Modelling and Control of a Small-Scale Distributed Generation System based on Wind-PV and Battery

Puneet Kumar Srivastava[1], Nitesh Tiwari[1*], Amar Nath Tiwari[2], Alok Soni[1]

[1]Department of Electrical Engineering, KIPM College of engineering and Technology Gorakhpur, U.P., India

[2]Department of Electrical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, U.P., India

*Corresponding author's e-mail: niteshwr1994@gmail.com

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ABSTRACT

The paper presents modelling and control of an autonomous distributed generation system comprises of direct-drive permanent magnet synchronous generator (PMSG) based wind turbine, solar photovoltaic (PV) array and battery. The main objective of the present work is to achieve maximum power point tracking (MPPT) operation of both wind turbine and solar PV array along with delivery of quality power to the end user. A battery bank is connected across DC link through bidirectional boost converter and controlled to maintain the DC link voltage constant by charging/discharging under the events of surplus/deficit generation. Incremental conductance (INC) and tip-speed-ratio (TSR) algorithms of MPPT are used for harnessing maximum power from both the renewable energy sources. The load side inverter is controlled in order to provide a voltage of constant magnitude and frequency to the end user. The proposed system is modelled in MATLAB/Simulink and performance of the system is analysed under changes in wind speed, solar irradiance, and load demand. Controller Performance are found satisfactory in both transient as well as steady state in addition MPPT operation of both wind turbine and PV array is achieved.

Keywords: Hybrid Systems, Distributed Generation, Energy Management, Solar Photovoltaic, Micro-Grid

1 Introduction

Now a days distributed generation based on renewable energy sources are contributing significantly to clean energy production. Concept of zero net energy buildings is becoming popular, such buildings fulfil their energy requirement from renewable sources only [1], [2]. In addition, for remote locations, where grid has not reached, customers are being supplied with distributed generation system. In absence of such distributed generation systems, remote communities generally depend on diesel generators for their electricity needs, which may not be cost effective and environment friendly. Distributed generation systems based on renewable energy sources are becoming most interesting and economical solution for such isolated customers [3]. Intermittent nature of wind and solar irradiance needs battery support in standalone distributed generation systems [3]– [5]. Distributed generation systems solely based on solar or wind are not reliable due to intermittency and seasonality in such sources, combining these two sources results in more reliable system [6], [7]. Due to distinct nature of output voltages from different sources, different power electronic interfaces are required in distributed generation and must be controlled intelligently for effective management of power and efficient operation of the system [8]– [10].

As wind turbines are low speed prime movers, multi-pole permanent magnet synchronous generators (PMSGs) are being popular in such applications. Along with its low operational speed, several other favourable attributes are associated with PMSGs that advocates its use in renewable energy generation. Self-excitation capability, gearless/direct-drive operation, higher energy efficiency, low cost of energy generation and high power factor are some salient features of PMSGs making it suitable for such applications [3], [11].

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Solar photovoltaic systems are in a form off PV panel or PV module. These panels or modules are series and parallel combination of numbers of cells. Such series-parallel combinations of unit cells are required for increasing the power generation capability of individual panel or module. For higher power generation these panels/modules should be further connected in series and parallel [10], [12].

Effective energy management can improve performance of the distributed generation by proper control of different renewable energy sources. In standalone-distributed generation, the control of voltage at consumer terminal is the main challenge. Due to intermittency in solar irradiance and wind speed, voltage fluctuations are introduced in the voltage at the consumer terminal and power electronic interfaces may act as primary cause of harmonics, which are not tolerable by the end users and needs to be addressed.

The objective of this paper is to model a small-scale microgrid utilizing hybrid energy resources such as, wind, solar PV, and battery. It is noticeable that both solar irradiance and wind speed directly affect the DC link voltage due to which maintaining the voltage at consumer terminal will be difficult. Actually, the voltage at consumer terminal is affected by variation in DC link voltage as well as variation in load. In this paper, we have achieved a proper coordination among different sources by keeping DC link voltage at a constant level and with this maintaining the consumer terminal at required level becomes easier.

