost converter, also called a step-up converter, is a DC-DC power converter with an output voltage greater than its input voltage. It is a class of Switched-Mode Power Supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple.

Power for the boost converter can come from any suitable DC sources, such as batteries, solar panels, rectifiers and DC generators.

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in Fig. 6.39.

When the switch is ON, inductor stores energy and current through the load would increases from I_1 to I_2 as shown in Fig. 6.40. With switch ON, the source voltage is applied to inductor, $V_L = V_{in}$.

When the switch is OFF, the output stage receives energy from the inductor as well as from the input. The inductor current cannot comes down instantaneously;

Fig. 6.40 Boost converter operation

this current is forced to flow through the diode and load for a time T_{off}. As the current tends to fall from I_2 to I_1 and polarity of the emf induced in L is reversed. As a result voltage across the load exceeds the input voltage which is given by, $V_o = V_{in} + L\frac{di}{dt}$.

Design of Boost Converter
$V_i = 25$ V, $V_0 = 90$ V, $f = 20$ KHZ

1. **Duty cycle, D = 1-(Vs/Vo)**

   D = 1-(25/90)
   D = 0.7

2. **Ripple current, ΔIL $= \frac{VS * D}{Lf}$**

   ΔIL is 1 % of load current
   ΔIL = 0.01

3. **Inductance, L $= \frac{VS * D}{\Delta IL * f}$**

   L = 0.011H

4. **Ripple voltage, ΔVc $= \frac{I0 * D}{cf}$**

   ΔVc is 2 % of output voltage
   ΔVc = 0.02

5. **Capacitance, C $= \frac{I0 * D}{\Delta VC * f}$**

   C = 60uF

6.5.3   Implementation in MATLAB

6.5.3.1   Solar PV System

The Solar panel as per our requirement is designed in MATLAB. The MATLAB simulated model of the PV panel is shown in the Fig. 6.41.
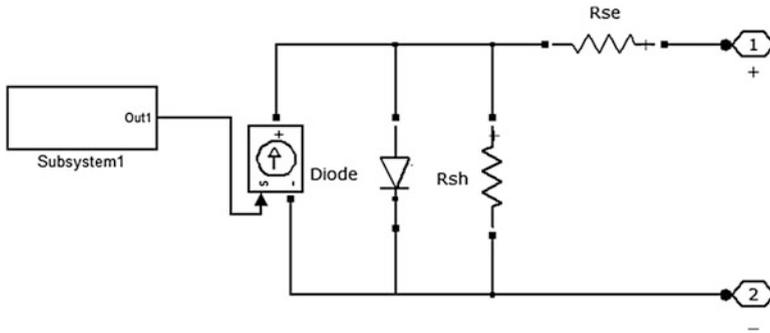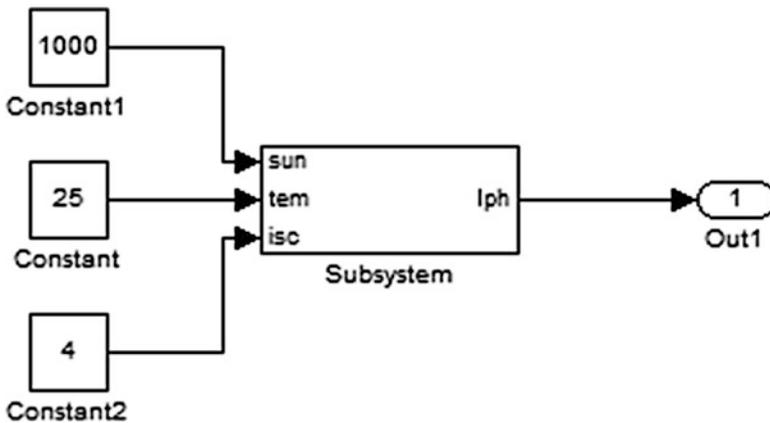
Fig. 6.41 Simulation model of the single PV cell

Fig. 6.42 Subsystem of the solar PV cell

The PV panel that is simulated has a subsystem connected to it. The solar irradiation, temperature and short circuit current are given as input to subsystem and current is taken as output from the subsystem. This current is given to the controlled current source which is connected to an inverted diode and two resistors one connected in parallel and other in series in the circuit as shown in the Fig. 6.41.

The value of the shunt resistance connected in parallel to the cell is selected as 1,000 Ω and the value of series resistance connected in series with the solar cell as 0.001 Ω.

The constant 1,000 given as input to the sun is the irradiation considered in W/m^2. The constant 25 given to the input term in Fig. 6.42, is the temperature considered in deg Celsius. The Constant 4 is the short circuit current of the solar PV. The subsystem of Fig. 6.41 is shown in Fig. 6.42.

The irradiation of 1,000 W/m^2 and temperature of 25 °C is considered to be standard testing condition. The system is simulated with various range of resistors
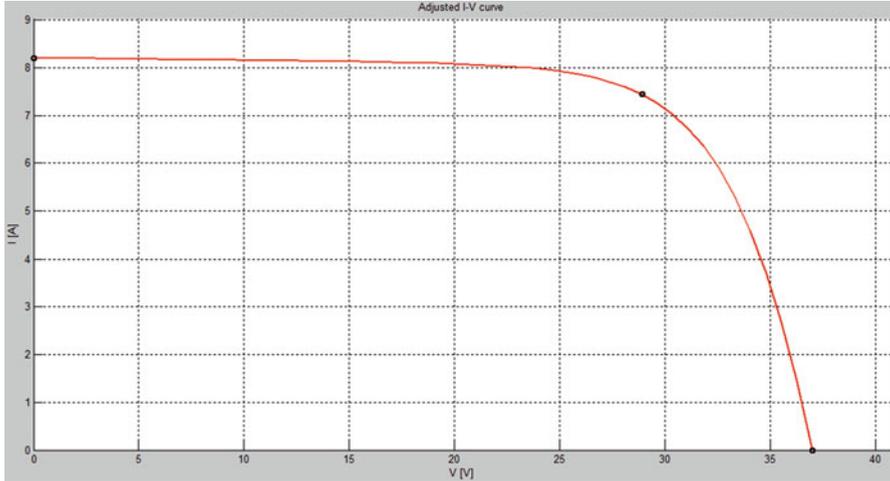
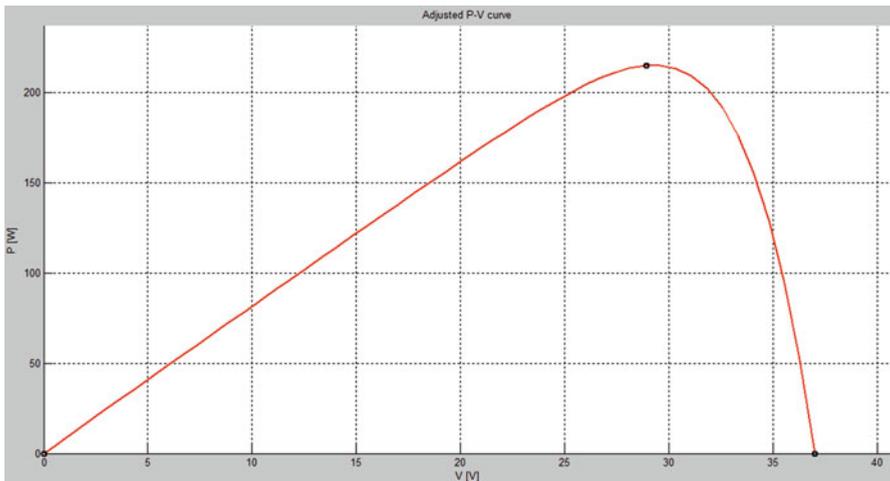**Fig. 6.43** I-V characteristic of single solar PV module

Fig. 6.44 P-V characteristic of single solar PV module

connected to it, in this condition. A single solar PV module parameters values are written in MATLAB M-File coding and get the following output characteristics.

The I–V characteristic of the photovoltaic device depends on the internal characteristics of the device (R_s, R_p) and an external influence such as irradiation level and temperature.

When the voltage and the current characteristics are multiplied we get the P-V characteristics as shown in Fig. 6.44. The Maximum Power Point (MPP) is the point at which the panel power output is maximum.

Fig. 6.45 WT subsystem
used in wind energy system
simulation

Generator speed (pu)	
Pitch angle (deg)	Tm (pu) >
Wind speed (m/s)	
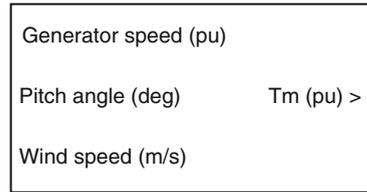
6.5.3.2 WECS in MATLAB

Initially a Wind Turbine (WT) system is simulated in MATLAB/SIMULINK and
output is analyzed. An inbuilt wind turbine is taken from MATLAB and the output
torque of the wind turbine is connected to a Permanent Magnet Synchronous
Generator (PMSG). The inbuilt function of WT used is shown in Fig. 6.45.

6.5.3.3 Fuzzy Logic Controller (FLC)

The mathematical system that analyzes analogue input values in terms of logical
variables that take on continuous values between 0 and 1, in contrast to classical or
digital logic, which operates on discrete values of either 1 or 0. A fuzzy can deal
with non-linearity and more robust than conventional logic controller.

FLC can be classified into four steps:

1. Fuzzification
2. Membership Functions
3. Rule base
4. Defuzzification

Fuzzy inputs are error (E) and change in error (CE), the output is duty cycle (D). FIS
editor is shown in Fig. 6.46. The corresponding rule base is provided in Table 6.4.

The Output from the FLC is compared with a repeating sequence of 5 kHz
frequency. The compared output is given to the MOSFET of the boost converter
which is connected to the system and the output voltage is accordingly boosted as
required.

6.5.3.4 Simulation of Photo-voltaic Array for Different Atmospheric Conditions

The single solar PV module consists of series and parallel solar cell, which is used
to increasing the voltage and current. The maximum current is given to the input of
a current controlled source. The output power of solar PV is 100 kW.

The PV array results can be varied according to the different atmospheric
conditions such as constant irradiation and varying temperature. The value of
constant irradiance is 1,000 (W/m^2) and temperature varying from 20 to 70 (K).
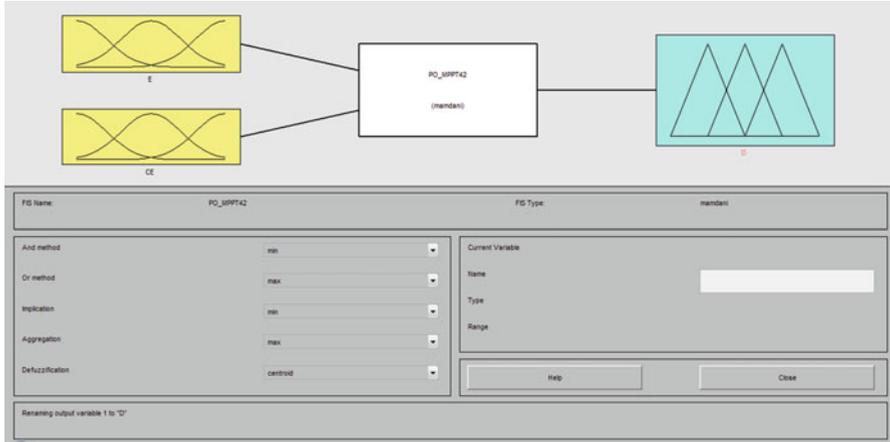
Fig. 6.46 FIS editor

Table 6.4 Fuzzy rule table

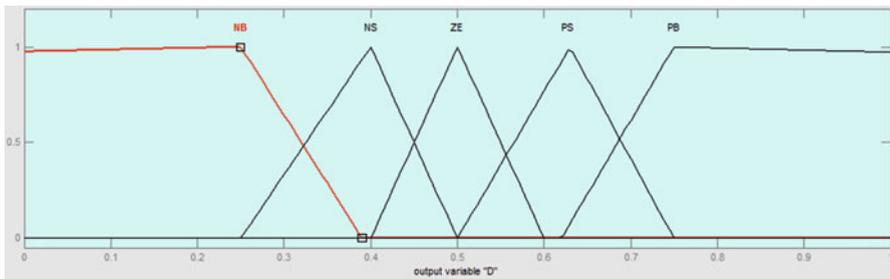| CE	E				
	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NS	NB	NB	ZE	ZE

Fig. 6.47 FLC output

Inference The output voltage of PV module is gradually increasing and output current and Power is varied according to the constant irradiance and changing temperature.

