Dynamic Modeling and Performance Study of a Stand-alone Photovoltaic System with Battery Supplying Dynamic Load

Jayalakshmi N. S.*‡, D. N. Gaonkar**, Anusree Balan*, Prasanna Patil*, Syed Adil Raza*

*Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal, India-576104
**Department of Electrical and Electronics Engineering, National Institute of Technology, Karnataka, Surathkal, India-575025
jayalakshmi.ns@manipal.edu, dngaonkar@gmail.com, anusree310@gmail.com, prsn.patil@yahoo.com, asmidesnavi@yahoo.co.in

‡ Corresponding Author: Jayalakshmi N.S., Department of Electrical and Electronics Engineering, Manipal Institute of Technology, Manipal, India-576104 Tel: +91-9481970925, jayalakshmi.ns@manipal.edu

Received: 17.06.2014 Accepted: 06.08.2014

Abstract- Autonomous photovoltaic power generation is weather and time dependent which need energy storage to balance generation and demand. This paper presents modeling, simulation and performance study of a stand-alone photovoltaic system along with battery back up. The modeling and simulation of the considered system are accomplished in MATLAB/Simulink environment. The simulation model consists of solar energy source, maximum power point tracking (MPPT) controller, battery energy storage element with controller with associated power electronics converters. A pulse-width-modulated (PWM) three-phase inverter controller is developed to regulate three-phase ac bus voltage and frequency. The dynamic load such as a three phase induction motor and DC load are considered to study the performance analysis of the system. Simulation results show that under dynamic and steady state condition the control strategies work satisfactorily to supply power to the load.

Keywords - Photovoltaic system, Battery energy storage, Stand-alone system, DC-DC Converter, Battery controller, PWM Inverter

1. Introduction

The production of electricity from renewable energy sources like photovoltaic (PV) increases in recent years due to environmental problems and the shortage of traditional energy sources. Sun is the most powerful source of energy which is readily available, environment friendly and is widely used in all stand-alone systems. For remote areas, which are isolated from utility grid, stand-alone operation is the best option. An energy storage system is essential in all stand-alone systems to store the excess energy and also provide power due to increase in load power or reduction in source powers.

Recently, solar energy has become a promising alternative renewable source due to the attractive features of the solar power generation systems, such as direct energy conversion, ease of integration and low environmental impacts. Solar panels which are made up of photovoltaic cells connected in series and parallel. These cells convert light energy into DC electricity and a silicon made semiconductor material is used [1, 2]. The conversion efficiency of the PV cell is low and to increase its operating efficiency a maximum power point tracking (MPPT) algorithm is required. There are different methods of MPPT and are discussed in [3, 4]. The stand-alone hybrid systems and their performance with battery storage have been studied and discussed in [5-8]. A battery storage system has a significant role in all stand-alone hybrid systems. Batteries are the most promising units for renewable energies, since their energy density is high and have high performance. In all stand-alone systems, a battery backup is needed to get the continuous power supply [9-11]. The different type of battery energy storage devices includes Lead-Acid, Nickel Cadmium, Sodium Sulphur, Nickel Metal Hydride and Lithium-Ion. In this work, Lead-Acid batteries are used since they are suitable for renewable energy applications due to its lengthy life span and low cost. Lead-acid batteries compromise its efficiency for longer charging and discharging cycles and a life span of 20 years [6-10].

In this paper a control algorithm of the battery charger for PV applications is presented to keep the DC link voltage constant during changes in source power or load. The continuous power may not be available most of the time especially during night due to the fluctuating nature of power supplies of the PV and the changes in load demands. When the solar energy is not sufficient, a battery backup is needed to get the continuous power supply. So this problem can be solved by a solar/battery hybrid system. To interface PV modules and battery to a common DC-link two DC-DC converters are used. The control strategy for the battery maintains the power balance in the system and load demand. To simulate the real data system, the solar irradiation values for one day for the month of January was collected from the innovation centre, MIT, Manipal and used for simulation. A dynamic load such as a three phase induction motor and DC load are considered to evaluate the system dynamic behavior. This type of hybrid system can be implemented in houses, apartments and industries rooftops in various parts of India and can contribute for effective harvesting of renewable energy resources.

