Chapter 7

Solar-Wind hybrid Roof-top wind energy conversion system

7.1 Introduction

The previous chapter has dealt with the design and testing of a mechanically field-weakened (MFW) DSAF PMSG based roof-top wind energy conversion system. The analysis of the results of the proposed system has been evaluated. The proposed system acts as a buffer and is well capable of regulating intermittency at the input side (wind) as well as at the output side (load). The system is a dedicated roof-top wind energy conversion system operating in stand-alone/weak-grid mode.

In recent times, roof-top solar energy conversion systems (RSECS) are prevalent. RSECS is usually preferred among all renewable energy-based electric power generation owing to the decreasing cost of the solar panels leading to low LCOE [19], higher efficiency solar panels [152], technological advancement in solar cell such as nano-structured hybrid perovskite solar cells [153], and improved grid-tied inverter topologies [154–156].The increased tapping of solar power through different techniques have been widely used throughout world. Two variants of RSECS, Offline RSECS, and Online RSECS exist.

Offline RSECS are battery supported and, therefore, can use the stored energy in the batteries to generate power in the absence of the solar irradiation, which ensures increased power reliability of the system. However, the inclusion of the battery increases the overall installation and maintenance costs of the system.

On the other hand, online RSECS do not support a battery; therefore, it reduces the overall cost of the system. Online RSECS are popular in urban areas. However, the power reliability of the system depends on the presence of the grid. In rural/remote areas, grid availability is very poor, therefore, offline RSPS is more prevalent in these areas.

RSECS is a matured technology. At this stage, it is good to analyze the effect of hybridizing the Solar power with the wind power. The prime advantage of hybridization of the two systems is their complementary nature and, therefore, the reduced intermittency of input renewable energy [157, 158]. Another advantage of the hybrid system is the reduction in the capacity of the energy storage device required in the system [159–162]. However, the complexity and cost of the system increases due to the requirement of an extra power converters, and the controller needed to control the power share between two energy sources.

In conventional practices, hybridization of solar and wind in off-grid power system, is achieved by operating solar and wind at MPPT and save surplus power in energy storage devices that could be used during low power generation [157, 158]. However, in the proposed work, the wind turbine does not operate at maximum power point. The generated power is regulated as per the demanded load. Reserve power is maintained in the system by field-weakening of the wind generator on the same line as done by X. Yuan et al. [65]. At the time of power shortage, the rotor speed of wind-generator-coupled-to-wind-turbine is varied to extract reserve power from the wind (within the capacity of the wind turbine).

In this thesis, the maximum power available is not extracted. Present chapter reports an approach of hybridizing wind enrgy and solar energy for rooftop generation with minimum number of active power electronic switches. Here solar energy conversion system acts as a supporting role to wind energy conversion system in supplying load. The simplification of the hybrid solar-wind energy system is achieved by regulating solar power with a single diode and regulation of wind power by using a field-weakened Permanent magnet synchronous generator.

7.2 Control strategy

Different techniques of integrating different types of renewable energy sources in a hybrid plant are available in the literature. All the techniques categorize among DC-coupled, AC-coupled, and hybrid-coupled systems [163]. All the techniques have their advantages and disadvantages. Choosing any particular technique depends on the type of application. All three categories are briefly introduced here.

DC-coupled systems: In a DC-coupled system, all RES are coupled to the same DC-link through multiple DC-DC converters in parallel [164]. One of the advantages that is also the most significant of using dc-coupled system is its simplicity. In a DC-coupled system, unlike the AC-coupled system, different RES need not be synchronized with each other. Furthermore, the DC bus-bar can be easily integrated with an AC grid using an inverter. Inverters provide an added advantage of controlling real and reactive powers injected into the grid. However, DC-coupled systems face single point operational failure at the inverter. The problem is solved by using multiple inverters in parallel as discussed in chapter 2 though, increases number of components and thus, the cost [165–167].

AC-coupled systems: AC coupled systems subdivide among power-frequency and high-frequency AC-coupled systems. In power frequency AC coupled systems, different renewable sources are converted to AC supply at power frequency through power electronics converters and then integrated to grid. High-frequency AC-coupled systems supply high-frequency AC loads [163].