The solar PV module contains 250 series cells and 100 parallel cells. A single solar cell has the voltage of 0.5 V and has the short circuit current value is 8A, which produces the power of 4 W. The total power produced by solar PV module is 100 kW due to the radiation of 1,000 W/m^2 and the temperature of 25 °C.
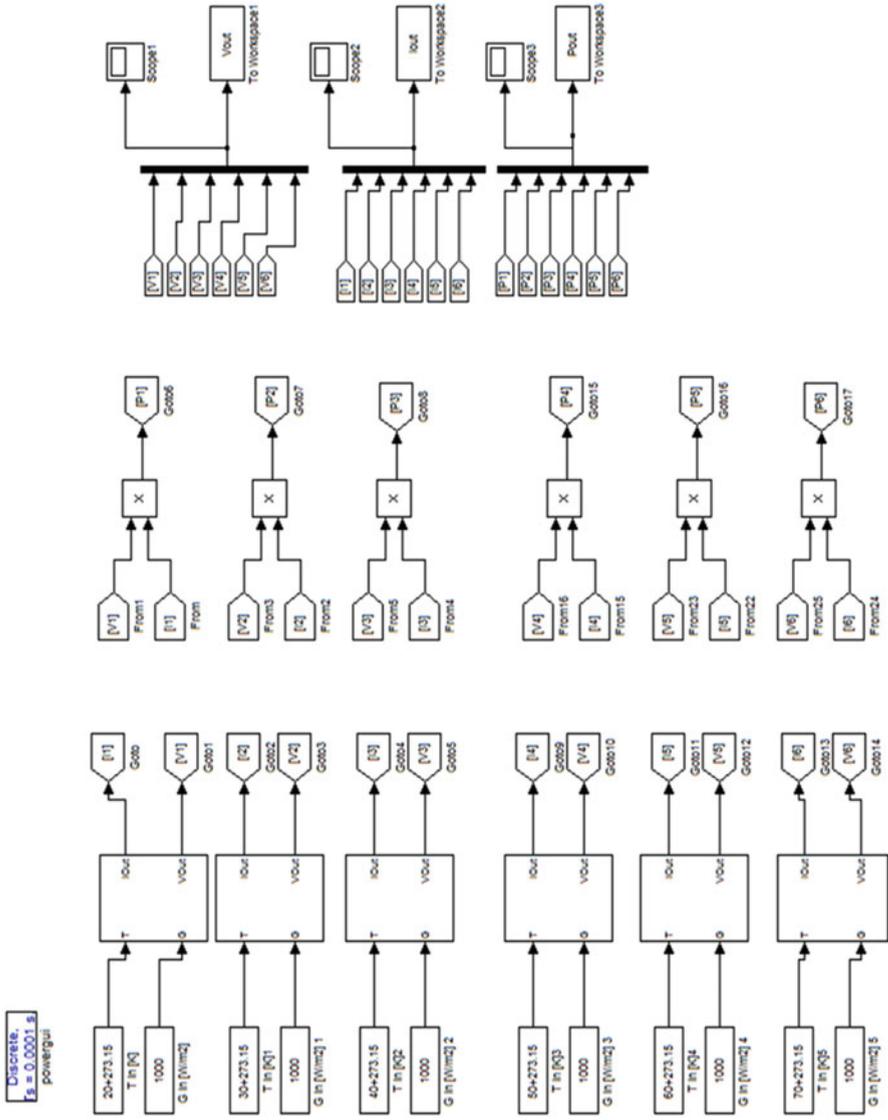
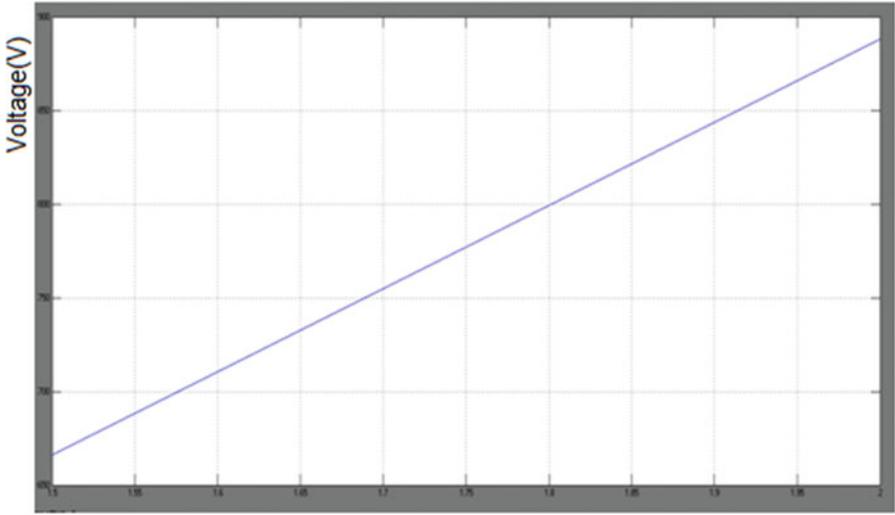**Fig. 6.48** Simulation of PV array for different atmospheric conditions

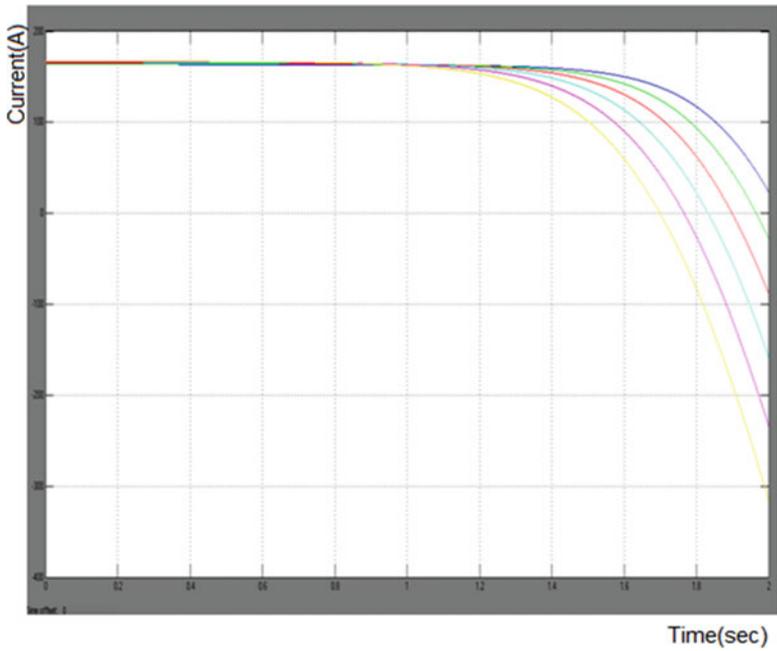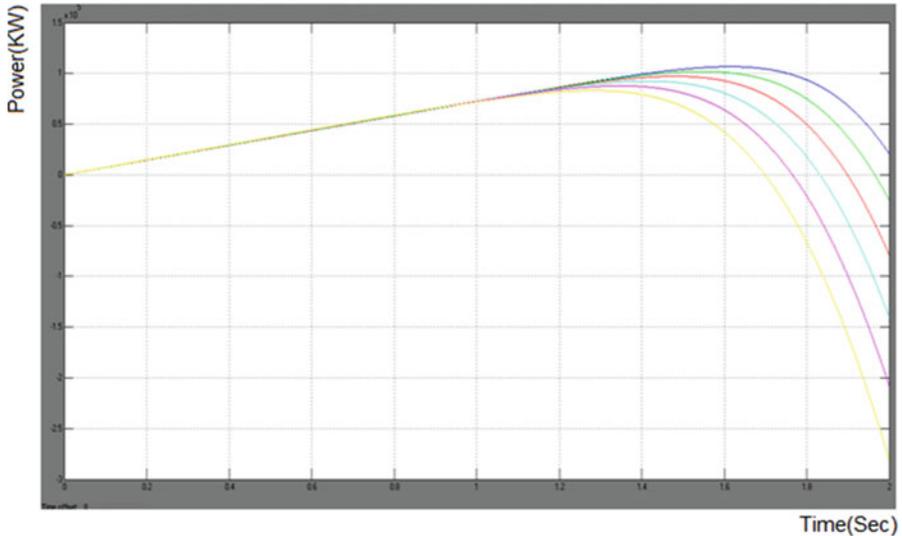**Fig. 6.49** Output voltage of single PV module

Fig. 6.50 Output current of single PV module

Fig. 6.51 Output power of single PV module

Inference The Output power of solar PV module can be varied according to the different values of radiation and fixed PV panel temperature.

Inference The input voltage is increased from 25 to 90 V. The output voltage is greater than that of an input voltage.

6.5.3.5   AC-DC Rectifier

The input supply ac source is converted into dc using rectifier. The three phase uncontrolled ac-dc rectifier using six diodes.

The first and foremost power quality parameter is the Total Harmonic Distortion (THD). The ac-dc rectifier supply current waveform is distorted. THD analysis can be done for one cycle.

The output of WT is given to an input of PMSG. If the output of mechanical torque is negative the PMSG works as generator and if the torque is positive the PMSG operating in motor mode. The ac is converted into dc by using rectifier.

Inference The output power of wind energy system is fluctuated. So the controller is needed to maintain the output voltage and power.
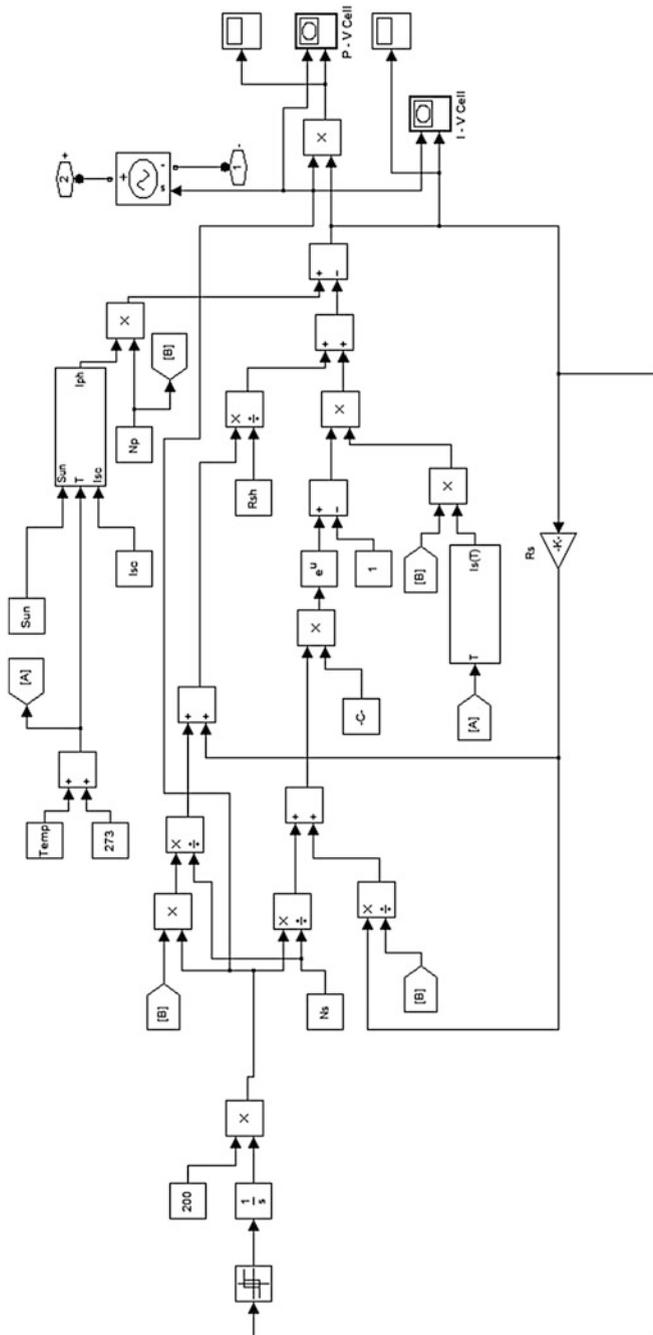
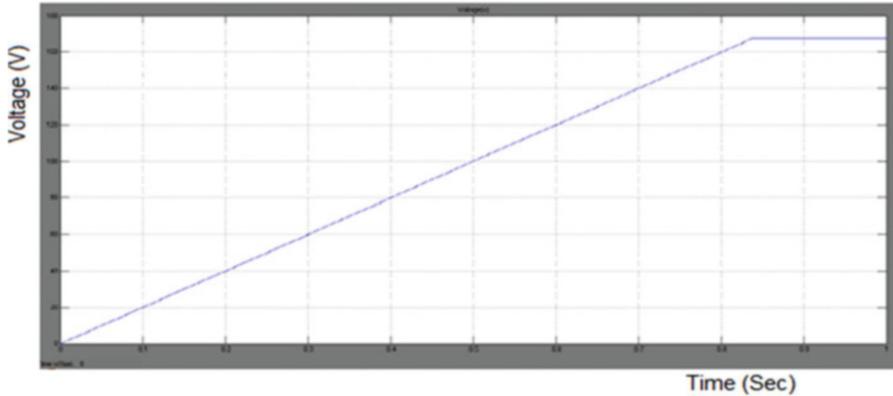**Fig. 6.52** Simulation of solar PV module
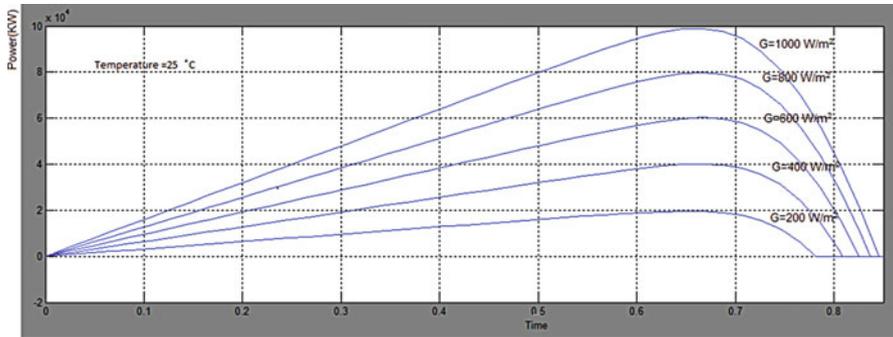
Fig. 6.53 Output voltage for solar PV module

Fig. 6.54 Output power for different values of solar radiation G (W/m^2) and fixed temperature
T = 25 °C

6.6   Fuzzy Logic Based MPPT for Hybrid Solar and WECS

According to many renewable energy experts, a small hybrid electric system that
combines wind energy system and solar PV system offers several advantages over
either single system. Combining the renewable energy generation with the conven-
tional diesel power generation will enable the power generated from renewable
energy sources to be more reliable and affordable.