2. System Configuration and Modeling

The developed hybrid system shown in Fig. 1 mainly consists of a solar energy source, battery storage device, DC/DC boost converters with MPPT controller, inverter with controller and loads. The objective of the work is to develop a Photovoltaic system along with a battery storage for stand-alone residential applications. Solar energy system along with a battery can provide more stable and reliable power to the load. In order to analyze the operation, both modeling and control are important issues. The simulation model consists of solar energy source, energy storage element, MPPT control and its associated conditioning units. A PWM Inverter controller is developed to regulate three-phase ac bus voltage and frequency. A Control strategy for DC-DC buck/boost converter is essential to keep the DC link voltage constant during changes in source power or load. The PV/battery system can be implemented in houses, apartments and industries rooftops in various parts of India and can contribute for effective harvesting of renewable energy resources.

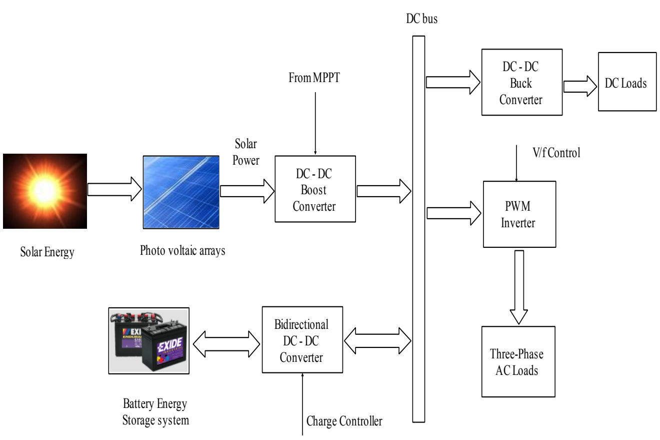

Fig. 1. The PV/Battery hybrid system representation

For photovoltaic array modeling, the mathematical equations are utilized. Due to low conversion efficiency of PV modules, MPPT controller is used. For modeling of a PV cell, the electrical equivalent circuit shown in Fig. 2 is considered. It includes a current source in parallel with a diode, a resistance in series and shunt resistance.

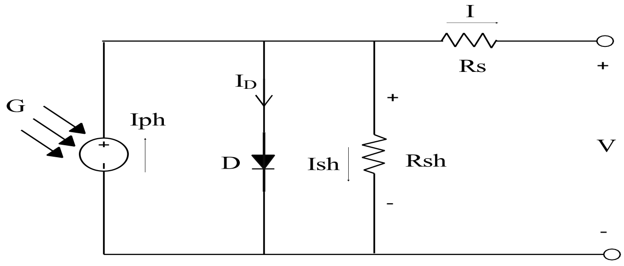

Fig. 2. Circuit diagram of the Photovoltaic cell

The net current in terms of the photocurrent I_{ph}, the normal diode current I_o and leakage current is given by [12, 13]

$$I = N_P I_{ph} - N_P I_S \left\{ e^{\frac{q}{AkT}\left(\frac{V}{N_S}+\frac{IR_S}{N_P}\right)} - 1 \right\} - \frac{N_P}{R_{Sh}}\left(\frac{V}{N_S}+\frac{IR_S}{N_P}\right) \quad (1)$$

Where N_p= number of parallel and N_s= number of series connected cells, the shunt resistance is not considered in the study. Since both photocurrent I_{ph} and diode current I_o depends on temperature, these currents are given by

$$I_{ph} = I_{ph}(T_1) + K_O(T - T_1) \quad (2)$$

$$I_{ph}(T_1) = I_{SC}(T_1, nom)\frac{G}{G(nom)} \quad (3)$$

$$K_O = \frac{\mathrm{Isc(T2)} - \mathrm{Isc(T1)}}{(T2 - T1)} \quad (4)$$

$$\mathrm{I}_0 = \mathrm{I}_0(T_1) \times \left(\frac{T}{T1}\right)^{\frac{3}{n}} e^{\frac{qVq(T_1)}{nk\left(\frac{1}{T}-\frac{1}{T1}\right)}} \quad (5)$$

$$I_O(T1) = \frac{Isc(T1)}{\left(e^{\frac{qVoc(T1)}{nkT1}} - 1\right)} \quad (6)$$

$$X_V = I_O(T_1)\frac{q}{nkT1} e^{\frac{qVoc(T1)}{nkT1}} - \frac{1}{Xv} \quad (7)$$

$$R_S = -\frac{dV}{dI_{Voc}} - \frac{1}{Xv} \quad (8)$$

3. Control Strategies

A. Photovoltaic MPPT Control

A MPPT controller is essential in all PV systems to deliver the highest possible power to the load. There are different approaches like fractional open-circuit voltage method, fractional short-circuit current method, Perturb and Observe (P&O), incremental conductance, etc. to track the maximum power [3, 4]. In this paper, the incremental conductance method is used as it has the ability to track the maximum power under fast changing atmospheric conditions.