Hybrid-coupled systems: Hybrid coupled systems consist of DC bus as well as the AC bus [168]. All DC/AC sources are directly, or through appropriate power converters are connected to DC bus or/and AC bus. DC/AC loads are also directly, or through appropriate power converters are connected to DC or AC bus bar. The advantage of such systems is the reduction in total number of components used. However, the complexity of the system increases, owing to the need for energy management among different converters.

In the proposed system, solar power and wind power are integrated using DC-coupling. DC coupling has been chosen because of its ease of operation, which is necessary for the simplification of the system, especially in remote area electrification applications. In DC-coupled systems, it is not necessary to synchronize different energy sources between themselves. Here, DC supply from solar panels connects to the DC bus bar directly or through a DC-DC converter. On the other hand, the AC supply generated by the wind generator is first rectified, filtered, and then is connected to the DC bus bar.

The control strategy of proposed rooftop hybrid solar-wind energy conversion system (RHSWS) is based upon regulating DCV at the coupling point of solar and wind generation by regulating power generation by wind turbine and solar panel, as per load demand [169, 170]. Fig. 7.1 presents a block diagram model of the proposed RHSWS. Solar power and wind power couple to DC-link through power regulators. DCV compares to a reference voltage V_{ref} and control signals are generated for the solar power regulator and wind power regulator to regulate power supplied to the load. Mathematically the governing equation of DCV dynamics is written by power balance equation in the system as given in Eq. 7.1

$$P_S + P_W - P_L = CV_{dc}\frac{dV_{dc}}{dt} \tag{7.1}$$

P_S represents input solar power, P_W represents input wind power, P_L represents output load power, C is the DC-link capacitor, and V_{dc} is DCV. To regulate V_{dc}, total input power

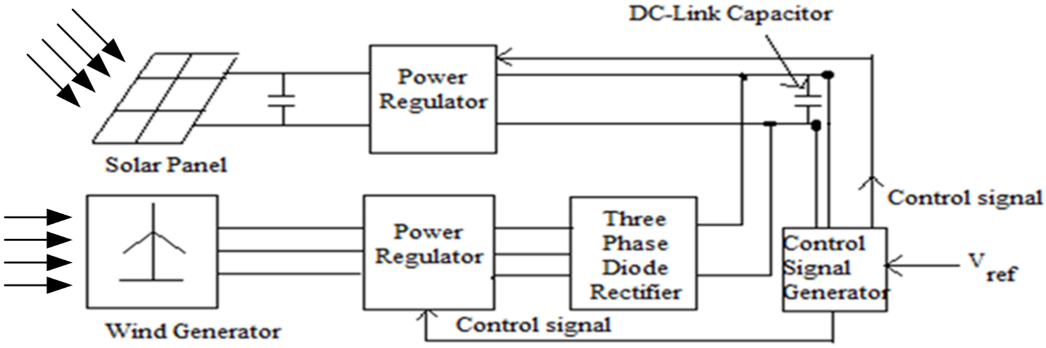


Fig. 7.1 Block diagram representation of proposed hybrid solar wind system.

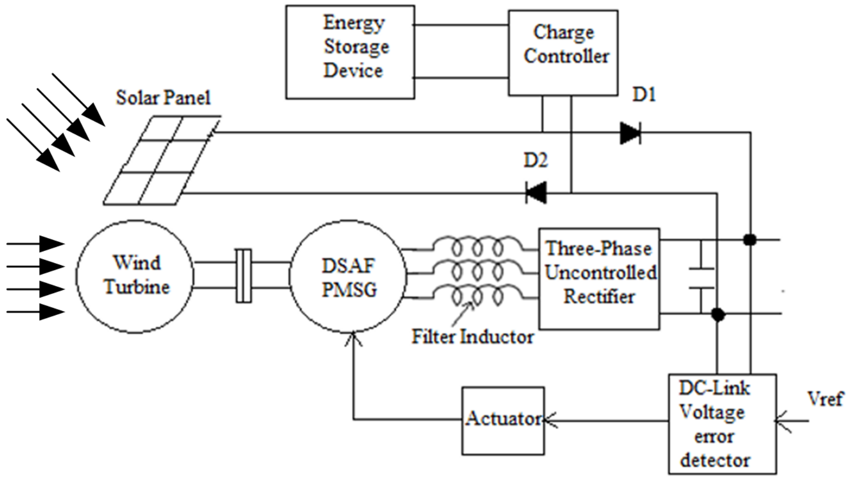


Fig. 7.2 Block diagram model of proposed rooftop hybrid solar wind system in wind supportive mode.

from RE, $(P_S + P_W)$ is regulated to deliver total output load power, P_L. In wind supportive mode (WSM), solar power is injected into the system during wind variations while in solar supportive mode (SSM), the wind power is injected to match load power. The same system under grid fault may work in grid supportive mode (GSM) by working both energy sources at MPPT and injecting maximum reactive power into the grid [171].