Due to the non-availability of solar PV and wind energy at all times, it is
necessary to model a system that would give reliable source of power. When a
direct connection is made between the source (Solar PV, Wind) and load, the
operating point is not optimal. In order to track MPP and make the output voltage
constant, two stage of DC-DC conversion is required. Hence, MPPT Controllers
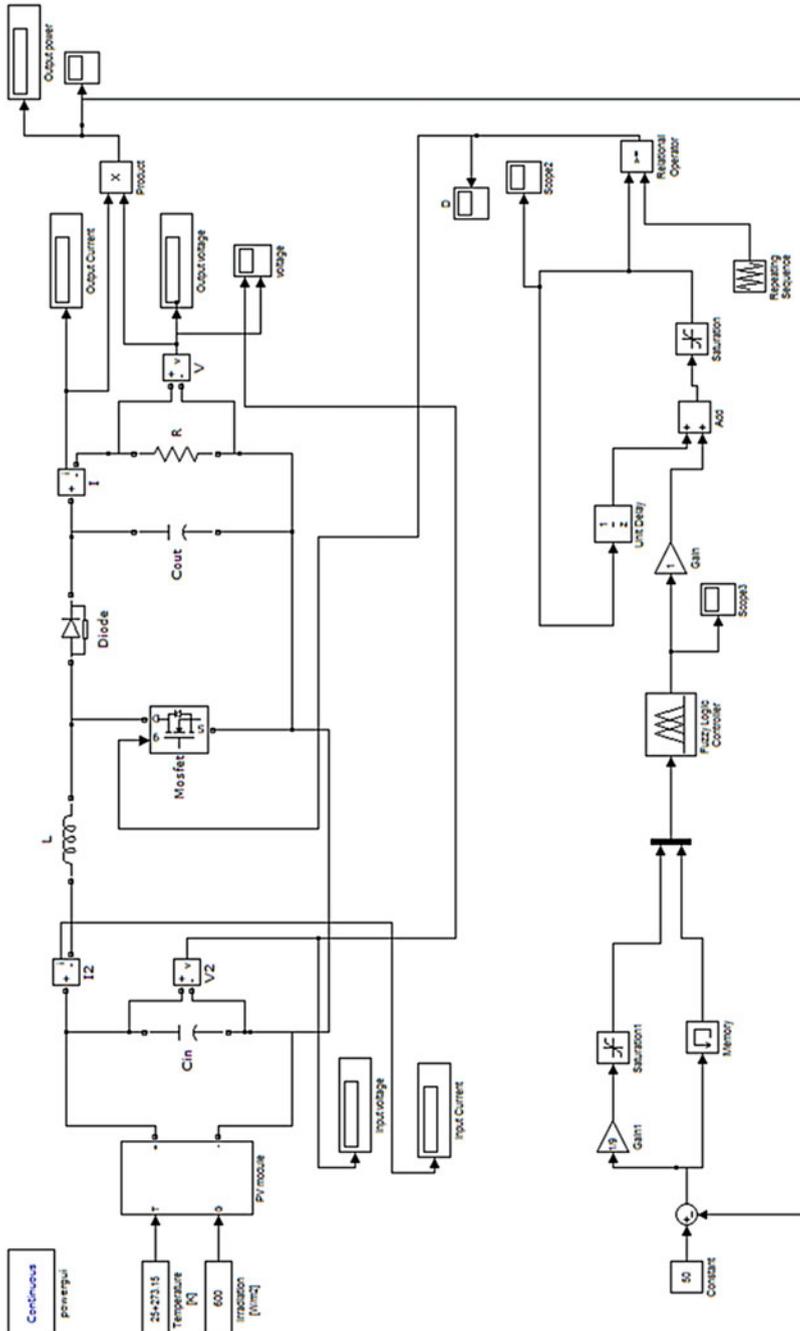with DC-DC converters is designed to obtain an efficient output for all operating

Fig. 6.55 Closed loop control of single solar cell
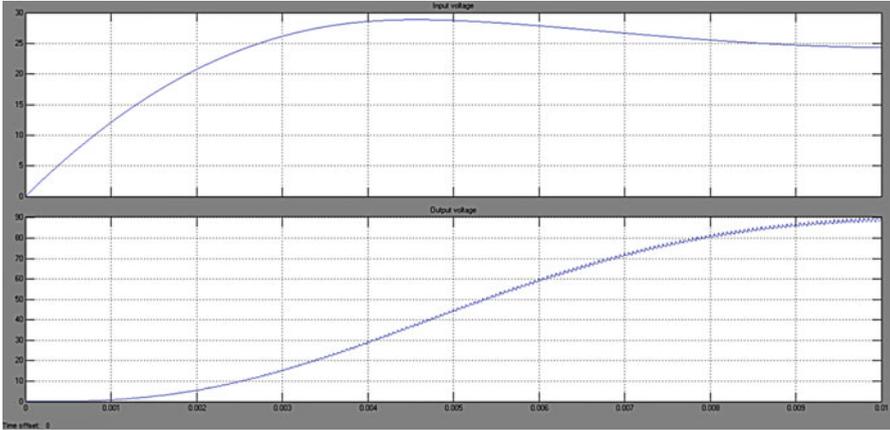
Fig. 6.56 Voltage waveform of boost converter
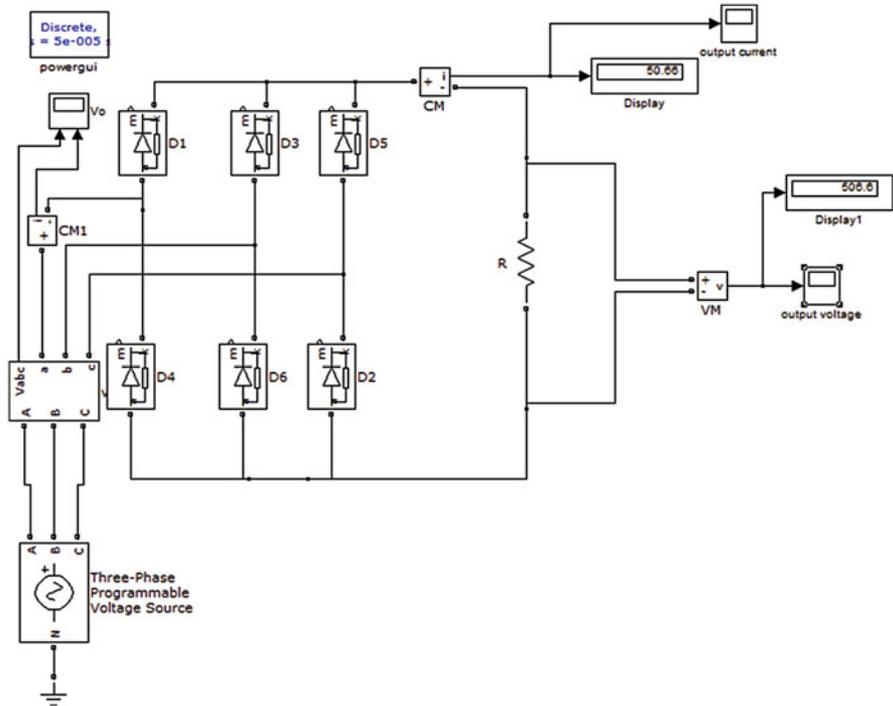
Fig. 6.57 Three phase uncontrolled ac-dc rectifier

Fig. 6.58 Output voltage for ac-dc uncontrolled rectifier
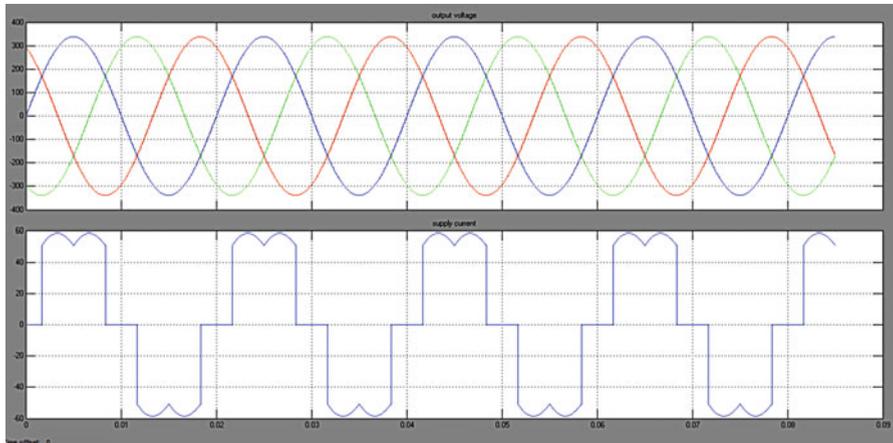
Fig. 6.59 Phase to ground voltage and supply current of ac-dc rectifier

conditions. As most of the consumer end applications are based on AC supply, the DC output obtained from the DC-DC converter are fed into the inverter for conversion into AC output filter is also designed to reduce the THD levels.

6.6.1   Methodology

In this section, a fuzzy logic based MPPT is proposed. The proposed fuzzy logic based MPPT can track the maximum power point faster and it can also minimize
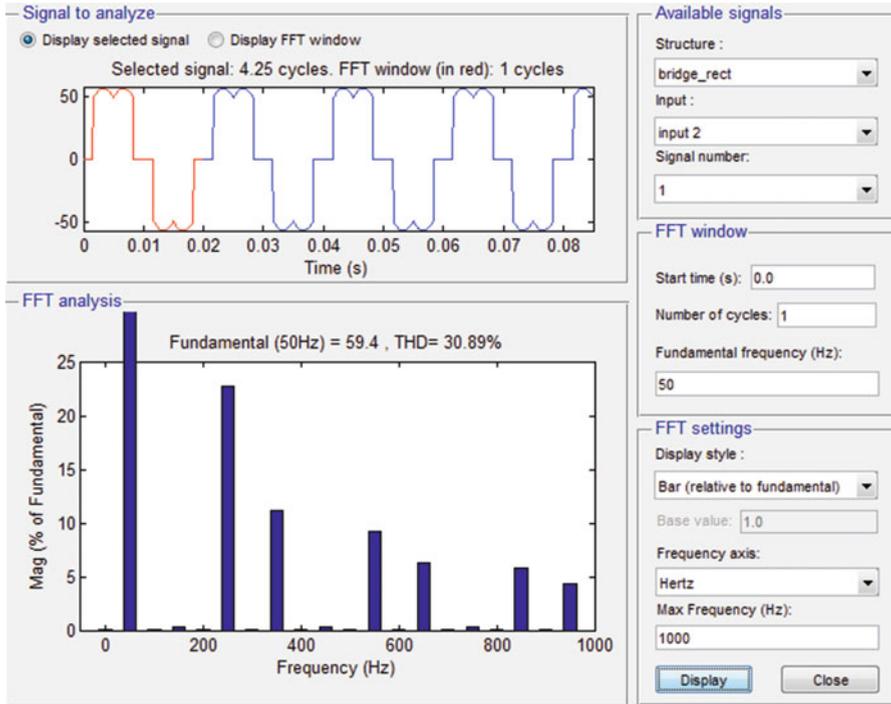
Fig. 6.60 THD analysis of source current in AC-DC rectifier

the voltage fluctuation after MPP has been recognized. In solar system the MPPT which depends on the atmospheric conditions such as solar cell temperature and irradiation conditions. When the MPPT will be implemented in wind, the maximum power can be extracted by varying the duty cycle of DC-DC Boost converter.

A fuzzy logic based MPPT has been implemented for both solar and wind energy system. MPPT control technique is implemented to generate the optimal voltage from PV and wind energy system by modulating the duty cycle and applied to the DC-DC boost converter. The output power from Solar PV and wind energy system are fluctuating. So the controller is required to make the DC bus voltage constant. PI controller has been implemented for DC-DC Buck-boost converter, which is used to vary the duty cycle and to maintain a constant voltage in DC-link capacitor. DC bus voltage is converted to AC by using PWM inverter, which is given to the AC load. The low harmonic distortion of the voltage and current at the output of the inverter is reduced by using an output L-filter.

The objective of the work is to design a hybrid wind and solar energy system and controlling it by means of a Fuzzy Logic Controller for domestic loads of about 100–200 kW. The main goal is to develop a simple, cost-effective stand alone
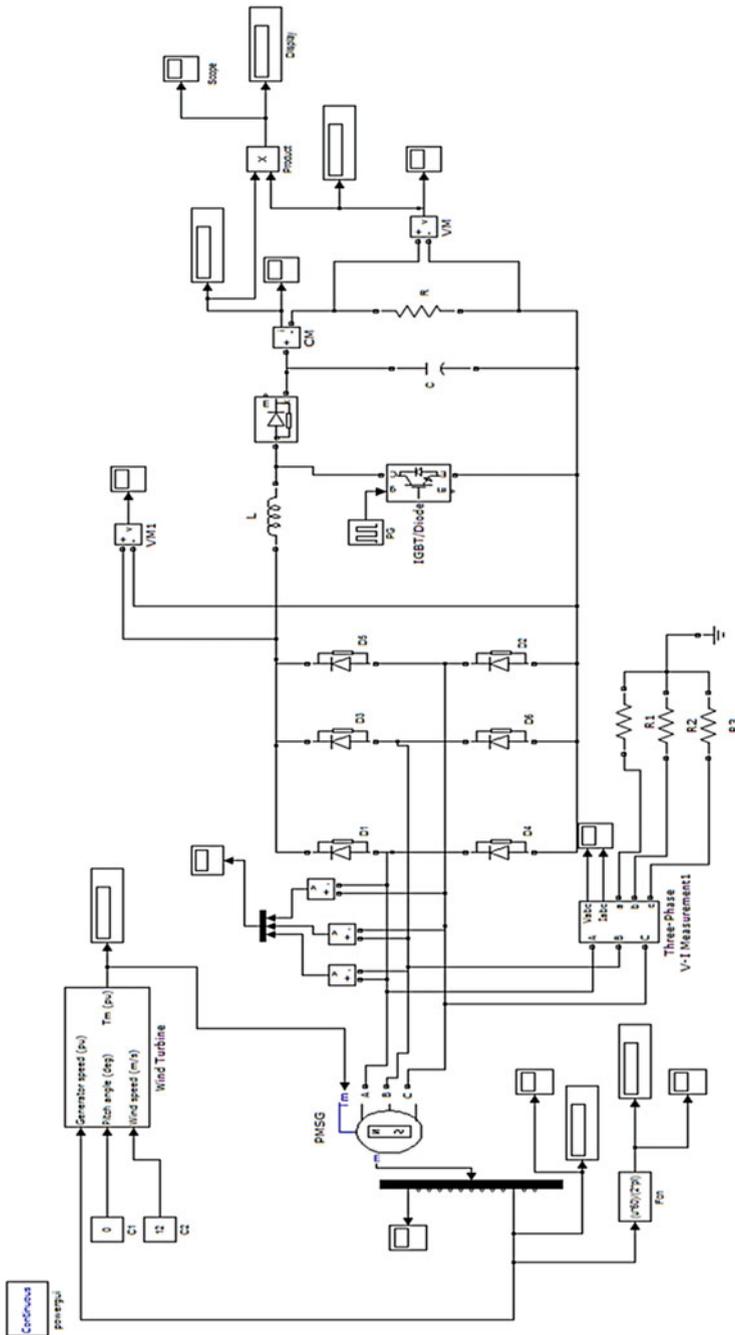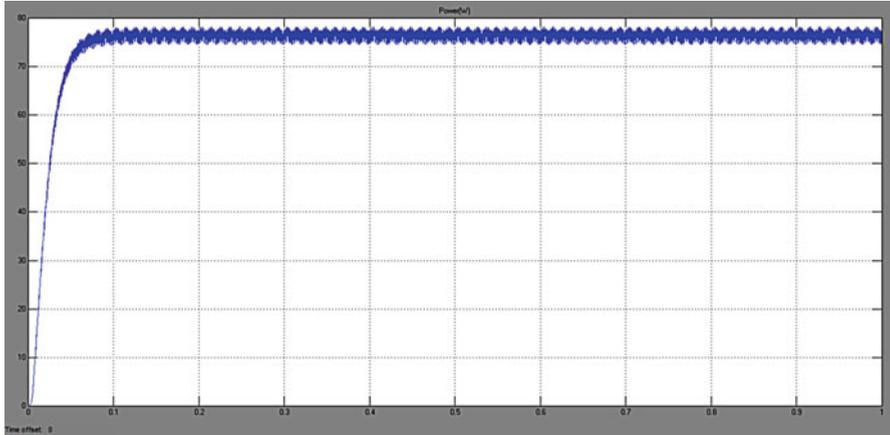
Fig. 6.61 Simulation of wind energy system with boost converter

**Fig. 6.62** Output power of wind energy system

hybrid wind and solar PV power system. In more detail, the objective of this work is as follows:

1. Development of a standalone hybrid wind and solar power generating system.
2. Design of FLC based MPPT for both Solar and Wind power system.
3. Development of a controller for the DC bus voltage.
4. Design of three phase PWM Inverter.
5. Design a low pass filter for an Inverter.