In this method, the PV module terminal voltage is adjusted according to the MPP voltage based on the incremental and instantaneous conductance of the PV module. The relationship between dI/dV and –I/V is based on the fact that when MPPT is towards the right side of the MPP, dP/dV is negative and when it is towards the left side of the MPP, dP/dV is positive. This algorithm can determine the MPPT has reached the MPP or not, while operating point oscillates around the maximum power point.

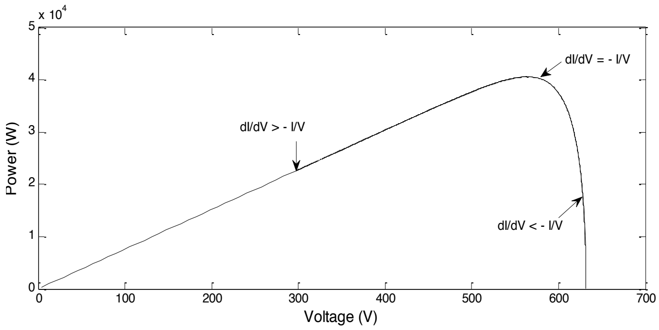

Fig. 3. P-V Curve of 40kW solar module

From Fig. 3 it is clear that at the point of MPP the slope of the P-V curve is equal to zero, positive on the left of the MPP and negative on the right of the MPP. The basic equations are given by [14].

$$\frac{dI}{dV} = -\frac{I}{V} \text{ at the point of maximum power} \quad (9)$$

$$\frac{dI}{dV} > -\frac{I}{V} \text{ to the left side of maximum power point} \quad (10)$$

$$\frac{dI}{dV} < -\frac{I}{V} \text{ to the right side of maximum power point} \quad (11)$$

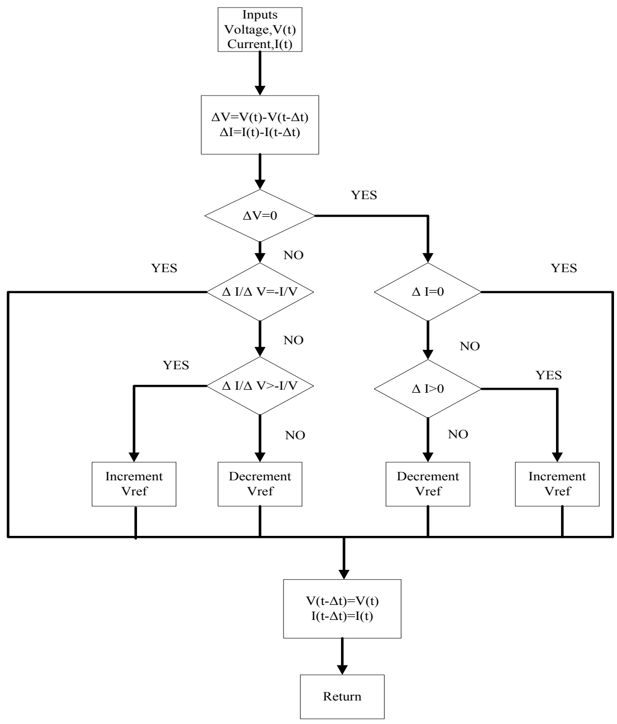

Fig. 4. Flowchart based on IC method

Since dP/dV=0, at the point of maximum power, in terms of V and I, the equation could be written as dP/dV = [d(VI)]/dV = 0;

$$\therefore \; dI/dV = -I/V$$

The PWM control signal of the converter is regulated by the MPPT until the condition (dI/dV)+(I/V)=0 is occurred. The Fig. 4 depicts the flowchart for incremental conductance MPPT method [14].