The proposed system is a dedicated rooftop hybrid energy system for areas rich in wind energy and low in solar energy. Therefore, the present work analyses RHSWS working in WSM. Fig. 7.2 gives the block diagram representation of the control strategy of proposed RHSWS working in WSM. It is proposed to couple solar system to the DC-link through a diode, D1, and DSAF PMSG, through a three-phase diode rectifier. MFW of the generator regulates the output power of the wind generator. The wind power is regulated such that the total power generation (wind plus solar) tracks the load demand. Variations in the tip-speed to wind-speed ratio, λ of the wind turbine creates reserve power in the system. At the time of higher load demand, the λ of the system is varied to extract higher power from the wind (within the capacity of the wind turbine).

The same process also controls power fed by solar by controlling DCV as per Eq. 7.1. The solar panel connects to DC-link through diode D1. The voltage across D1, V_D, is as given in Eq. 7.2.

$$V_D = V_S - V_{dc} \tag{7.2}$$

The V_{dc} is controlled with respect to the solar panel to forward bias diode D1, connecting the solar system to the DC-link. It is proposed to include a battery connected to the solar system through a conventional charge controller to store solar energy at the time solar energy is disconnected from the DC-link. Following are three cases that are possible during the operation of the proposed technique

7.2.1 Case 1: Extracted Wind Power Greater than Load Demand

In case wind power is sufficient/excess compared to the load demand, the excess power reflects at the dc-link, and thus, V_{dc} starts increasing beyond the value of V_S. Therefore, diode D_1 reverse biases and solar panel gets disconnected from the DC-link. As per the control circuit diagram in Fig. 7.2, the V_{dc} is compared to a reference DCV, V_{ref}. V_{ref} is set to be higher than the no-load voltage of the solar panels. The DCV error signal, thus generated, is then used to generate a signal for the mechanical actuator to rotate the RS of the wind generator. The signal for the actuator is generated by using MATLAB SIMULINK and interfaced to the actuator driver by dSPACE 1104 microprocessor board.

The Generator RS is angularly displaced in such direction as to reduce the DCV error. Consequently, DCV regulates at V_{ref}. In other words, power generated from wind generator regulates such that, is equal to load power.

7.2.2 Case 2: Extracted Wind Power Less than Load Demand

In case, WECS is not able to supply load, V_{dc} dips from its rated value as per Eq. 7.1. If DCV dips beyond the no-load voltage of solar panel, diode D1 conducts. Subsequently, the solar panel gets coupled to the DC-link and starts supplying power to the load; thus, balancing the power shortage due to the low wind speed. Here, solar panel and wind generator simultaneously share load demand.

7.2.3 Case 3: Extracted Wind Power and Solar Power Less Than Load Demand

In case, Solar power is not able to compensate for the decrease in wind power, V_{dc} dips without control. To avoid such a scenario, an energy storage device should be incorporated in the system (depending upon the degree of reliability of the system needed and socio-economic status of remote area) that stores solar power. Possible energy solutions may be