2 System Description

Schematic of the proposed distributed generation system is shown in Fig. 1, where direct drive PMSG, solar PV array and battery are different sources. Wind turbine output is fed to a pulse width modulated (PWM) rectifier whereas PV array output is fed to a boost converter. Rectifier and boost converter are controlled to operate both these sources in order to extract maximum power from wind and solar irradiance respectively. Basic incremental conductance (INC) and tip-speed-ratio (TSR) methods of maximum power point tracking (MPPT) is used for solar PV and wind respectively.

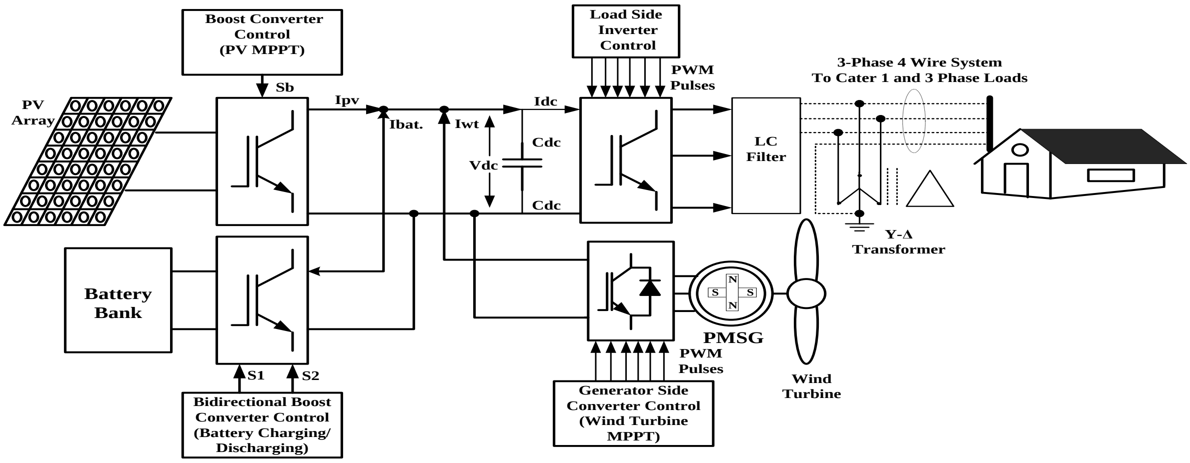

Figure 1: *Proposed Distributed Generation System based on Wind-PV-Battery*

Output of both rectifier and boost converter is fed to a common DC link. The PV array voltage is set to the nominal value of DC link voltage and INC algorithm maintains the PV array voltage at DC link reference so that the array delivers the current corresponding to its maximum power point. PMSG speed/torque is controlled through controlling the active current component of stator, whereas reactive current component of stator is maintained at zero in order to achieve maximum torque per ampere operation of the PMSG. This makes the PMSG to operate at maximum power point and to deliver the active current in accordance with its maximum power characteristics. Rectifier is controlled to achieve MPPT operation of the wind turbine by controlling PMSG speed to a reference speed obtained from TSR algorithm.

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Further, the load side inverter is connected to the DC link capacitor. In the event of variation of load, DC link voltage varies which also reflects in inverter output. In addition, if the load demand is more/less than the next generation from solar PV and wind, the DC link voltage drops/rises. In order to address this, we have deployed battery storage, which discharges/charged in order to keep the DC link voltage at its nominal value in the event of reduced/surplus generation. As single-phase loads require neutral, we have used star-delta transformer to provide neutral to such loads.