The Hybrid Power System (HPS) consists of solar PV module, Variable speed Wind Turbine (WT), AC-DC Diode bridge rectifier, DC-DC Boost converter, PWM Inverter and load are shown in Fig. 6.63. Individually the solar system and wind energy system are controlled and their outputs are connected in parallel.

The output of solar PV module is DC and the output of Wind energy system is AC, before combining these two output sources, they are converted to anyone of the source. Hence the output of WECS is converted into DC by using Diode Bridge Rectifier. Converting AC to DC is more preferred when boosting the voltage. The voltage applied by the PV array does not have constant values; it fluctuates according to the atmospheric conditions such as solar irradiation and temperature.

Here, Boost converter and Buck-boost converter are used. The Boost converter is used for increasing the output voltage magnitude obtained from solar PV module is shown in Fig. 6.63. The Boost converter is used to regulate a chosen level of the solar photovoltaic module output voltage and to keep the system at the maximum possible power from solar panels at all times. Buck-boost converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. The output voltage is varied according to the duty cycle. They can produce a range of output voltages from an output voltage much larger than the input voltage. A fuzzy logic based MPPT control technique is implemented to
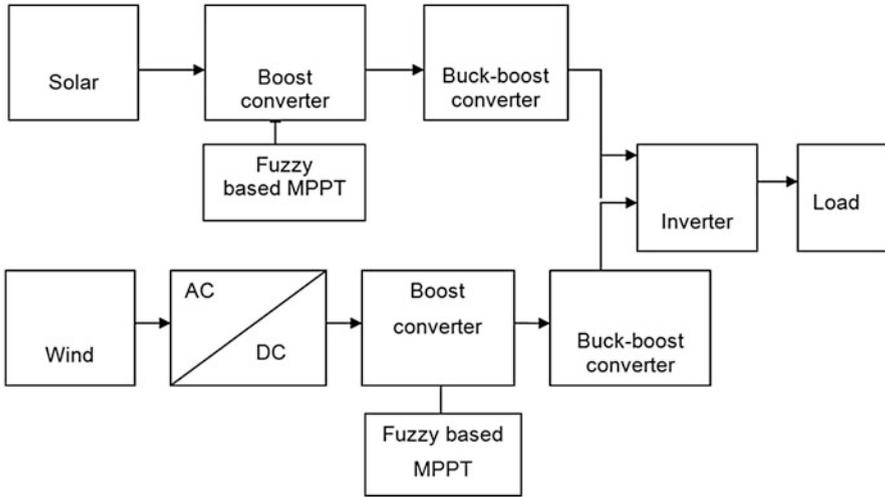
Fig. 6.63 Hybrid solar and wind power generation system

generate the optimal voltage from the PV system by modulating the duty cycle which is applied to the Boost converter. The Boost converter is used to regulate a chosen level of the solar photovoltaic module output voltage and keeps the system at the maximum possible power from solar panels and wind turbine at all times. The fuzzy logic based MPPT can track the Maximum Power Point (MPP) faster and can also minimize the voltage fluctuation after MPP has been recognized. According to V_{ref}, FLC boost converter forces the terminal voltage of PV array and wind energy systems to operate at its maximum power point. The boost converter output voltage is fluctuating, in order to make the DC bus voltage constant, two stage of DC-DC conversion is required. The DC bus voltage is converted into AC by using PWM inverter, which is given to AC load.

6.6.2   Design Considerations

Since the theoretical explanation for Solar PV module, wind turbine and rectifier are discussed in Sect. 6.5, we directly move on to the design considerations.

6.6.2.1   Design of Boost Converter

The parameters of Boost converter for solar and wind generation system values are calculated by using the following formulae tabulated in Tables 6.5 and 6.6.

Input voltage, $V_s = 150–950$ V, Output voltage, $V_o = 230–1,120$ V, Switching frequency, $F_s = 20$ kHz, ΔI_L is 3 % of output current, ΔV_c is 4 % of output voltage.

Table 6.5 Parameters of boost converter for solar PV system

Parameter	Symbol	Formula	Value
Duty cycle	K	$k = 1 - \frac{V_s}{V_0}$	0.727
Inductance	L	$L = \frac{Vs * k(1-k)}{\Delta I_L * f}$	8.9 mH
Capacitance	C	$C = \frac{Vs * k(1-k)}{8Lf^2 \Delta V_C}$	57 μF

Table 6.6 Parameters of boost converter for wind generation system

Parameter	Symbol	Formula	Value
Duty cycle	K	$k = 1 - \frac{V_s}{V_0}$	0.85
Inductance	L	$L = \frac{Vs * k(1-k)}{\Delta I_L * f}$	7.4 mH
Capacitance	C	$C = \frac{Vs * k(1-k)}{8Lf^2 \Delta V_C}$	86 μF

Fig. 6.64 Schematic diagram of buck-boost converter

Input voltage, $V_s = 120$–925 V, Output voltage, $V_o = 400$–1,000 V, Switching frequency, $F_s = 20$ kHz, ΔI_L is 2 % of output current, ΔV_c is 3 % of output voltage.
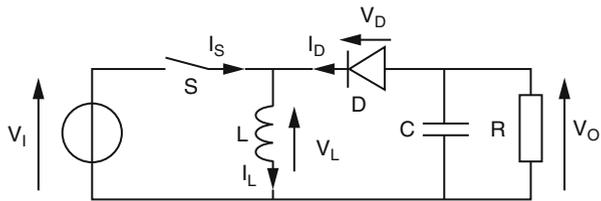
6.6.2.2 Design of Buck-Boost Converter

The Buck-boost converter is a case of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. The yield voltage is of the contrary polarity as the input. This is the switched mode power supply with a similar circuit topology to the boost converter and the Buck converter. The output voltage is changeable based on the duty cycle of the switching transistor. The schematic diagram of Buck-boost Converter is shown in Fig. 6.64.

When the switch is turned ON as shown in Fig. 6.65, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in inductor. In this stage, the capacitor supplies energy to the output load.

When the switch is opened as shown in Fig. 6.66, the inductor supplies current to the load through the diode D. While in the OFF state, the inductor is connected to the output load and capacitor, so energy is transferred from inductor to Capacitor, and resistor.

Fig. 6.65 Buck–boost
converter-ON state
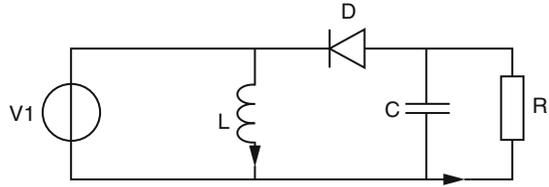
Fig. 6.66 Buck-boost
converter-OFF state
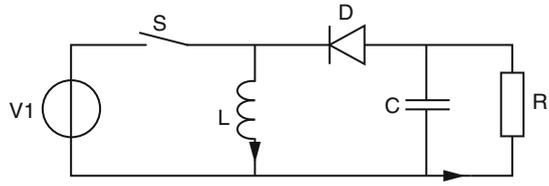
Compared to the Buck and boost converters, the characteristics of the Buck–boost converter are mainly:

1. Opposite Polarity of the output voltage compared to that of the input.
2. The output voltage can vary continuously from 0 to $-\infty$ (for an ideal converter). The output voltage ranges for buck and boost converter are respectively 0 to V_i, and V_i to ∞.

6.6.2.3   Design of Buck-Boost Converter

The Buck-boost Converter parameter values are calculated by using the following formulae.

Input voltage, $V_s = 160–1,100$ V, Output Voltage, $V_o = 850$ V, Switching frequency, $F_s = 20$ kHz, ΔI_L is 2 % of Output current, ΔV_c is 4 % of Output voltage.

1. Duty Cycle, $k = \frac{V_O}{V_O + V_S}$

$$= 850/(850 + 1,100)$$
$$k = 0.435$$

2. Inductance, $L = \frac{V_S * k}{\Delta I_L * f}$

$$= (160*0.4)/(0.17*20\mathrm{e}^3)$$
$$L = 8 \text{ mH}$$

3. Capacitance, $C = \frac{I_0 * k}{\Delta V_C * f}$

$$= (0.17*0.4)/(34*20\mathrm{e}^3)$$
$$C = 85 \text{ μF}$$

Fig. 6.67 Schematic diagram of diode bridge rectifier
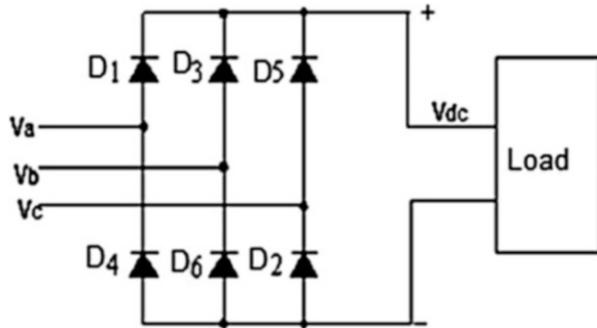
6.6.2.4 Diode Bridge Rectifier

A Diode Bridge Rectifier circuit converts AC input voltage into fixed DC voltage. Semiconductor diodes are used extensively in power electronic circuits for the conversion of power from AC to unidirectional DC. A rectifier circuit shown in Fig. 6.67 employing diodes is called an uncontrolled rectifier, because its average output voltage is a fixed DC voltage. The output voltage from the PMSG based WECS is a three phase AC voltage and it has to be rectified into a DC voltage. For rectification, a diode bridge rectifier is used and it rectifies the three phase AC to DC respectively. The diode bridge consists of six diodes from D1 to D6 as shown in Fig. 6.67.

The impedance of the diodes is neglected assuming to be very small values. The output rectified voltage from the diode bridge rectifier is boosted as required voltage.

The three phase circuit consists of two groups of diodes, positive group and negative group. The positive group of diodes are turned on when the supply voltages are positive and negative group diodes are turned on when the supply voltages are negative. If D1 is triggered at a particular instant, it can conduct provided there is a return path for the current. Since phase B is the maximum negative, the return path should be to phase B which means D5 must be triggered simultaneously with D1.

6.6.2.5 Three Phase PWM Inverter

An inverter is converted fixed DC voltage to a variable AC voltage. The output may be variable voltage and variable frequency. The output voltage from the PMSG is a three phase AC voltage and it has to be rectified into a DC voltage. For rectification a diode bridge rectifier is used and it rectifies the three phase AC to DC respectively. Pulse Width modulation is the process of modifying the width of pulses in a pulse train in direct proportion to a small control signal. Three phase inverters are normally used for high power applications.
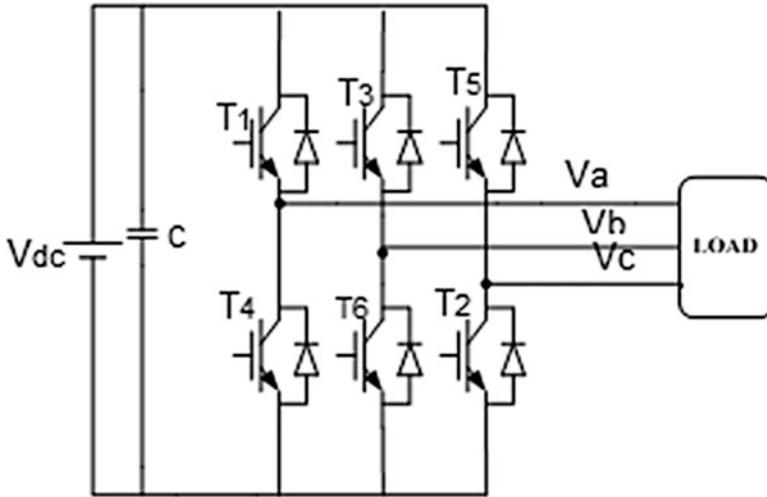
Fig. 6.68 Three phase PWM inverter

Three Phase inverter output can be obtained from topology having six transistor and six diodes as shown in Fig. 6.68. When transistor T1 is switched ON, terminal a is connected to the particular positive terminal from the DC input potential. When transistor T4 is started up, terminal a is actually brought to the actual negative terminal on the DC source. Switches of any kind of leg of this inverter (T1 & T4, T3 & T6, and T5 & T2) can not be switched simultaneously; this could result in a brief short circuit across the actual DC-link current supply. Similarly, in order to avoid undefined states therefore undefined AC line voltages, the switches of virtually any leg of the actual inverter cannot end up being switched off concurrently because this could result in changes in the voltages with respect to the current polarity.

If two changes: one upper then one lower conduct concurrently such that the actual output voltage is +Vs or −Vs, the switch point out is 1, although if these switches are off at the same time, the switch state is 0. To generate a given wave form, the inverter goes from one point out to another condition. The output of current has harmonics; hence your L filter is employed to reduce this harmonics in output current.