1. Battery storage
2. Water pumping
3. Flywheel

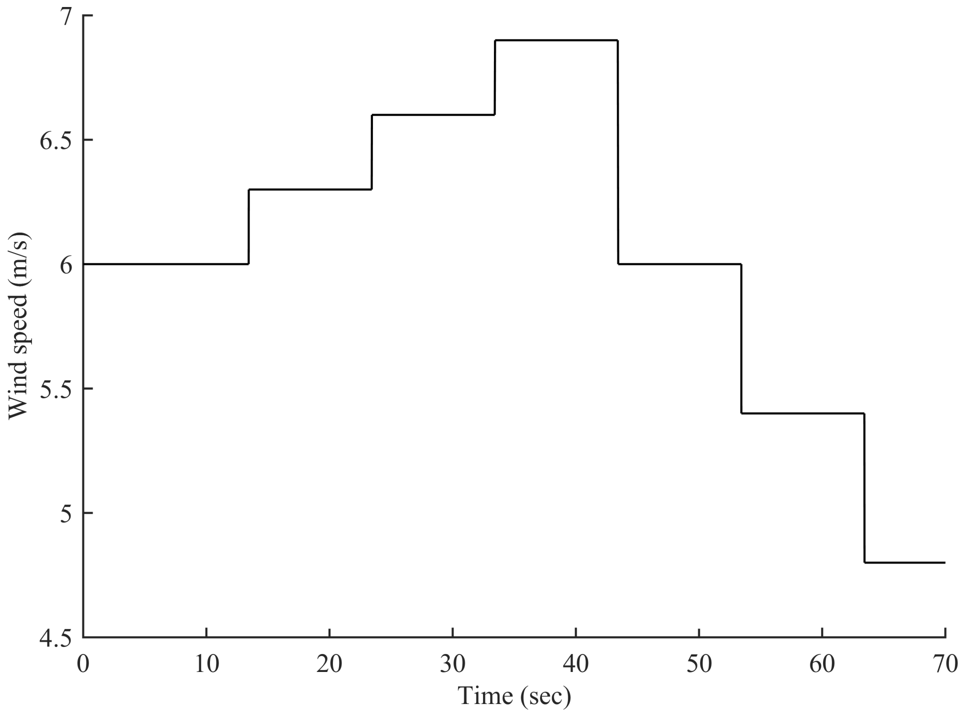


Fig. 7.3 A typical wind profile during experimentation.

7.3 Results and discussions

The objective of this chapter is to test the performance of the proposed hybrid system under highly intermittent wind conditions. The same hardware set up, as discussed in Chapter 4 has been considered for the testing of the hybrid system. As per the circuit diagram given in Fig. 7.2, a solar panel is coupled to the DC-Link capacitor through a diode. The specification of the solar panel has been provided in the Table C.1.

The tests have been conducted at variable wind conditions. Fig. 7.3 gives a typical wind profile. It is to be noted that no variations in solar power have been introduced due to the use of a physical solar panel. The performance of the proposed hybrid system is analyzed in two parts. First, wind speed above 6 m/s (rated wind speed) and second, below 6 m/s.

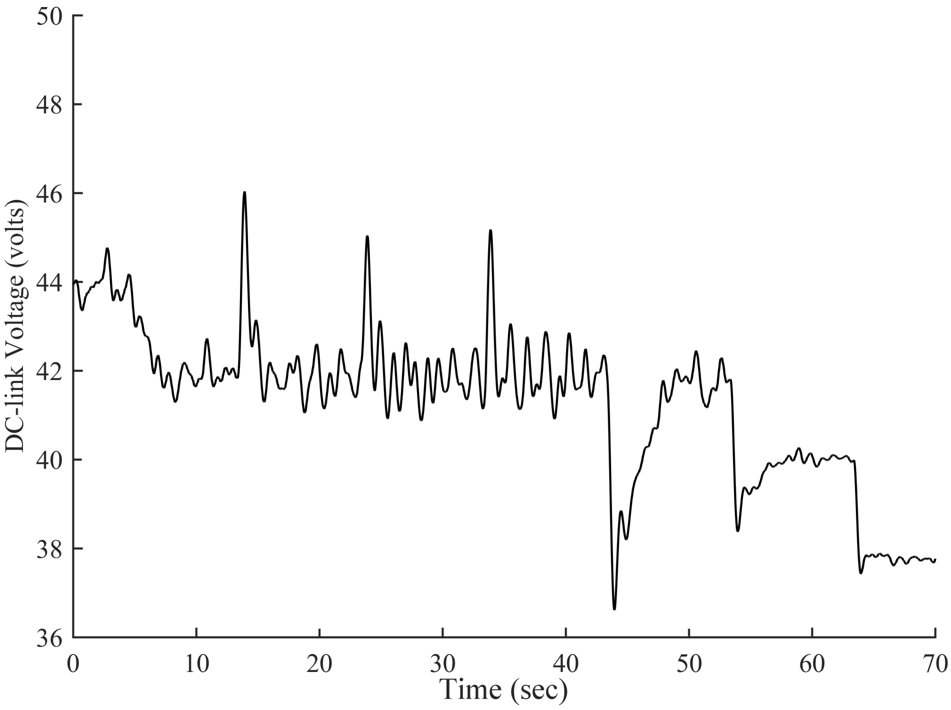
7.3.1 Extracted wind power higher than load demand

As detailed before, an experimental setup has been designed to test the performance of the proposed hybrid system under constant load and variable wind conditions. Rated wind speed in the following experimentations has been assumed to be 6 m/sec at which resistive load across dc-link capacitor is fixed, and DCV has been observed to be 44 V.