3 DC link Voltage Control

In autonomous/standalone distributed generation systems, the key concern is offering voltage of constant magnitude and frequency at consumer terminal. In the system proposed, wind and solar PV are used, and both these sources are connected to a common DC link through power electronic interfaces. Finally, the load side inverter is connected to the DC link. The DC link voltage varies with variation in wind speed, solar irradiance, and load. In order to maintain the inverter output voltage at required level, the modulation index must be kept at 1, which can be achieved by maintaining the DC link voltage at its reference value [3], [13], [14]. In addition, frequency of the inverters output can be maintained at a specified value by choosing the frequency of sinusoidal reference during pulse with modulation process.

In the system proposed, battery is connected to the DC link though bidirectional boost converter, to maintain the DC link voltage through its charging and discharging during surplus and deficit of generation from wind and solar PV systems. Using bidirectional boost converter, the battery voltage can be kept bellow than DC link voltage reference and number of series connected batteries will be fewer. In this work two 200 V Nickle Metahydride (Ni-MH) batteries are connected in series, whereas DC link reference value is 652 V. Controller schematic of bidirectional boost converter is shown in Fig. 2. The objective of this control is to maintain the DC link voltage at its specified reference by regulating the battery current. Measured DC link voltage and its corresponding reference is compared, and the obtained error is processed through a PI controller to produce reference battery current. Further, this reference and actual battery current are compared and in order to limit the error a hysteresis band is used. Considering life of the battery it's charging and discharging is limited in accordance with its status of charge (SOC) and maximum depth of discharge (DOD) which is 80% and 20% respectively.

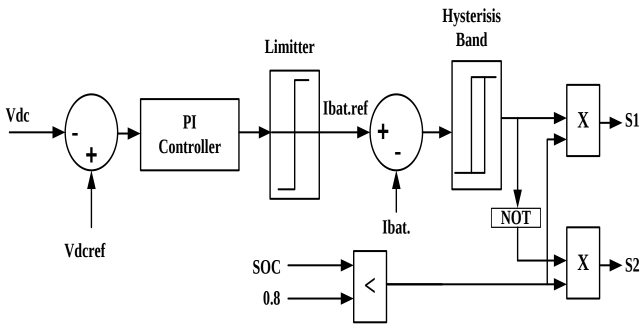

Figure 2: *Bidirectional Boost Converter Control*

Incremental conductance and tip-speed-ratio based MPPT algorithm have been adopted to achieve MPPT operation of both renewable energy sources. Detailed theory of these algorithms are available in [15], [16] and [17]–[20], hence it is not repeated here. The load side inverter is controlled in order to provide voltage of constant amplitude and frequency to the customers. Output of the load side inverter will contain harmonics due to high frequency modulation, which is provided to the customers, so they may face power quality problem. In order to address this LC filter has employed at the point of common coupling (PCC).

4 Control of Load Side Inverter

As in autonomous systems, single-phase loads will also be there along with three-phase loads. Unbalance loading on PCC results in flow of unequal currents in different phases which leads to unequal voltage drops across LC filters used in each phase. Relation for obtaining value of L and C is given in [3]. This may lead to voltage unbalance at PCC and needs to be addressed. In order to address this, the rms value of actual phase voltages are measured and compared with their required reference value through comparators. The comparator outputs are then processed through PI controllers and controller output thus obtained is multiplied with a sinusoid reference of unit amplitude and required frequency. In this way, sinusoidal reference for generating PWM pulses for turning ON/OFF the inverter switches is obtained. The control block diagram for load side inverter control is shown in Fig. 3.