6.6.3 Intelligent Controller

Intelligent control describes the discipline where control methods are developed that attempt to emulate important characteristics of human intelligence. An intelligent controller system has the ability to act appropriately in an uncertain

environment, where an appropriate action is that which increases the probability of success. In intelligent control problems, which are most often complex and challenging, there may not be a clear separation of the plant and the controller; the control laws may be defined and be part of the system to be controlled.

6.6.3.1 Fuzzy Logic Control

A fuzzy control system is based on a mathematical system that will analyzes analog insight values in regards to logical variables which take on continuous values between 2 and 1, contrary to classical or electronic digital logic, which is run on discrete values associated with either 1 or perhaps 0 (true or false, respectively). Using fuzzy logic command has become well-liked over the final decade because it could deal with imprecise inputs, does not need an accurate model and can handle nonlinearity. Microcontrollers in addition have helped in your popularization of fluffy logic control.

Fuzzy logic seems closer to the way regarding human brains employment. We aggregate the information and form a number of partial truths which we aggregate further into higher realities which in switch, when certain thresholds exceeds the range. Fuzzy logic continues to be extended to take care of the concept connected with partial truth, where the truth value whitethorn range between completely accurate and completely mistaken.

6.6.3.2 Fuzzy Logic Controlled Design

P&E method for MPPT tracking is not going to respond quickly in order to rapid changes in temperature or irradiance. And so the Fuzzy Logic Control (FLC) algorithm is definitely capable of increasing the tracking performance. The FLC is intended for rapid prototyping because the system designer doesn't need to know every little thing about the program before starting this will achieve steady condition in a quicker time interval. FLC can handle non-linearity and it does not demand the exact model of the system and more lustiness than conventional judgement controller.

FLC can be classified into four steps:

1. Fuzzification
2. Membership function
3. Inference
4. Defuzzification
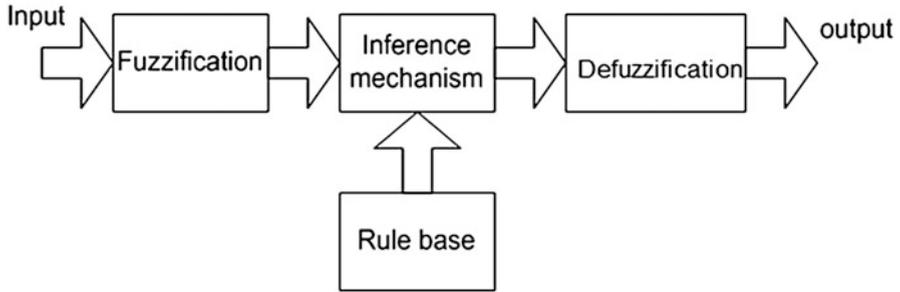
Fig. 6.69 Block diagram of fuzzy logic controller

Fuzzification

The operation of converting a crisp input value into right fuzzy value is termed "fuzzification". The input variables inside a fuzzy control system are in general mapped by sets of membership functions is known as "fuzzy sets". The membership function values are assigned towards linguistic variables using seven fuzzy subset called as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB).

Membership Function

The membership function is often a curvature that describes each point of membership value from the input space. The volume of membership functions used will depend on the mandatory accuracy in the controller. The fuzzy logic based MPPT technique the error (E) and difference in error (CE) are taken as input variables which might be as below for Kth sample time.

$$E(K) = \frac{dp}{dv} = \frac{P_K - P_{K-1}}{V_K - V_{K-1}}$$
$$CE(K) = E(K) - E(K-1)$$

where Error E(k) is the load operation point at the instant k is located on right or left of MPPT. The Change of Error, CE(k) expresses the moving direction of MPPT. The input variable of Error E(k), Change in Error CE(k) are shown in Figs. 6.70 and 6.71, respectively. The output variable of V_{ref} is shown in Fig. 6.72.
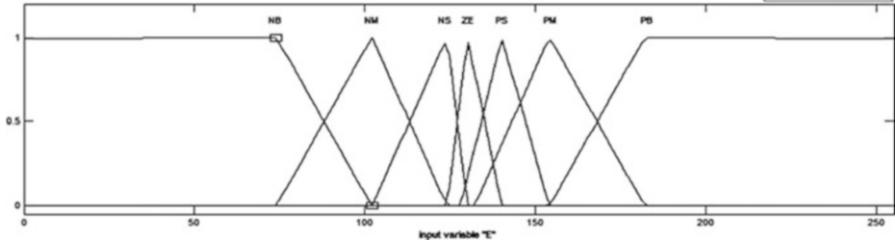
Fig. 6.70 Membership function of input variable 'error'
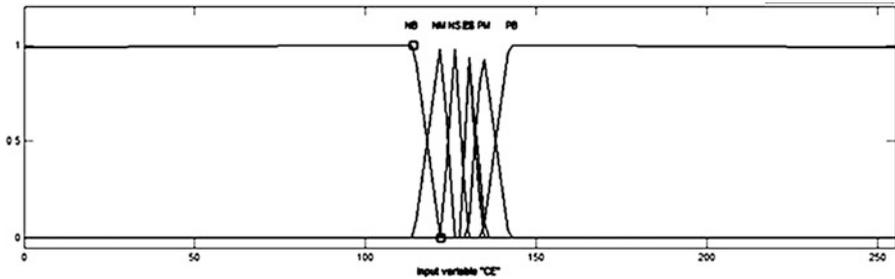
Fig. 6.71 Membership function of input variable 'change in error'
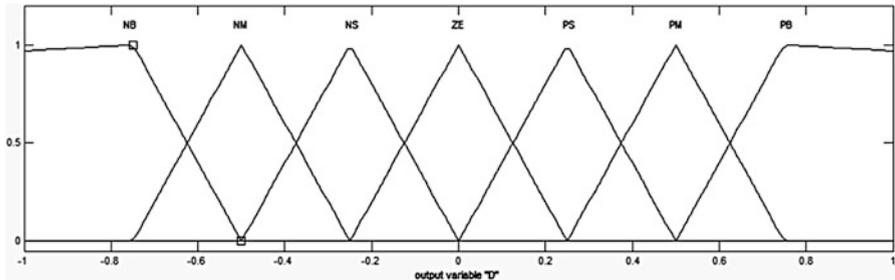
Fig. 6.72 Membership function of output variable 'V_{ref}'

Inference

Fuzzy rule base is an accumulation if-then rules which has all the info for the controlled parameters. A fuzzy inference method, Mamdani's strategy is used with Max-Min operation fuzzy combination. Fuzzy inference is founded on fuzzy rule base system. Rules are framed in inference block. The common strategy is MAX-MIN. The output membership function of every rule is given by MIN (Minimum) operator and MAX (Maximum) operator. The behaviour of the control surface which relates the input and output variables with the strategy is governed with a list of rules.

Defuzzification

Defuzzification is the procedure of conversion of fuzzy value into crisp value. The output of fuzzy controller can be a fuzzy subset. Because actual system requires a non fuzzy importance of control, hence the defuzzication is necessary. There are numerous methods for sale to defuzzification. Probably the most prevalent one is Centroid method, which utilizes the following formula:

$$\int \frac{x\mu(x)dx}{\mu(x)dx}$$

where μ is the membership degree of output x.

6.6.4 Fuzzy Logic Controller Based MPPT for HPS

P&O means for MPPT tracking will not respond quickly to rapid changes in photovoltaic cell temperature or irradiance. Meaning that the fuzzy control algorithm is competent at enhancing the tracking performance. A FLC makes for rapid prototyping for the reason that system designer doesn't have to recognize everything regarding the system before commencing this will achieve steady state in a shorter interval. FLC can take care of non-linearity also it does not require the precise mathematical model of the system and more robustness than conventional logic controller.

A Fuzzy based MPPT and DC-DC Boost converter are proposed within this project. Conventional Controller put in at home are straightforward to implement, however it contains the disadvantage to dependence system parameters especially in photovoltaic and WECS with massive amount uncertainties as being a sequence of changing wind speed and solar irradiance.

Due to inherent robustness and uncertainties in fuzzy logic controller, it can be used effectively in solar PV and WECS. The Maximum Power Point Tracking (MPPT) extracts the maximum power from the (wind turbine from cut in to rated wind velocity by sensing the output DC power of the wind generator.

The maximum power can be extracted at a certain operating point, with coordinates of V_{MPP} and I_{MPP} as shown in Fig. 6.73. Since the MPP depends on solar irradiation, cell temperature and Wind speed, it is never constant over time, thereby MPPT should be used to track its changes. Some of the advantages of FLC are

- Allows for rapid prototyping because the system designer doesn't need to know everything about the system before starting.
- Rule base or fuzzy sets are easily modified.
- Relates input to output in linguistic terms, making it easy to understand.
- Cheaper because they are easier to design.
- Increased robustness.
- It can achieve less overshoot and oscillation.
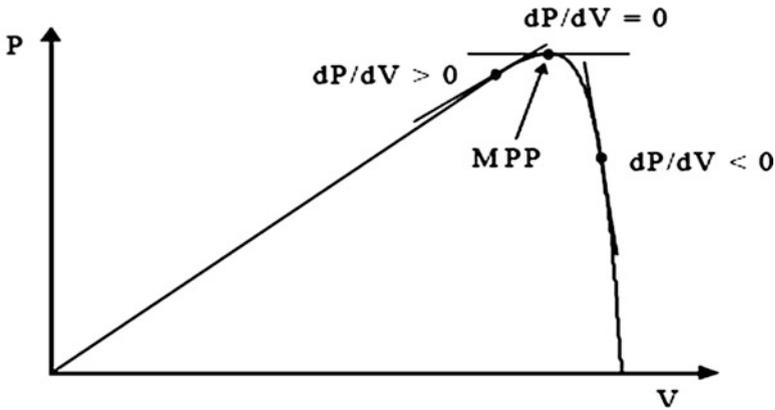- It can achieve steady state in a shorter time interval.
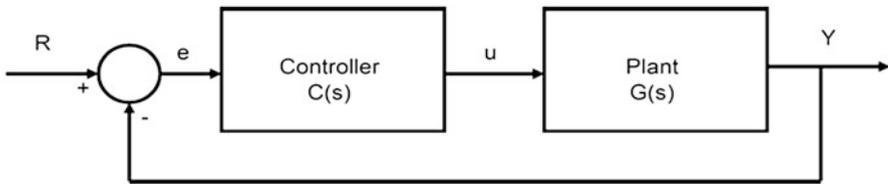
Fig. 6.73 P-V characteristics

Fig. 6.74 Structure of PID controller

6.6.5   PID Controller

PID controller is a control loop feedback mechanism (controller) widely used in industrial control systems.

A PID controller calculates a problem value as the visible difference between a scored process variable and a desired set level. The controller tries to minimize the error in outputs aside adjusting the physical process control inputs.

The particular PID controller criteria involves three distinct constant parameters, and is accordingly sometimes referred to as three term command the proportional, integral and derivative prices denoted P, i, and D; i.e., these beliefs can be interpreted in terms of your energy: P depends within the present error, My partner and i on the accumulation of past errors, and D is a prediction of foreseeable future errors, based about current rate involving change.

By tuning the three guidelines in the PID controller algorithmic rule, the controller offers control action designed for the specific method requirements. The response of the control can be explained in terms with the responsiveness of the particular controller to a blunder, the degree this agreement the controller overshoots the arranged point, and the degree of system cycle. PI controllers tend to be fairly common, since derivative action is sensitive to rating noise. The
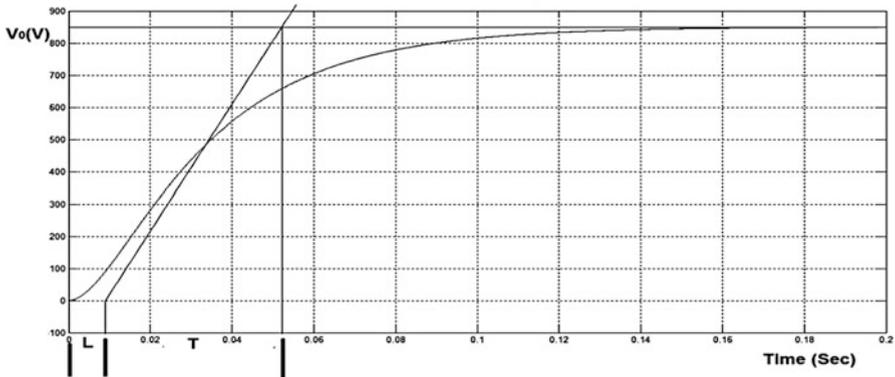
Fig. 6.75 S-shaped reaction curve method

essential term is proportional to both magnitude of the error and the continuance of the fault.

The S-shaped reaction curve can be characterized by two constants as shown in Fig. 6.75, delay time L and time constant T, which are determined by drawing a tangent line at the inflection point of the curve and finding the intersections of the tangent line with the time axis and the steady-state level line.

The proportional and integral gain values can be calculated by using the following formulae,

$$\text{Proportional gain, } K_P \ = \ 0.9 * \frac{T}{L}$$

$$\text{Integral gain, } K_I \ = \ 0.27 * \frac{T}{L^2}$$

where T is the time constant and L is the delay time constant.

6.6.5.1   Characteristics of PID Controllers

A proportional controller (Kp) will have the issue of lowering the rise time and will reduce but never remove the steady-state error. A integral control (Ki) could have the issue of eliminating the steady-state error for a constant or step input, nevertheless it will make the transient response slower. A derivative controller (Kd) will have the issue of helping the stability of the system, lowering the overshoot, and increasing the transient response.

The effects of each of controller parameters and on a closed-loop system are summarized in the Table 6.7.

Typical steps for designing a PID controller:

1. Determine what characteristics of the system need to be improved.
2. Use K_p to decrease the rise-time.

Table 6.7 PID controller rules

Response	Rise-time	Overshoot	Settling-time	Steady-state error
K_P	Decrease	Increase	No change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Decrease	Increase	Increase	No change

Table 6.8 Ziegler–Nichols tuning rule table

Controller	K_P	K_I	K_D
P	$\frac{T}{L}$	0	0
PI	$0.9 * \frac{T}{L}$	$0.27 * \frac{T}{L^2}$	0
PID	$1.2 * \frac{T}{L}$	$0.6 * \frac{T}{L^2}$	0.6 T

3. Use K_d to reduce the overshoot and settling-time.
4. Use k_i to eliminate the steady-state error.

6.6.5.2   Ziegler-Nichols Tuning Rule Table

Using the parameters L and T, one can set the values of K_P, K_I and K_D according to the formulae as shown in the Table 6.8.