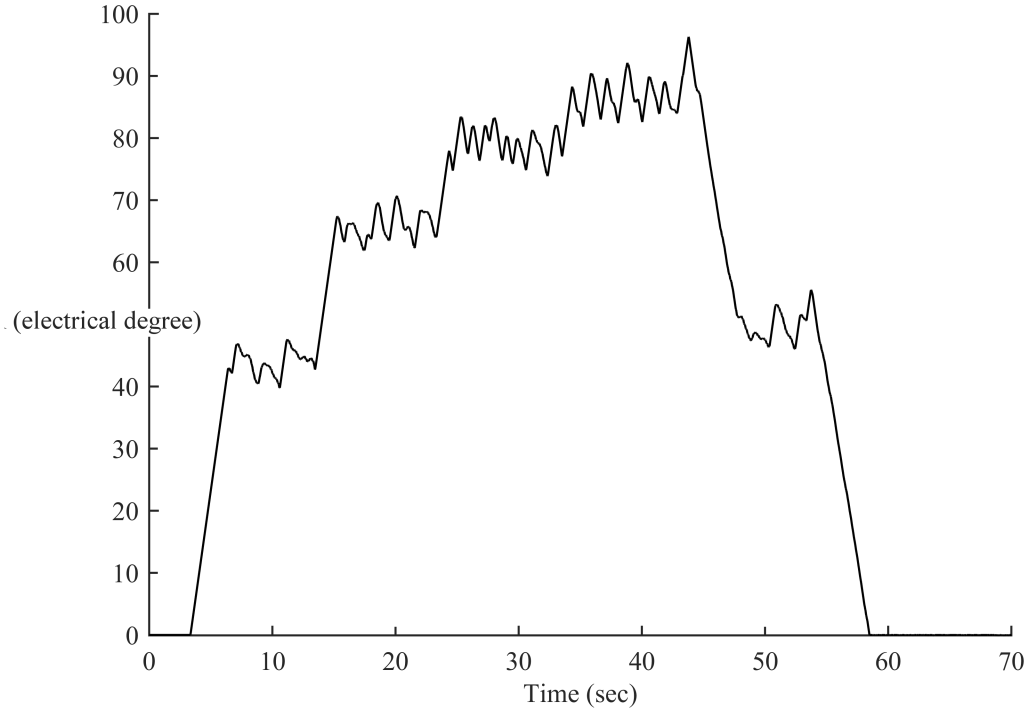
At the above-rated wind speed, wind generator power output became higher than load power. Subsequently, the voltage/power control of the wind generator is initiated by MFW of the generator. During voltage/power control, DCV regulates at 42 V. Fig. 7.4 (a) shows the DCV profile during the experimentations. In the DCV profile, spikes are present at the instant of instantaneous changes in wind speed. These spikes will be absent in practical systems because wind speed variations are smoother than considered in the experimentation. Fig. 7.4 (b) presents the dynamic angular position of RS with respect to SS during the variations of wind. Fig. 7.4 (c) shows the dynamic rotor speed profile during the DCV control. The voltage regulation capability of MFW based wind generator is limited due to the mechanical time constant involved in angular displacement of the generator's RS, as can be seen in the DCV profile at t=41 sec in Fig. 7.4 (a). However, solar energy time response is faster owing to its lower time constant, and therefore, the transient response of the proposed hybrid system is improved as can be seen by the stability of load current profile in Fig. 7.4 (d).