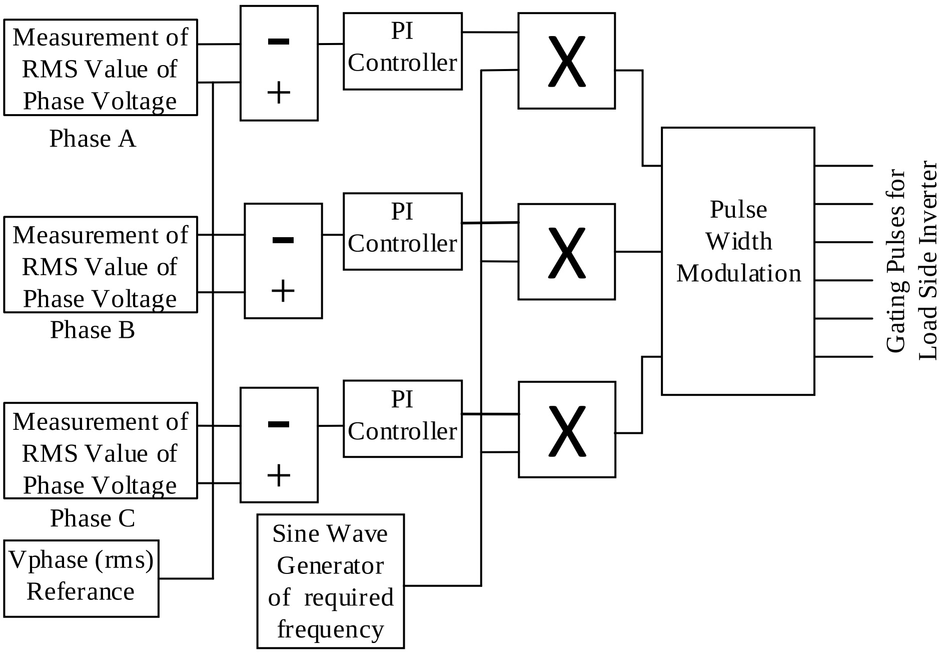

Figure 3: *Load Side Inverter Control*

5 Results

The simulation model of the proposed hybrid distributed generation system combining wind, solar and battery as energy sources for feeding power to remote customers is built in MATLAB/Simulink platform. The schematic of the system proposed is shown in Fig. 4 a. The battery used in the system acts as source and sink depending upon cumulative generation and load demand. During surplus generation, it acts as sink and as a source if generation is insufficient to cater the load demand. It remains idle during balance that is both generation and demand are equal. The PMSG is modelled in d-q reference frame [19], [21] and PMSG parameters are obtained and are given in Table 1. General mathematical model of PV cell is available in [22], [23], in this paper we have considered a commercially available PV module, and the parameters are made available in Table 2. Base wind speed and base solar irradiance are considered 12 m/s and 1000 W/m^2 respectively. In the present work we have implemented a generic battery model which is presented in [24] and experimental validation of which is presented in [25], battery parameters are reproduced in Table 3.
As wind turbine is a slow speed prime mover, we have used PMSG with higher number of poles to couple it directly with the turbine. This is done in order to avoid gearbox and increase the reliability of the system. Torque and speed response of the wind turbine and PMSG under variation of wind speed can be observed from Fig. 4 a to Fig. 4 d. The wind speed changes from 9.6 m/s to 10.8 m/s at t = 3 s and from 10.8 m/s

to 12 m/s at t = 6 s. It can be seen from Fig. 4 b and Fig. 4 c that torque and rotational speed are acquiring higher values for increasing wind speed as per the MPPT requirement that is optimum rotational speed as obtained by MPPT algorithm, which is TSR. It is interesting to note here that as the turbine and generator torque matches the speed becomes constant. The power produced from wind turbine is shown in Fig. 4 d. Further, we have used PV array of 12 series connected module and 3 parallel connected strings of a commercially available module developed by SunPower SPR-305E-WHT-D for which voltage and current corresponding to MPP are 54.7 V and 5.58 A respectively. INC algorithm is used for achieving MPPT operation of PV array. During MPPT the array voltage is maintained at DC link voltage reference and the array produces current in direct proportion of the solar irradiance to generate power corresponding to the MPP operation. The MPP operation of PV array can be observed from Fig. 4 e to Fig. 4 h. The solar irradiance changes in step from 600 W/m^2 to 800 W/m^2 at t = 2 s and from 800 W/m^2 to 1000 W/m^2 at t = 5 s Fig. 4 e. Variation in array current corresponding to variation in solar irradiance can be seen from Fig. 4 f to Fig. 4 g and array power from Fig. 4 h.