B. Controller for Buck/Boost Converter

The lead-acid battery used in the system mainly operates in two modes, in which the battery must be charged or discharged to store excess energy from solar source or to supply load power when solar power reduces. To maintain continuous power flow between the DC bus and battery storage device with constant DC link voltage, a buck/boost DC-DC converter is used [15, 16]. The reference DC link voltage of 780V is considered, so that the DC bus voltage will remain stable during changes in the source power or load variations.

Two PI control loops are used to regulate the DC-link voltage. The inner loop controls battery current against any parameter variations and the outer loop regulates the voltage. The power balance between fluctuating source power and time varying load is mantained by battery charging or discharging process. The control strategy for battery converter is shown in Fig. 5.

From the Fig.5, it is clear that there are two IGBTs in the configuration of converter in which both operates in complimentary driven by PWM signal. The voltage V_{dc} is then compared with a reference voltage (V_{dcref}) to get an error signal, after that the I_{bref} is compared with battery current to get a PWM signal and the error obtained is compensated by the PI controller as shown in the Fig. 5.

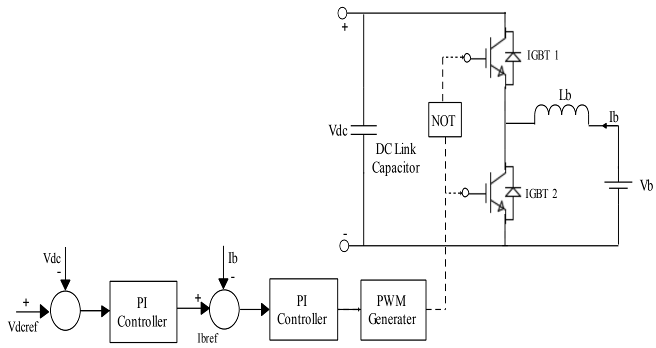

Fig. 5. Control strategy for DC-DC converter

C. Inverter controller

To provide electric power to industrial applications, the inverter converts the dc bus voltage to a regulated three phase ac voltage with appropriate amplitude and frequency. Since no grid exists in the stand-alone system, the output voltage and frequency have to be controlled based on rotating reference frame theory [17-19]. By generating a reference angular velocity ω, the frequency of the system is controlled. The voltage equations across the RL filter are given by [19, 20]

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = Rf \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + Lf \frac{d}{dt} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} Va1 \\ Vb1 \\ Vc1 \end{bmatrix} \quad (12)$$

Where R_f = resistance and L_f = inductance of RL filter and i_a, i_b, i_c are 3-phase load currents. The *d-axis* and *q*-axis load voltages are given by:

$$V_d = V_{di} - i_d R_f - L_f \frac{did}{dt} + \omega L_f i_q \quad (13)$$

$$V_q = V_{qi} - i_q R_f - L_f \frac{diq}{dt} - \omega L_f i_d \quad (14)$$

The voltage V_{di} and V_{qi} are given to PWM signal generator so that the output voltage is controlled as shown in Fig. 6.

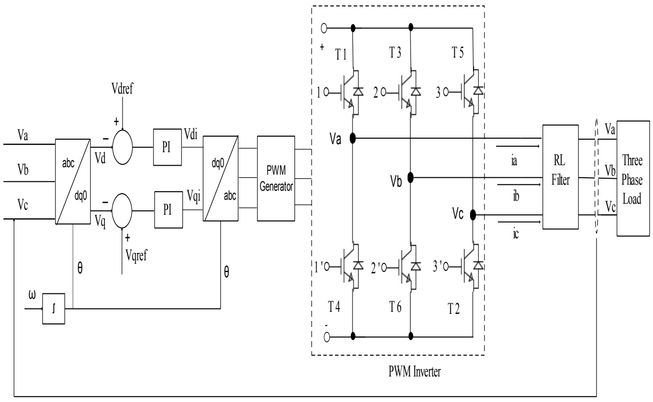

Fig. 6. V/f Control of Inverter

4. Results and Discussions

The simulated responses of the system for different operating conditions in Matlab/Simulink environment are presented in this section. A simulation time of 2.4 sec has been considered. The Solarex MSX60 PV module was used in this study and the simulation parameters of PV cell and battery are given in Table 1 [13]. To simulate the real data system, the daily global solar radiation data at Manipal, India during January month is considered for the study [21]. The DC bus voltage is maintained constant by the battery controller. A PWM inverter controller is developed to regulate high quality of three-phase AC bus voltage and frequency. The reference value of DC-link voltage is set at 780V and the initial charge for battery is 70%. The following different cases are considered for the analysis with variations in solar irradiation and load conditions.