7.3.2 Extracted wind power less than load demand

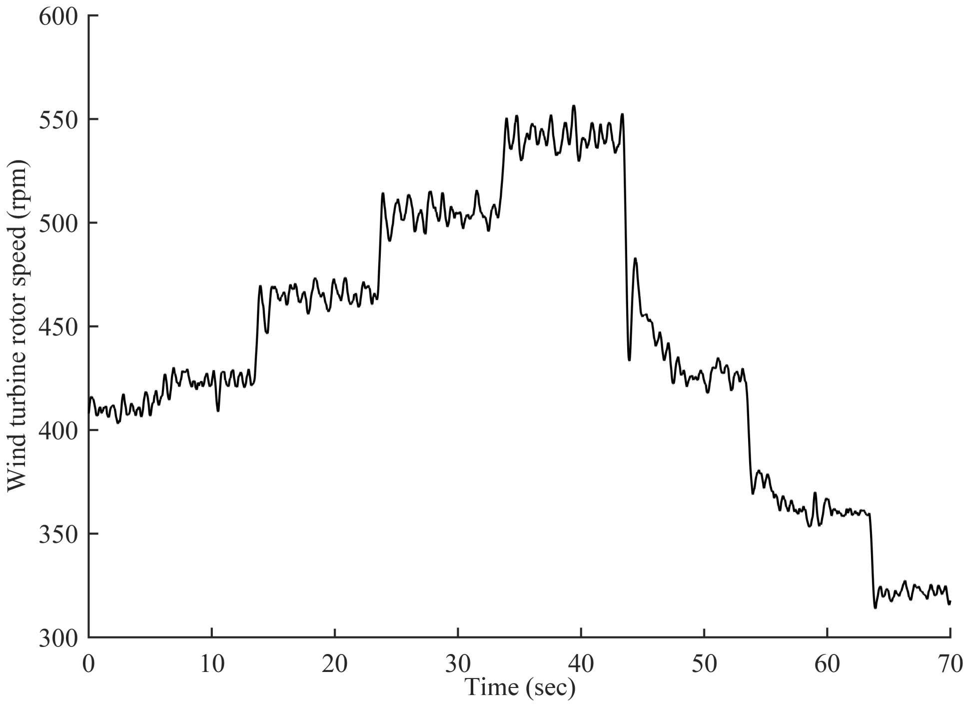
At t=51 sec, wind speed is less than rated speed as per wind speed profile in Fig. 7.3. In this case, due to the shortage of active power, DCV dips, as observed in Fig. 7.4 (a), and thus, diode D1 gets forward biased and starts conducting. Subsequently, the solar system starts supplying power to the load. Fig. 7.4 (e) shows current generated by solar since t=51 sec. It is to be noted that power share by solar system depends on the ability of



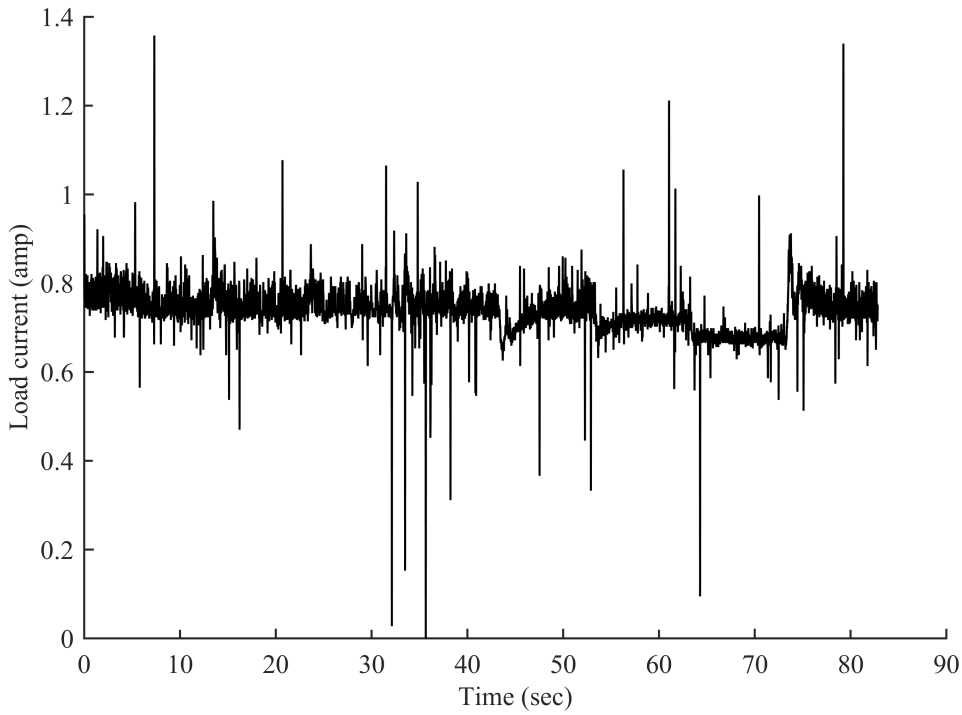
(a) DC-link voltage transient.