Table 1: *Parameters of PMSG based Wind Turbine*

PMSG Power	10 kW
Rated Speed	32 rad/s
Armature Resistance	0.055238 ohm
Armature Inductance	0.041236 H
Peak flux	1.86294 Wb
Number of Poles	10
Tip Speed Ratio	8.1
Base Wind Speed	12 m/s
Blade Radius	3.1 m

Table 2: *Parameters of PV Array*

Model Type	SunPower SPR-305E-WHT-D
Maximum Power	305.226 W
Open Circuit Voltage (Voc)	64.2 V
Voltage at Maximum Power Point	54.7
Temperature Coefficient of Voc	-0.27769 %/^{0}C
Cells per Module	96
Short Circuit Current (Isc)	5.96 A
Current at Maximum Power Point	5.58 A
Temperature Coefficient of Isc	0.061745 %/^{0}C
Photo Current	6.0092 A
Diode saturation Current	6.3014x10^{-12} A
Diode Ideality Factor	0.94504
Shunt Resistance	269.5934 ohm
Series Resistance	0.37152 ohm
Number of Series Connected Module	12
Number of Parallel Connected Strings	3

Table 3: *Parameters of the Battery*

Battery Type	Ni – MH (Nickle Metahydride) Battery
Battery Voltage	200 V
Battery Capacity	6.5 Ah
No. of series connected batteries	3
No. of parallel connected strings	12

Test Conditions 1: *Performance under varying wind speed, solar irradiance, and load demand (3-phase balanced)*

The performance of the proposed distributed generation system is examined under the events of variation of wind speed, solar irradiance, and load demand. The system comprises of PMSG based direct-drive wind turbine, Solar PV array and Nickle Metahydride (Ni-MH) battery to cater the load demand. For the evaluation of the system's performance considered variation in wind speed, solar irradiance and load demand are given in Fig. 4 a, Fig. 4 e and Fig. 4 i respectively. DC link voltage response for the changes in wind speed, solar irradiance and load demand is given in Fig. 4 j. It is observed that there is no noticeable change found in it with previously mentioned variations. It is interesting to observe that at t = 3 s and t = 6 s, where wind speed sees stepped rise in it; DC link voltage transients are noticeably small. This is due to combined inertia of the wind turbine in view of which the PMSG output power follows the change in wind speed with a delay. At t = 2 s and t = 5 s, where solar irradiance changes, small voltage transients are observed in DC link voltage. Further, at t = 4 s, load demand is stepped to a higher value, and with this too the DC link voltage transients are found almost missing. This clearly demonstrates the effectiveness of DC link voltage controller in both transient as well as steady state conditions. Voltage at the load terminal is maintained constant at 231 V (phase-ground) Fig. 4 k; it is observed that the output voltage has not affected considerably by the variations in wind speed and solar irradiance. However, transients are seen in this on the events of variation in load demand which is at t = 4 s, as load is directly connected at inverter output terminals. Instantons line voltages and line currents are given in Fig. 4 l and Fig. 4 m respectively and THD in both are found below 2% for all the phases, which shows that the proposed supply system offers voltage and current of satisfactory quality to the customer.

Response of wind turbine, PV array and battery and load demand has shown in Fig. 4 n. The responses of various sources shown in figure 14 are in view of variation in wind speed, solar irradiance along with actual load demand. The battery used in the system acts only in case of power mismatch between total generation from renewable energy sources and load demand. The results shown in Fig. 4 n is with initial state of charge (SOC) of the battery to be 60%. If the total generation is more than the demand then surplus amount of power available on the DC link goes to the battery and it is charged, whereas if there is generation deficit then batter discharges and feed power to the DC link and in this way DC link voltage is maintained at its reference. Important events of concern are at t = 2 s to t = 6 s. At 2, 3, 5 and 6 s power from one of the renewable energy sources is constant and of the other source changes, in such events prompt response of the battery can be seen. It is worthwhile to note that PV power attains it new reference at once, but wind turbine lacks in this due to its larger inertia. On 3 and 4 seconds when wind speed varies and power is changed, it takes time to come in steady state, under such events a huge transient could be seen in load power in absence of the battery.