These parameters will typically give the response with an overshoot about 25 % and good Settling-time. The Ziegler-Nichols tuning rule is suitable reaction curve method when initial estimate of parameters are known. The proportional and integral gain control is determined by using the formulae as shown in Table 6.8. PI Controller is designed to control the output of Buck-boost converter based on Ziegler-Nichols tuning method.

6.6.6   Simulation of Solar PV Under Atmospheric Conditions

The single solar PV module consists of series and parallel solar cells, which is used to increasing the voltage and current. The maximum current is given to the input of a current controlled source. The maximum output power of solar PV is 100 kW. The amount of produced power is generated by solar cell is very small. So the cells are arranged in series and parallel to produce the useful range of electric power.

Figures 6.76 and 6.77 which represent the I-V and P-V characteristics of solar cell TITANS6_60 which is written in M-file coding.

The solar PV module consists of 24 modules connected in series and 20 strings connected in Parallel. The specifications of solar cell TITANS6_60 considered for simulation are tabulated in Table 6.9. In the event the modules are wired together in series, their voltage rating is increased while the current remains constant. In the event the modules are wired in parallel, their current is increased even though the voltage remains constant. The absolute maximum power can be had by varying
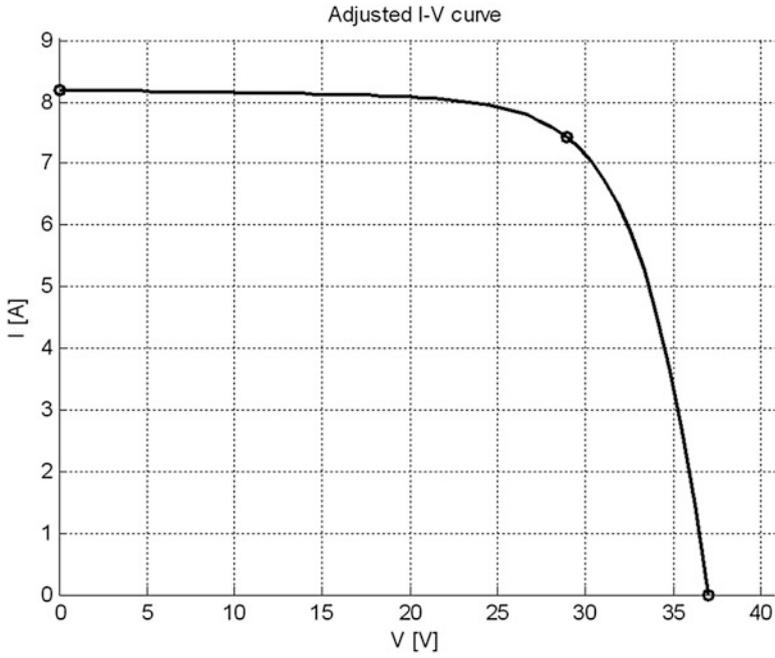
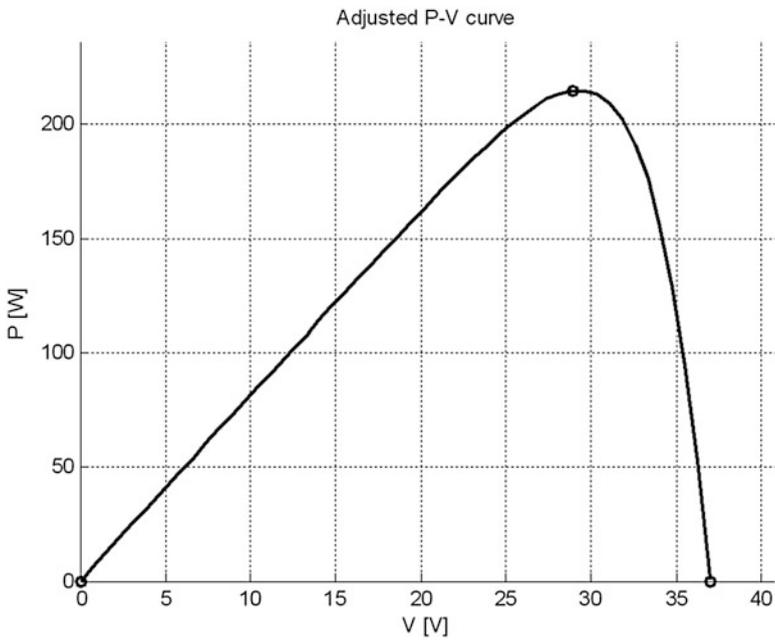**Fig. 6.76** I-V characteristics of solar PV system

Fig. 6.77 P-V characteristics of solar PV system

Table 6.9 Parameters of the TITANS6_60 PV module at 25 °C and 1,000 W/m^2

Parameter	Symbol	Value
Peak power	P_{MPP}	215.015 W
Peak power voltage	V_{MPP}	28.9 V
Peak power current	I_{MPP}	7.44 A
Open circuit voltage	V_{OC}	37 V
Short circuit current	I_{SC}	8.21 A
Temperature coefficient of current	K_i	3.183e^{-3} mA/°C
Temperature coefficient of voltage	K_v	−0.123 mV/°C
Number of series cells	N_s	60
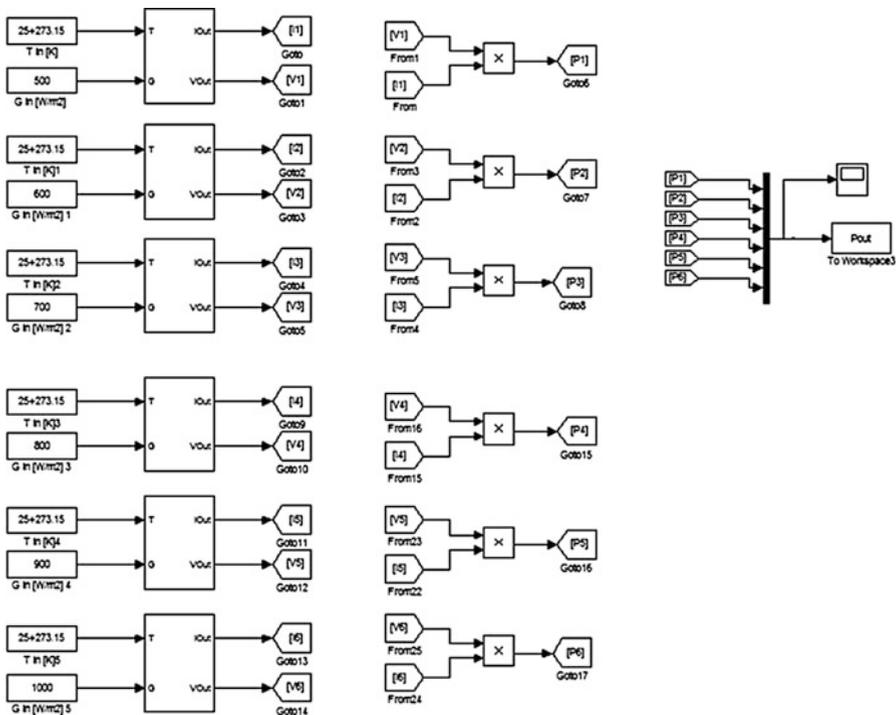
Fig. 6.78 Solar PV array for different values of solar irradiance and fixed cell temperature

the solar cell temperature and solar irradiance. The photovoltaic module is simulated for different values of solar irradiance and fixed cell temperature as shown in Fig. 6.78.

The maximum power can be obtained from solar PV module in the voltage range from 700 to 800 V as shown in Fig. 6.79.
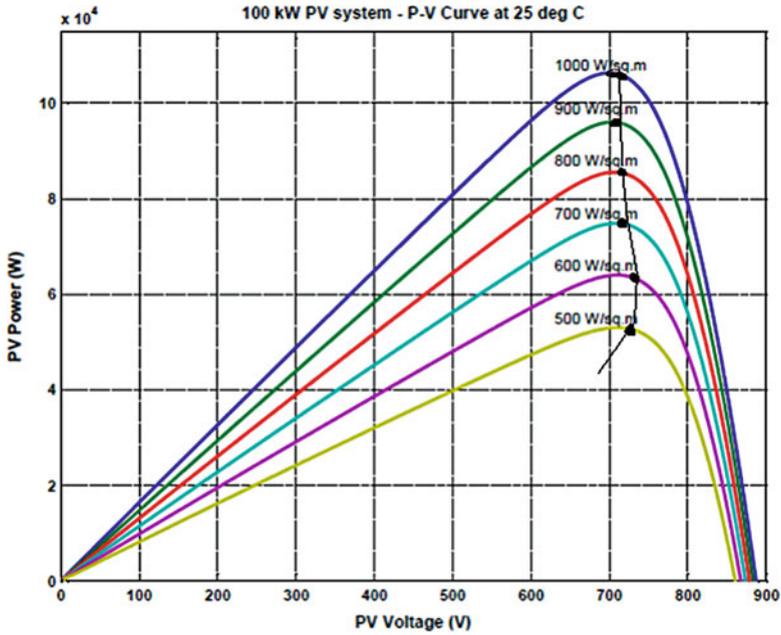
Fig. 6.79 P-V characteristics of solar PV module-different solar irradiance & fixed cell temperature

Table 6.10 Output power for different operating conditions

Sl. No.	Irradiance (W/m^2)	Output power (kW)
1	500	55
2	600	64
3	700	78
4	800	85
5	900	98
6	1,000	110

The solar PV output power is obtained according to the variable irradiance levels between (500–1,000 W/m^2) and fixed solar cell temperature of 25 °C as shown in Table 6.10. The solar PV voltage and current are varied corresponding to the solar irradiance as shown in Fig. 6.80.

The maximum power is obtained according to different solar irradiance levels between 200 and 1,000 W/m^2 as shown in Fig. 6.81. The maximum solar PV output power is 100 kW which is obtained at the solar irradiance of 1,000 W/m^2 as shown in Table 6.11.
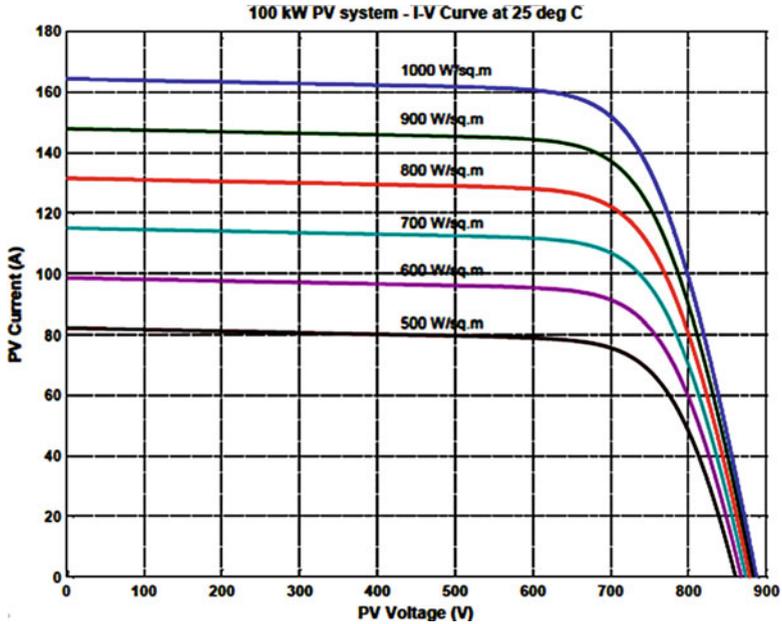
Fig. 6.80 I-V characteristics of solar PV module-different solar irradiance & fixed cell temperature
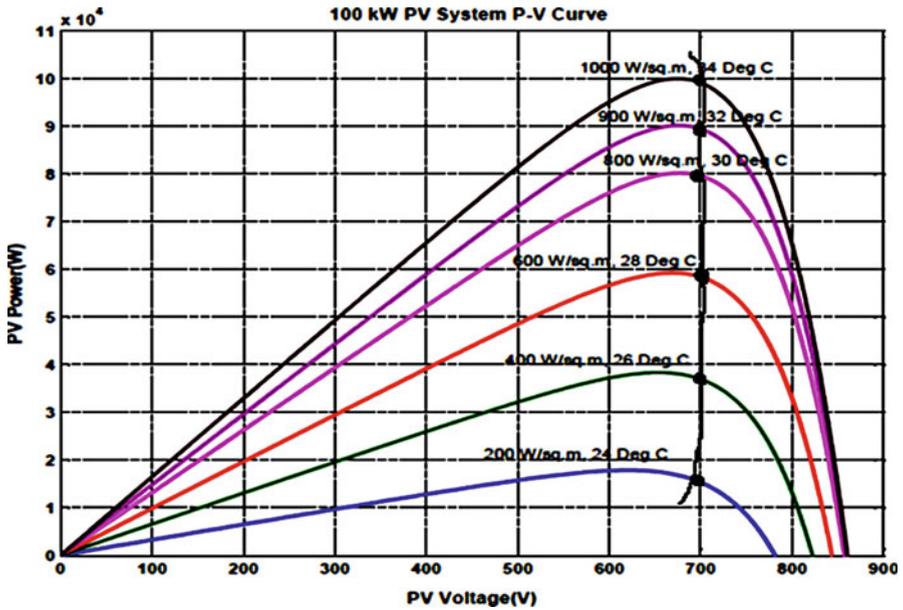

Fig. 6.81 P-V characteristics of solar PV module-different cell temperature & solar irradiance

Table 6.11 Output power for different solar irradiance conditions

Sl. No.	Irradiance (W/m^2)	Output power (kW)
1	200	20
2	400	38
3	600	60
4	800	80
5	900	90
6	1,000	100

6.6.7 Simulation of FLC Based MPPT

The simulations are carried out in MATLAB/SIMULINK environment and the results are discussed in this section.

6.6.7.1 Solar PV

The solar PV system model consists of FLC based MPPT, DC-DC converters and load. The system is simulated in MATLAB/SIMULINK environment at cell temperature of 25 °C and Solar Irradiance of 1,000 W/m^2.

The Solar output voltage and current are measured and fed to the fuzzy based MPPT control circuit for MPP tracking. Based on the change of power with respect to change of voltage dp/dv and Δdp/dv, fuzzy control determines the voltage reference from solar PV system by modulating the duty cycle in the boost converter.