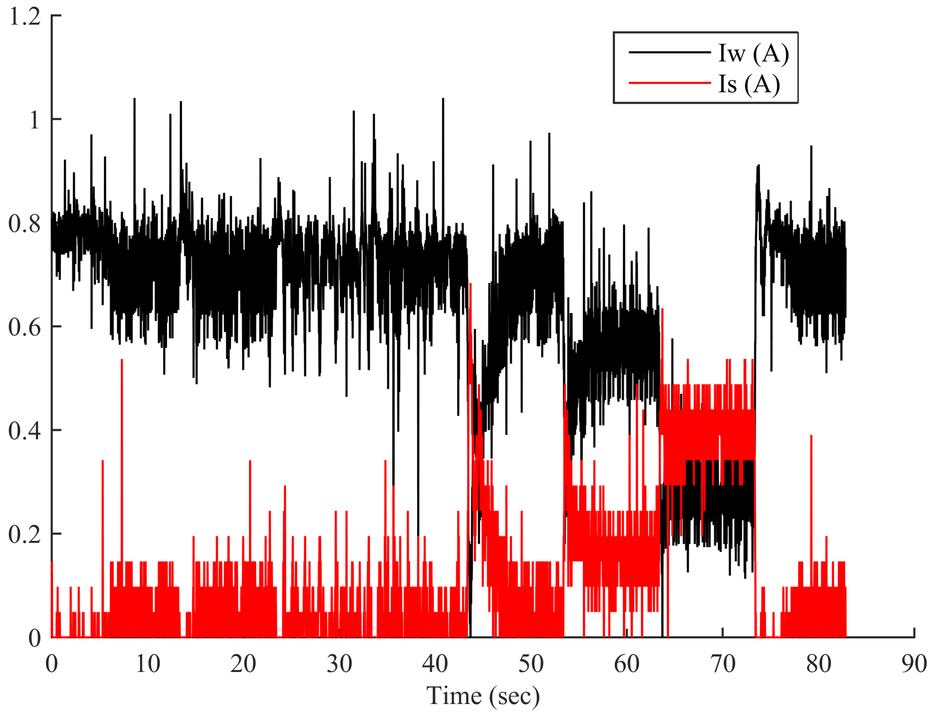
(b) Stator displacement angle of wind generator.



(c) Rotor speed dynamics.



(d) Load current profile.



(e) Dynamic wind generator current, I_W and Solar panel current, I_s.

Fig. 7.4 Performance evaluation of proposed hybrid solar-wind conversion system.

the wind generator to feed load demand. In case the wind generator is not able to supply power to load, solar system support is automatically actuated. The system may contain an energy storage device that could store solar energy during its standby phase and increase the system power reserve. However, in case the energy storage device is fully charged, the solar power load share may be controlled manually as well. In manual mode, V_{ref} is controlled below the no-load voltage of the solar system. Thus, controlling the conduction of the diode and intern connecting the solar panel to the DC-link.

Here, it is inferred that by controlling V_{ref}, the amount of power shared between wind and solar can be varied as per the state of charge of the battery. Small variations thus present in DC-link, owing to control of V_{ref}, is to be compensated by controlling the amplitude modulation index of the inverter present in the proposed system.

It is to be noted that the power share between wind and solar is being governed without using any active switches and thus saving cost, reducing complexity, and improving the reliability of the proposed RHSWS.

It is to be noted that a battery has not been included in the experimental setup in interconnection with the proposed system, and the expected results are in conformity to the earlier published results [161, 162]. The inclusion of a battery/DC generator/ supercapacitor is suggested for sustainable energy.

7.4 Conclusion

In this Chapter, a suitable cost-effective technique of hybridization of solar and wind power has been proposed. The principle of concept of hybridization is to regulate power from solar and wind supply as per demanded load. Power regulators in the proposed technique have been realized through passive switches, thus, reducing cost and complexity and improving the reliability of the system. Power regulation of solar is realized using a diode and of wind by using a field-weakened PMSG. A reduced scale hardware setup is realized for the experimentations. Experimentations have been targeted to test the performance of the proposed technique under variable wind conditions supplying constant load. Results verify the power support from solar at low wind and transient conditions. Under good wind conditions, solar energy is to be stored in an energy storage device. The stored energy would increase the power reliability of the system.