The response of the system is also examined for a different load cycle, clearly displaying the charging, and discharging of battery during surplus and deficit generation from renewable energy sources. Positive power of battery should be considered as discharging mode and negative for charging mode Fig. 4 o. Excellent DC link voltage controller response can be observed from Fig. 4 p.

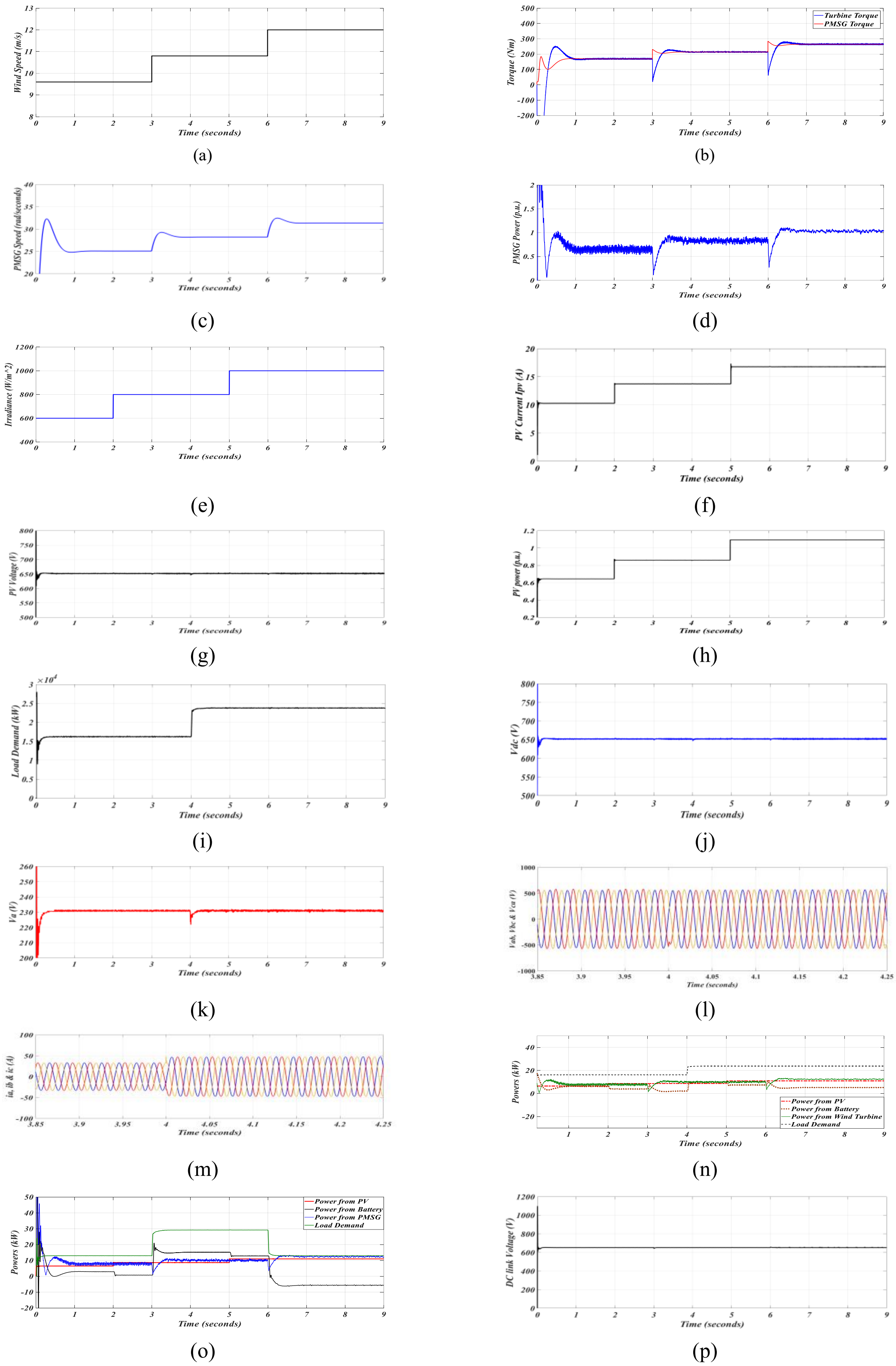

Figure 4. (a) *Wind Speed (m/s)* ***(b)*** *Turbine and Generator Torque (N/m^2)* ***(c)*** *PMSG rotational Speed (rad/s)* ***(d)*** *Power from WT (p.u.)* ***(e)*** *Solar Irradiance (~~w~~ W/m^2)* ***(f)*** *Array Current (A)* ***(g)*** *Array Voltage (V)* ***(h)*** *Array Power (p.u.)* ***(i)*** *Load Demand (kW)* ***(j)*** *DC link Voltage (V)* ***(k)*** *rms voltage (V)* ***(l)*** *Line voltages (V)* ***(m)*** *Load Currents (A)* ***(n)*** *Powers from different sources (kW)* ***(o)*** *Powers from different sources (kW)* ***(p)*** *DC link Voltage (V)*

Test Conditions 2: *Performance under varying wind speed, solar irradiance, and Unbalance Load Demand*

As distributed generator systems are mainly have connections with high number of single-phase loads, so loading on different phases may not be equal all time and the supply system may be unbalanced due to this unbalanced loading of different phases. In order to observe the performance of the proposed distributed generation system, the model is simulated under unbalanced loading conditions. Instantaneous currents of different phases during unbalanced loading conditions are shown in Fig. 5 a. Instantaneous value of different phase voltages has shown in Fig. 5 b. It is interesting to observe that voltage at PCC is immune to such unbalance. Such unbalance in load might affect the DC link voltage too in absence of battery support. Fig. 5 c and Fig. 5 d respectively shows rms values of three phase voltages and powers from different sources along with the load demand. For the present test, we have connected single-phase loads of different magnitude to different phases in the duration of 1-2 s. It can be seen in figure 5 c, that vary small variation appears in voltage. Modulation indices for different phases are given in Fig. 5 e. Effort of battery charging/discharging (DC link voltage regulator) controller can be observed by comparing Fig. 5 d with Fig. 4 o. During 1-2 s, previously three-phase balanced loads were applied, and the generation was insufficient to fulfil the load demand, hence battery discharges in order to cater the load as per its requirement. Now, with additional single-phase loads in the said duration, the scenario worsens, and battery instantly offers help in order to feed the load as per its requirement. Therefore, it has observed the all the controllers are demonstrating excellent performance in transient as well as steady state under the events of variation in wind speed, solar irradiance, and load.