When the solar PV output power is positive, the system will keep the perturbation in same direction. The system will change the perturbation in reverse direction, when the change of power is negative.

6.6.7.2 DC-DC Converters

A fuzzy logic based MPPT control technique is implemented to generate the optimal voltage from the PV system by modulating the duty cycle is applied to the boost converter switch. Buck-boost converter is used to maintain the constant DC-link capacitor voltage which is controlled by PI controller. Thus a constant DC voltage is obtained from the PV system as shown in Fig. 6.83. This DC power is supplied to DC load. The same power is inverted and it is supplied to AC load.

The PV module has variable irradiance and fixed cell temperature. For analysis purpose, irradiance levels of 200, 1,000, and 850 W/m^2 are considered. The PV module output power is 40, 100, and 87 kW are shown in Fig. 6.83.

The Buck-boost converter output voltage is maintained at constant 850 V as shown in Fig. 6.84. The Buck-boost Converter and PI Controller parameter values are shown in Table 6.12.
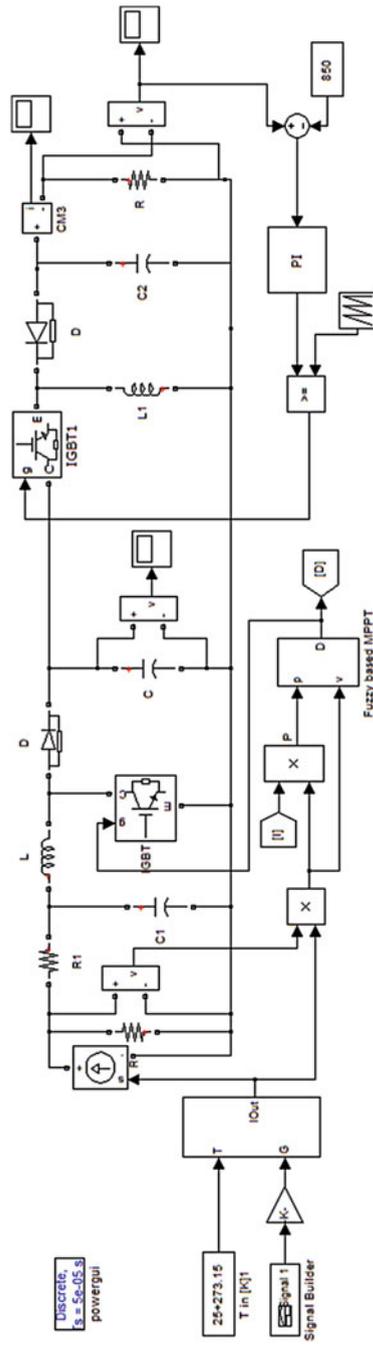
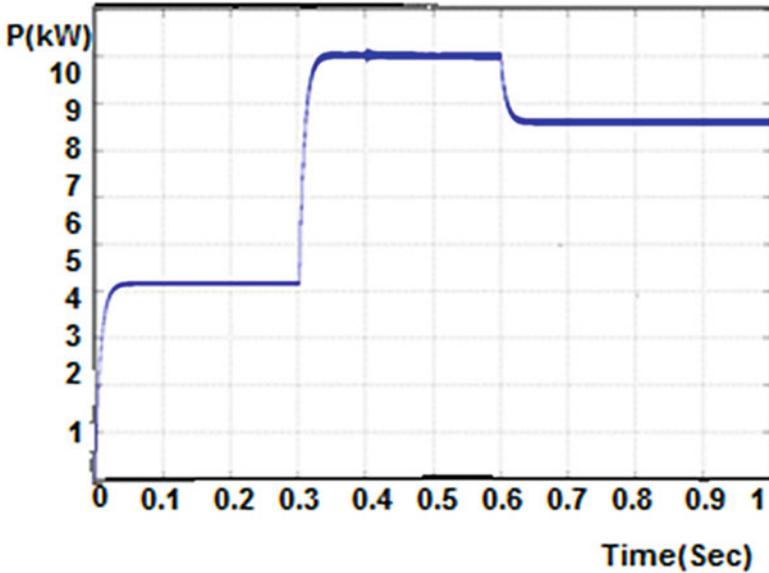**Fig. 6.82** Simulation of solar PV system

Fig. 6.83   Output power of solar PV system
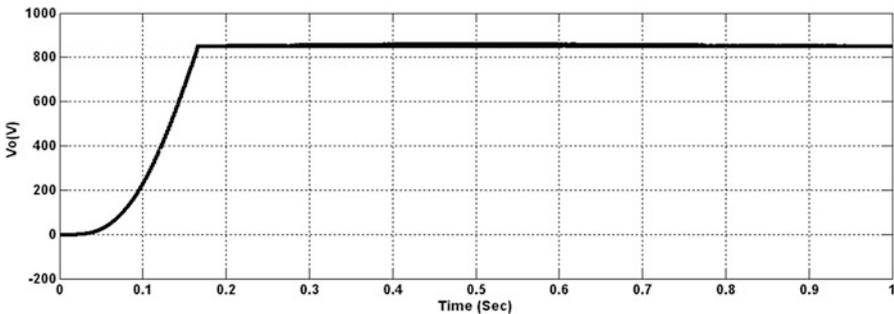
Fig. 6.84   Output voltage of buck-boost converter

6.6.7.3   Wind Generation System

The wind energy system has been developed and simulated in MATLAB/ SIMULINK as shown in Fig. 6.85. The maximum output power of Wind generation is 200 kW. The Wind generation system has Wind turbine, two mass Drive Train, PMSG. By running the wind turbine generator in variable speed mode, the maximum power can be extracted at low and medium wind speeds. The output of wind turbine is Mechanical torque (T_m), which is not directly connected to PMSG, T_m is given to PMSG through Drive train.

Table 6.12 Parameters of buck-boost converter and PI controller

Parameter	Symbol	Value
Input voltage	Vs	350–1,200 V
Output voltage	V_0	850 V
Switching frequency	F_s	20 kHz
Inductance	L	8 mH
Capacitance	C	85 μF
Proportional gain	K_p	2
Integral gain	K_i	50

The PMSG converts the mechanical power from the wind turbine into output power of AC, which is then converted into DC power through a converter with DC-link voltage is supplied to DC load. The mechanical power converted from the turbine is a function of the rotational speed, and the converted power is maximized at the particular rotational speed for various wind speeds. The fuzzy logic based MPPT can track the MPP faster and it can also minimize the voltage fluctuation after MPP has been recognized. The Buck-boost converter is used to maintain the constant voltage and it is done by controlling with PI Controller. The DC voltage source is converted to AC and it can be supplied to AC load.

The maximum output power 200 kW is obtained at the wind speed of 11 m/s. The output power is varied according to the rotor speed variation as shown in Fig. 6.86 and Table 6.13.

The 200 kW Wind Generation system parameters and their values are tabulated in Table 6.14. The specification of ITALTECH 200 kW wind turbine is considered for simulation.

The maximum power is extracted at pitch angle of 0° and wind velocity of 11 m/s. The RMS line voltage is 500 V and output power of wind generation system is 200 kW, obtained at wind velocity of 11 m/s as shown in Fig. 6.87.

The Buck-boost converter output voltage is maintained at 850 V as constant and it is shown in Fig. 6.88. The parameter values of Buck-boost converter and PI Controller as mentioned in Table 6.15.

6.6.7.4   Hybrid Solar and Wind Generation System

The solar PV system is integrated with the wind energy system to form the hybrid system as shown in Fig. 6.89. The hybrid renewable energy system ensures continuous power flow to the load. The proposed fuzzy based MPPT for hybrid system comprises of a Wind turbine and a Solar PV system to the load. The only adaptation needed is the requirement to maintain the DC bus voltage constant. Both Solar PV and Wind are connected in parallel to a common PWM inverter through their individual AC-DC rectifier and DC-DC converters. The Fuzzy logic based MPPT can track the maximum power point faster and it can also minimize the voltage fluctuation. The Solar PV and Wind turbine voltage are measured and controlled
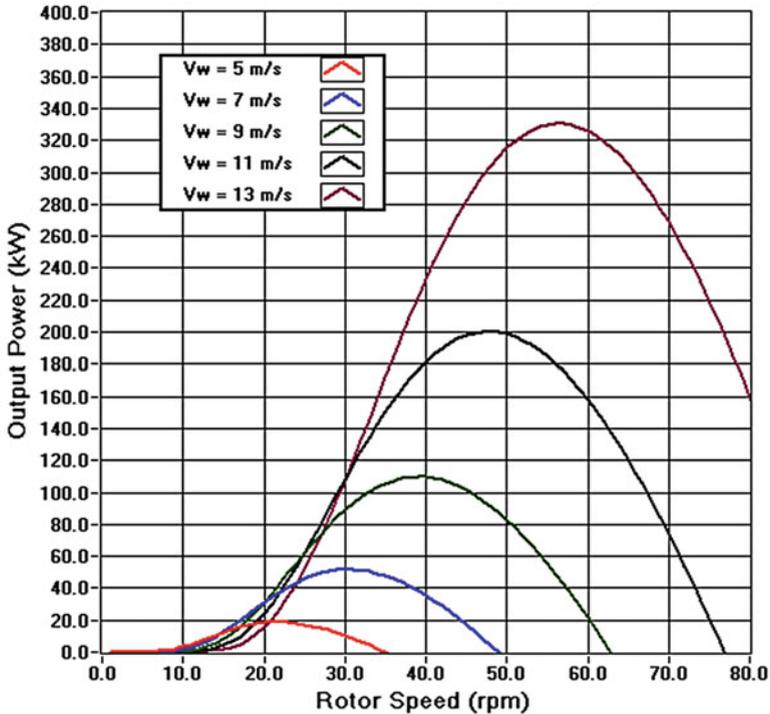
Fig. 6.85 Simulation of wind generation system

Fig. 6.86 Output power versus speed characteristics of wind generation system

| Table 6.13 Output power of wind generation system	Wind speed (m/s)	Output power (kW)
	5	30
	7	60
	9	110
	11	200
	13	325

based on the error signal. The error is fed into the controller, to generate the pulses for DC-DC Boost converter. The Boost Converter output voltage is varied corresponding to the MPP output by varying the duty cycle. Hence, DC-DC Buck-boost converter has been implemented to maintain the output voltage constant. The DC bus voltage is converted into AC by using inverter.

The function of the inverter is to transfer the maximum power to the load. The low harmonic distortion of the voltage and current at the output of the inverter is achieved by using an output filter. The filter is the most favourable one for the attenuation of the harmonics of the inverter. The PWM inverter is connected to the load through a low pass L-filter. The operating values of three phase PWM inverter is tabulated in Table 6.16.

Table 6.14 Parameters of wind generation of 200 kW system

Permanent magnet synchronous generator		
Parameter	Symbol	Value
Stator resistance	R_s	0.005 Ω
Armature inductance	L_a	0.000835 H
Static friction	T_f	0.54 N-m
Flux linkage	φ	0.283 Wb
Moment of inertia	J	0.1197 kg-m^2
Viscous damping	F	0.1189 N-m
Pole pairs	P	24
Wind turbine model		
Parameter	Symbol	Value
Mechanical output power	P_m	200 kW
Base wind speed	V_w	11 m/s
Maximum power at base wind speed	P_{max}	0.9 pu
Pitch angle	β	0°
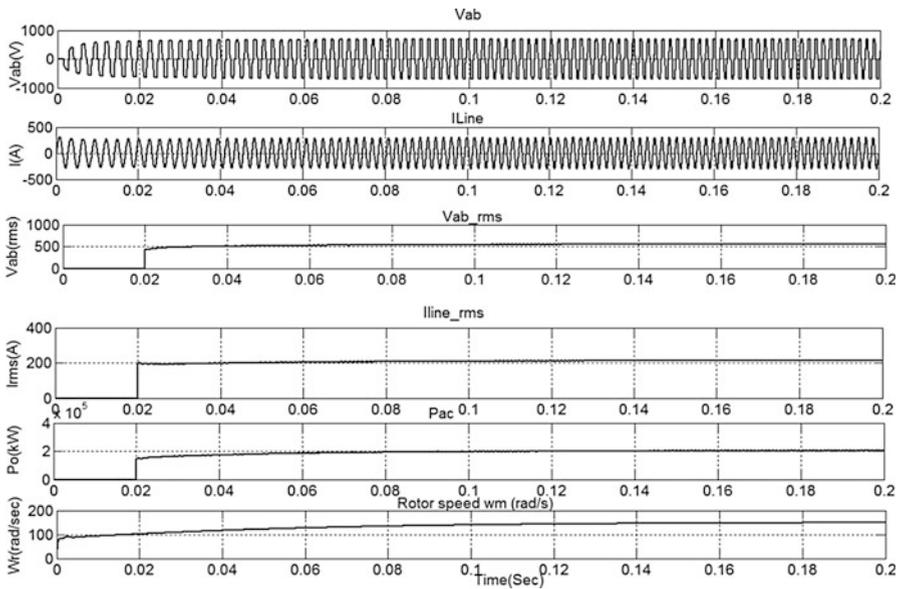
Fig. 6.87 Output waveforms of PMSG

The three phase RMS output voltage is 415 V and it is shown in Fig. 6.91. The THD spectrums for output current without and with filter are shown in Figs. 6.92 and 6.93, respectively. The Peak Voltage of Three Phase PWM Inverter is 586 V and it is shown in Fig. 6.90.
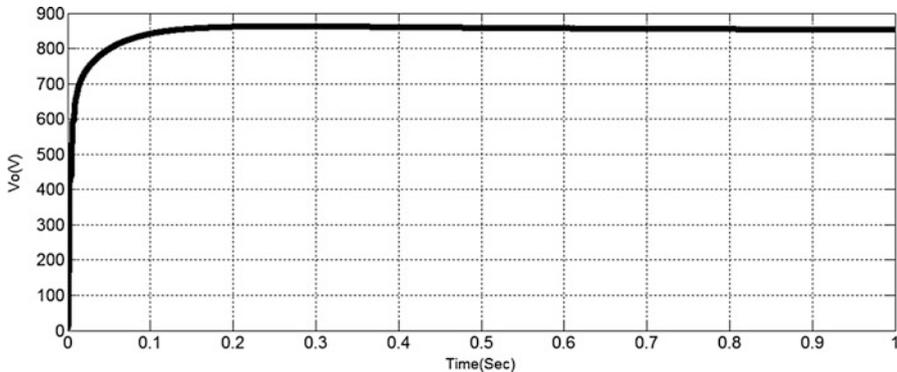
Fig. 6.88   Output voltage of buck-boost converter

Table 6.15   Parameters of buck-boost converter and PI controller

Parameter	Symbol	Value
Input voltage	Vs	300–1,100 V
Output voltage	V_0	850 V
Switching frequency	F_s	20 kHz
Inductance	L	9 mH
Capacitance	C	57 μF
Proportional gain	K_p	3.86
Integral gain	K_i	500

The output current of three phase inverter without filter has 51.82 % THD, which is shown in Fig. 6.92. By using L-filter, the current harmonic is reduced to 1.6 % THD as shown in Fig. 6.93.