Case I: Variable AC and DC load

A 3phase resistive load, three phase squirrel-cage induction motor (10HP, 415V, 50Hz, 1440RPM) load and DC load are considered to study the dynamic behavior of the system. In this case, initially the resistive load is 13kW and is suddenly increased to 18kW at t=1.2sec. The load torque applied to the shaft of the 3 phase induction motor is 50 N-m initially and is suddenly increased to 70 N-m at t=1.2sec. The DC load is varied from 0 to 10kW. The simulated results for active power outputs of PV system, battery, inverter output power, power consumed by loads and reactive power requirement of induction motor are shown in Fig. 7. From figure it is clear that if the PV system produces more power than load requirement, the battery stores excess power. If the load demand is more than power produced by PV system, the battery gives required power temporarily.

Table 1. The parameters of PV module

	Variable Name	Value
Maximum Power	P_m	60W
Voltage at MPP	V_m	17.1V
Current at MPP	I_m	3.5A
Open-Circuit voltage	V_{OC}	21.1V
Short circuit current	I_{SC}	3.8A
No of series connected cells	N_s	36 × 32
No of Parallel connected cells	N_p	21
Temperature coefficient of open circuit voltage	β	-(80±10)mV/^{0}C
Temperature coefficient of short circuit current	α	(.0065±0.015)%/^{0}C
Temperature coefficient of power		-(0.5±0.05)%/^{0}C
Rated Capacity of battery		6.5Ah, 600V
Initial State Of Charge	% SOC	70%

Fig. 8 shows the simulated results for DC-link voltage. During any variations in source power and load demand, the DC-link voltage is nearly constant at 780V. The simulated results for percentage state of sharge (SOC) of battery and system frequency are shown in Fig. 9 and Fig. 10 respectively. From Fig. 10 it is seen that the frequency remains constant during the changes in source or load power. As the load on the induction motor increases the electromagnetic torque also increases. The results for induction motor torques for step change in torque T_m are shown in Fig. 11.