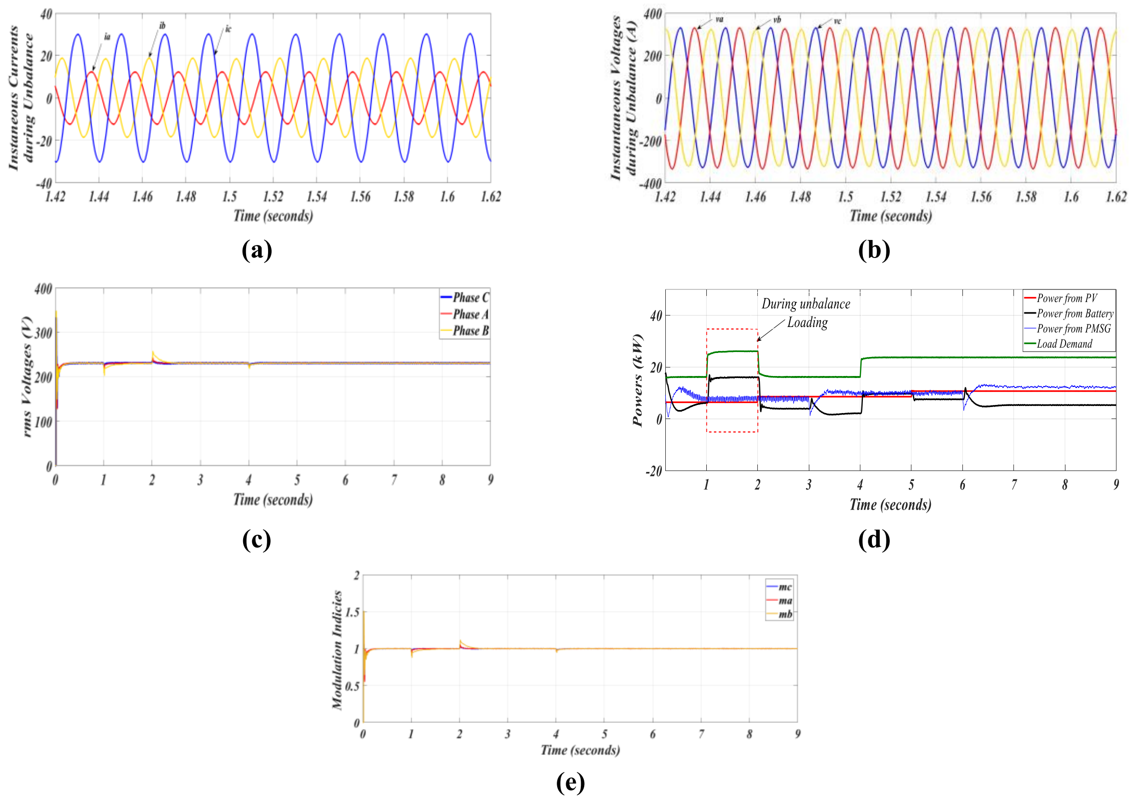

Figure 5: (***a)*** *Instaneous Currents (A)* ***(b)*** *Instantaneous Voltages (V)* ***(c)*** *rms Voltages (V)* ***(d)*** *Powers (kW)* ***(e)*** *Modulation Indecies of phase a, b and c*

6 Conclusions

This paper presents a standalone distributed generation system for remote customers. The system includes wind turbine, solar PV, and battery to cater the load demand. The objective of the present work is to achieve

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MPPT operation of both the renewable energy sources and providing quality voltage to the customers. In order to make the inverters output voltage immune to the variation in load, DC link voltage must be maintained at its specified reference. We have employed a battery in the system and connected it to the DC link through bidirectional boost converter, whose control maintains the DC link voltage at its reference by allowing charging and discharging of the battery during surplus and deficit of total power generated. Further, LC filter have been employed at inverter output to filter out the harmonics to enhance the quality of power fed to the load. The load side inverter is controlled to provide voltage of constant amplitude and frequency to the load. Simulation results demonstrates effective performance of the different controllers in providing voltage of constant amplitude and frequency to the customers which is perfectly immune to the variation in wind speed, solar irradiance, and load demand. Excellent performance of controllers has observed in transient as well as in steady state conditions.

7 Declarations

7.1 Competing Interests

The authors declare no conflict of interest.

7.2 Study Limitations

There are no limitations that significantly affect the research outcome.

7.3 Warning for Hazard

The does not involve any chemicals, procedures, or equipment with unusual hazards.

7.4 Ethical Approval

Ethical approval is not required for this study.

7.5 Informed Consent

No human or animal subjects were involved in this research; hence no informed consent was obtained.

7.6 Publisher's Note

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