The stand-alone 100 kW Solar PV and Wind Energy Systems are designed, simulated for a load of 100–200 kW. The proposed fuzzy logic based MPPT technique can track the maximum power point faster than the conventional controller. It has the ability of reducing the voltage fluctuation after MPP has been recognised. The Solar PV and wind energy system not only boosts up the voltage but also produce a signal, free from transient noise. Hence the performance of the closed loop system has been improved by using FLC.

The synchronized hybrid Solar and Wind energy systems are simulated in MATLAB/SIMULINK. After obtaining the constant output voltage, from both Wind and Solar energy systems, they are connected in parallel. The DC source from hybrid power system is converted to AC by using PWM inverter. In order to produce a pure sine wave output with low harmonics, an L-filter is used. The output current of the inverter has 1.6 % THD which is lower than the IEEE-519-1992 standard. The hybrid power system can be utilized either for remote generation plants or it can be utilized for grid integration.
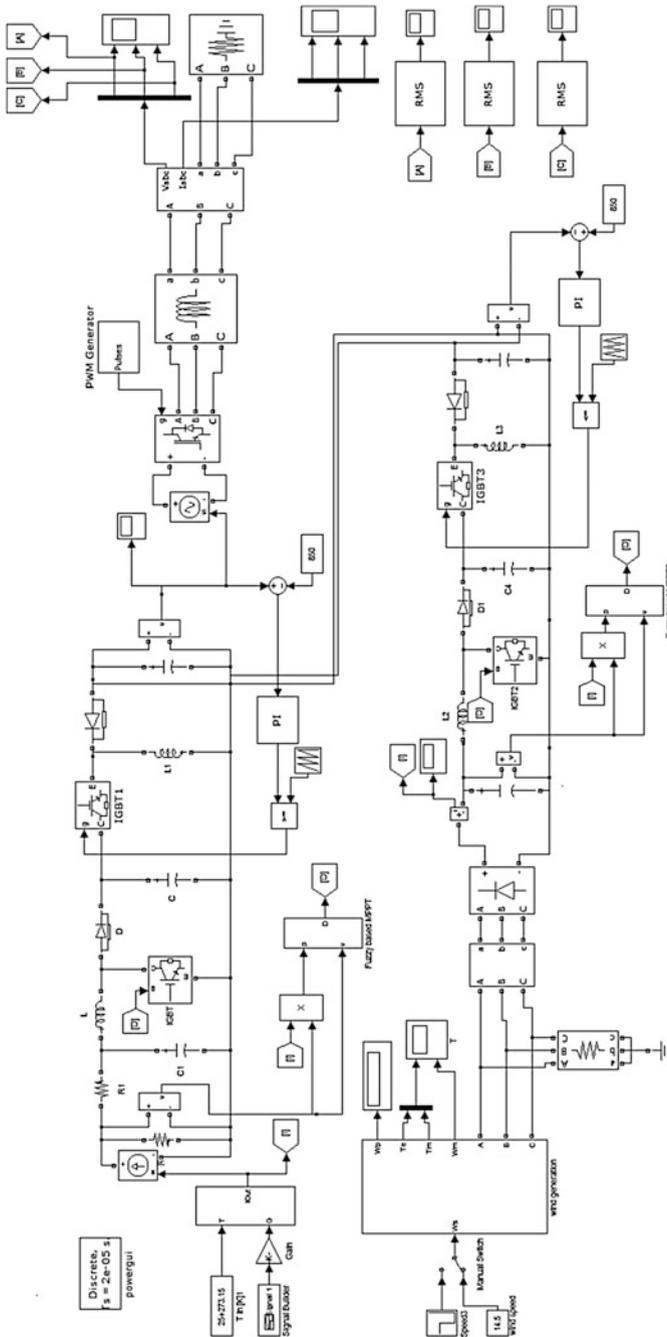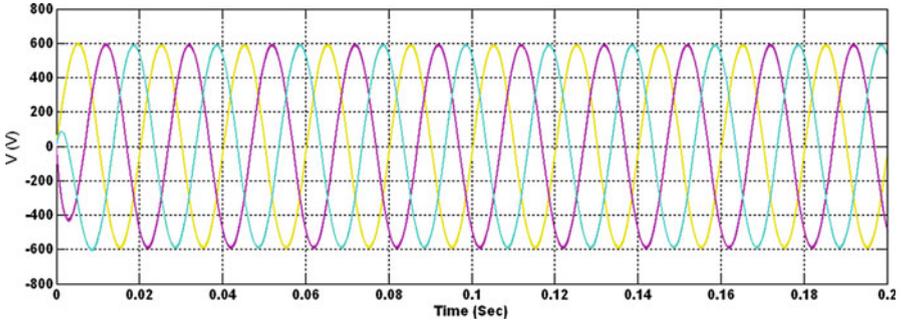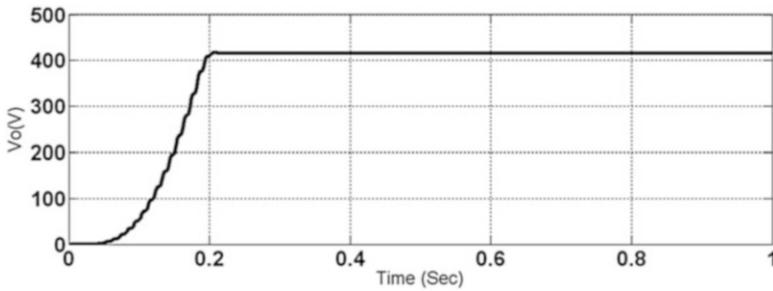
Fig. 6.89 Hybrid solar PV and wind generation system

Table 6.16 Operating values of three phase PWM inverter

Parameter	Symbol	Value
DC input voltage	V_s	850 V
AC input voltage	V_0	415 V
Carrier frequency	F_c	10 kHz
Modulation index	m	0.9
Filter inductance	L	4 mH

Fig. 6.90 Output voltage of three phase inverter

Fig. 6.91 RMS voltage of three phase inverter
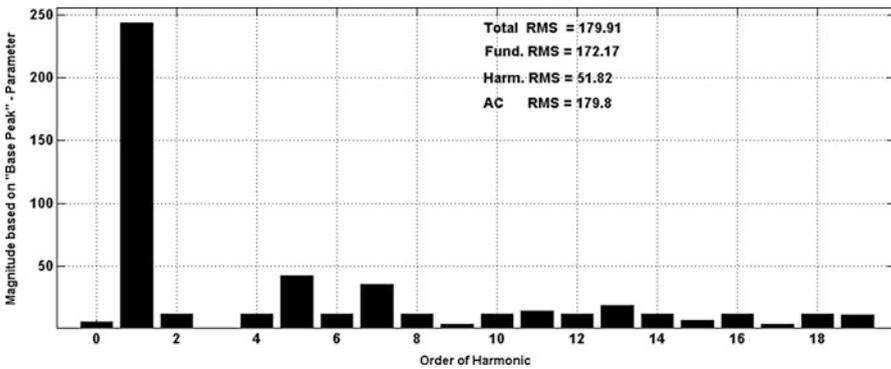
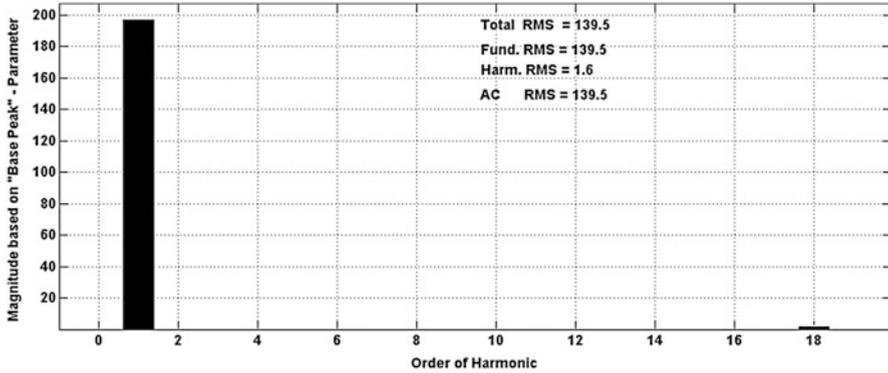**Fig. 6.92** THD spectrum of output current without filter

Fig. 6.93 THD spectrum of output current with filter

6.7   Summary

Hybrid energy system including several (two or more) energy sources with appropriate energy conversion technology connected together to feed power to local load/grid. Since, it is coming under distributed generation umbrella, there is no unified standard or structure. It receives benefits in terms of reduced line and transformer losses, reduced environmental impacts, relived transmission and distribution congestion, increased system reliability, improved power quality, peak shaving, and increased overall efficiency. HES allow wide variety of primary energy sources, frequently renewable sources generation as the stand alone system for rural electrification where grid extension is not possible or uneconomic. The hybrid combination of Solar PV and Wind energy conversion system, along with solar PV with diesel energy are discussed in this chapter. Suitable MATLAB/SIMULINK models and their results are also presented. Design and development of various HES components has more flexibility for future extension and growth. Device can be added as the need arises and assure the promising operation with existing system.

Review Questions
1. What are the advantages of hybrid solar PV with diesel over hybrid solar PV with wind energy conversion systems?
2. Discuss the different types of converters used for hybridising solar PV and wind energy conversion systems.
3. What is the need for agentification in hybrid energy systems?
4. Mention the need for filters in the modelling of HES.
5. State the design considerations involved in Buck Boost converter.
6. Discuss the challenges involved while integrating hybrid energy system with grid connected system.

7. Develop a MATLAB/SIMULINK model of PV/wind hybrid system using cuk-sepic converter.
8. Define THD. Analyse the performance of converters used in HES based on THD.
9. Develop a MATLAB/SIMULINK model for MPPT control in HES using Artificial Neural Networks and Genetic Algorithms.

Bibliography

Abbey C, Joos G (2005) Energy management strategies for optimization of energy storage in wind power hybrid system. In: Proceedings of the 36th IEEE power electronics specialists conference, pp 2066–2072

Basso TS, DeBlasio RD (2003) IEEE P1547-series of standards for interconnection. IEEE, New York

Borowy BS, Salameh ZM (1996) Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Trans Energy Conv 11(2):367–375

Davidson J, The new solar electric home, 20th printing 2001

Dursun E, Kilic O (2012) Comparative evaluation of different power management strategies of a stand- alone PV/Wind/PEMFC hybrid power system. Electr Power Energy Syst 34:81–89, Elsevier

Haiwen Liu, Leon M Tolbert, Surin Khomfoi, Burak Ozpineci, Zhong Du (2008) Hybrid cascaded multievel inverter with PWM control method. IEEE, pp 162–166

Hart DW (1997) Introduction to power electronics. Prentice Hall, New Jersey

IEC 61000-3-6:1996 Electromagnetic compatibility (EMC) – Part 3: Limits – Section 6: Assessment of emission limits for distorting loads in MV and HV power systems. Basic EMC publication

IEEE recommended practice for utility interface of photovoltaic system, IEEE Std. 929–2000

Jain S, Agarwal V (2008) An integrated hybrid power supply for distributed generation applications fed by nonconventional energy sources. IEEE Trans Energy Convers 23:622–631

Jiang Z (2006) Agent-based control framework for distributed energy resources micro grids. In: Proceedings of the IEEE International conference on intelligent agent technology, pp 646–652

Kalantar M, Mousavi SMG (2010) Dynamic behaviour of a stand-alone hybrid power generation system of wind turbine microturbine, solar array and battery storage. Appl Energy 87:3051–3064, Elsevier

Kern EC, Gulachenski EM, Kern GA (1989) Cloud effects on distributed photovoltaic generation: slow transients at the Gardner, Massachusetts photovoltaic experiment. IEEE Trans Energy Convers 4(2):184–190

Kouro S, Bernal R, Miranda H, Silva CA, Rodriguez J (2007) High-performance torque and flux control for multilevel inverter fed induction motors. IEEE Trans Power Electron 22(6):2116–2123

Lagorse J, Simoes MG (2009) Multiagent fuzzy-logic-based energy management of hybrid systems. IEEE Trans Ind Appl 45(6):2123–2129

Musavi F, Edington M, Eberle W, Dunford WG (2011) Evaluation and efficiency comparison of front end AC-DC plug-in hybrid charger topologies. IEEE Trans Smart Grid 1–9

Nirmala Jyothi J, Sateesh S (2012) MATLAB/SIMULINK model of grid connected PV system With Maximum power point tracking. Int J Emerg Trends Eng Dev 7(2)

Pairodamonchai P, Sangwongwanich S (2009) Design and implementation of a hybrid output EMI filter for high frequency common-mode voltage compensation in PWM inverters. IEEE Trans Ind Appl 45(5):1647–1659

Rashid MH (2006) Power electronics devices, circuits and applications. Academic Press, San Diego

Rech C, Pinheiro H, Grundling HA, Hey HL, Pinheiro JR (2002) Analysis and comparison of hybrid multilevel voltage source inverters. ISSN: 0-7803-7262-x/02, pp 491–496

Schekulin D (1999) Grid-connected photovoltaic system. Germany Patent DE197 32218 Cl; Mar 1999

Sreedevi M, Paul PJ (2011) Fuzzy PI controller based grid-connected PV system. Int J Soft Comput 6:11–15

Zhong J (2006) PID controller tuning: a short tutorial. Mechanical Engineering, Purdue University, Spring