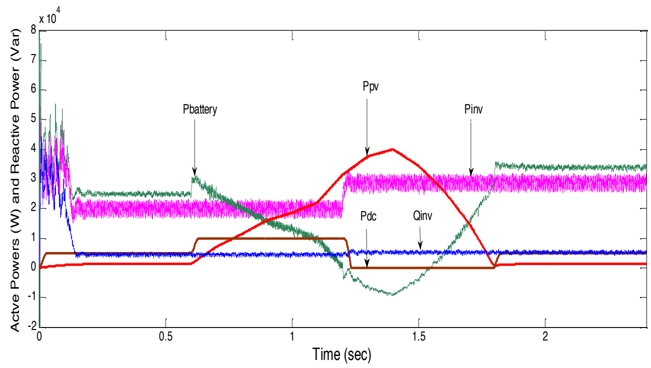

Fig. 7. Simulated results for active and reactive power

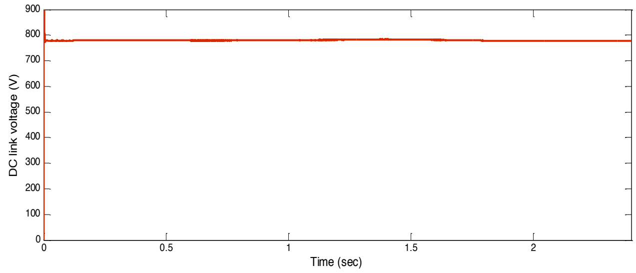

Fig. 8. DC link voltage

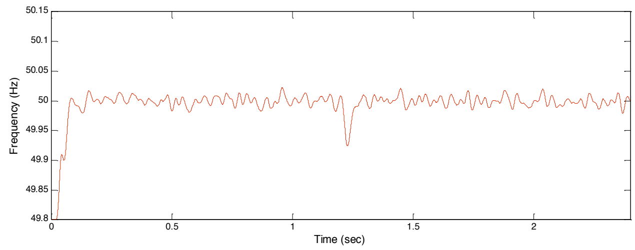

Fig. 9. System frequency

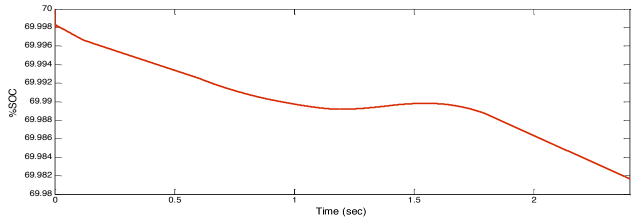

Fig. 10. State of Charge (%) of battery

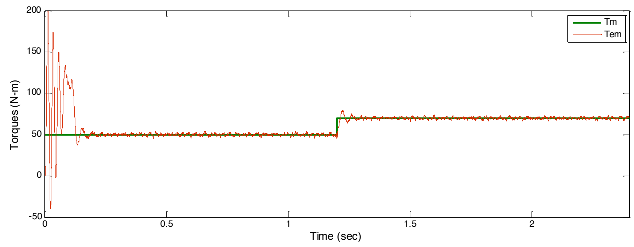

Fig. 11. Simulated results for induction motor torques

Case II: Constant AC and Variable DC load

In this case 3phase resistive load (13kW) and three phase squirrel-cage induction motor (50N-m) load are kept constant and the DC load is varied from 0 to 10kW. The simulated results for active power outputs of PV system, battery, inverter output power, power consumed by loads and reactive power requirement of induction motor are shown in Fig. 12.

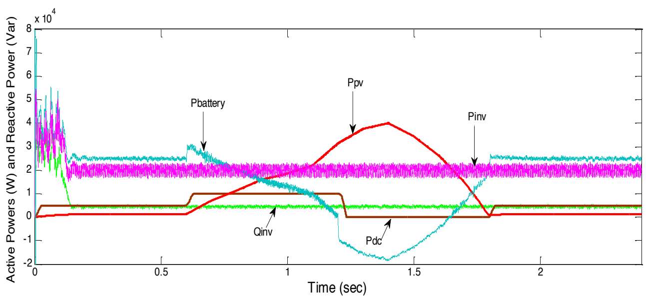

Fig. 12. Simulated results for active and reactive power

The battery covers the deficiency in generation or load demand depending on power generated by PV system and the load requirement as shown.

Case III: Constant AC and DC load

In this case 3phase resistive load (13kW), three phase squirrel-cage induction motor (50N-m) load and and the DC load (5kW) are kept constant. The daily variation in solar power is considered. The simulated results for active power outputs of PV system, battery, inverter output power, power consumed by loads and reactive power requirement of induction motor are shown in Fig. 13. Depending on power produced by PV source and the load demand, battery covers the deficiency in generation or load demand as shown. From the results it is observed that the power balance between PV system, battery and loads has been maintained while extracting maximum power from PV source. Also, it can be realized that the control strategy is capable of controlling the voltage and frequency irrespective of the load variability and PV power uncertainty.

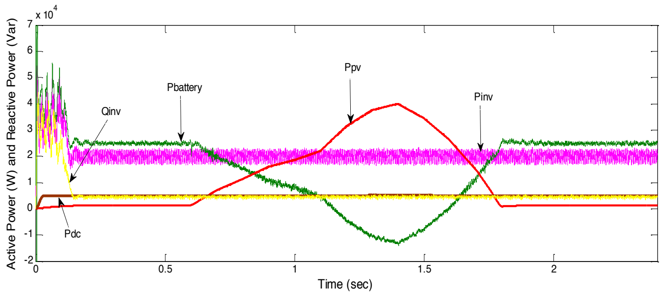

Fig. 13. Simulated results for active and reactive power

5. Conclusion

A detailed dynamic model of the system under study and the control strategy are investigated in the MATLAB /SIMULINK platform in order to study and analyse the system behaviour. The dynamic load such as a three phase induction motor and DC load are considered to analyse the performance of the system. The requirement of maintaining constant DC voltage is realized considering different operating conditions. Also from the simulation results, it can be realized that the control strategy is capable of controlling the voltage and frequency irrespective of the load variability and PV power uncertainty. This hybrid system can be implemented in houses, apartments and industries rooftops in various parts of India with PV system as the major power supply.

Acknowledgements

This work is supported in part by the Ministry of power, Government of India through Central Power Research Institute Bangalore, Karnataka under RSOP project scheme (CPRI letter no.3/5, R&D/RSOP/2011 Dated: 27/04/2011).

References

[1] A.M.K. El-Ghonemy, "Photovoltaic Solar Energy: Review", International Journal of Scientific and

Engineering Research, vol. 3, no. 11, pp. 1-39, November 2012.

[2] T. Salmi, M. Bouzguenda, A. Gastli, A. Masmoudi, “MATLAB/Simulink Based Modelling of Solar Photovoltaic Cell”, International Journal of Renewable Energy Research, vol. 2, no. 2, pp. 213-218, 2012.

[3] T. Esram and PL. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Technique”, IEEE Transactions on Energy Conversion, vol. 22, no. 2, pp. 439-449, June 2007.

[4] A. Nabil, A. Miyatake and M. Miyatake, “A Stand-Alone Hybrid Generation System Combining Solar Photovoltaic and Wind Turbine with Simple Maximum Power Point Tracking Control”, IEEE 5th International Power Electronics and Motion Control Conference (IPMEC’06), pp. 1-7, August 2006.

[5] S. Jain and V. Agarwal, “An Integrated Hybrid Power Supply for Distributed Generation Applications Fed by Nonconventional Energy Sources”, IEEE Transactions on Energy Conversion, vol. 23, no. 2, pp. 622 - 631, June 2008.

[6] C. Marisarla and K.R. Kumar, “A Hybrid Wind and Solar Energy System with Battery Energy Storage for an Isolated System”, International Journal of Engineering and Innovative Technology (IJEIT), vol. 3, no. 3, pp. 99-104, September 2013.

[7] S.W. Mohod and M.V. Aware, “Micro Wind Power Generator With Battery Energy Storage for Critical Load”, IEEE Systems Journal, vol. 6, no. 1, pp. 118-125, March 2012.

[8] C.A. Hill, M.C. Such, D. Chen, J. Gonzalez and W.M. Grady, “Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation”, IEEE Transactions on Smart Grid, vol. 3, no. 2, pp. 850 - 857, June 2012.

[9] Matthew Clayton Such, Cody Hill, “Battery Energy Storage and Wind Energy Integrated into the Smart Grid”, IEEE PES Innovative Smart Grid Technologies (ISGT’12), pp. 1-4, January 2012.

[10] J.F. Manwell and J.G. McGowan, “Lead Acid Battery Storage Model for Hybrid Energy Systems”, Solar Energy, vol. 50, no. 5, pp. 399-405, 1993.

[11] N. Garimella and N.K.C. Nair, “Assessment of Battery Energy Storage Systems for Small-Scale Renewable Energy Integration”, IEEE Region 10 Conference (TENCON’09), pp. 1-6, January 2009.

[12] G. Walker, “Evaluating MPPT Converter Topologies Using a MATLAB PV Model”, Journal of Electrical & Electronics Engineering, vol. 21, no. 1, pp. 49-56, 2001.

[13] F.M.G. Longatt, “Model of Photovoltaic Module in Matlab™”, II CIBELEC 2005, pp. 1-5.

[14] S.R. Chafle and U.B. Vaidya, “Incremental Conductance MPPT Technique for PV System”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 2, no. 6, pp. 2720-2726, June 2013.

[15] N.A. Zambri, A. Mohamed, H. Shareef and M.Z.C. Wanik, “Design of a Hybrid Fuel Cell with Battery Energy Storage for Stand-Alone Distributed Generation Application”, World Academy of Science, Engineering and Technology, vol. 78, 2013.

[16] M. Singh and A. Chandra, “Control of PMSG Based Variable Speed Wind- Battery Hybrid System in an Isolated Network”, Power & Energy Society General Meeting, pp. 1-6, July 2009,

[17] P.C. Klause, O. Wesynczuk and S.D. Sudhoff, “Analysis of Electric Machinary and Drive System” 2nd Edition, John Willey and Sons Inc. Publication, ISBN: 0-471-14326-X.

[18] K.N. Hasan, M.E. Haque and M. Negnevitsk, “Control of Energy Storage Interface with a Bidirectional Converter for Photovoltaic Systems”, Australasian Universities Power Engineering Conference (AUPEC'08), pp. 1-6, December 2008.

[19] M.E. Haque, K.M. Muttaqi and M. Negnivitsky, “Control of a Stand-Alone Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator”, IEEE Power and Energy Society General Meeting, pp. 1-9, July 2008.

[20] A.M.O. Haruni, A. Gargoom, M.E. Haque and M. Negnevitsky, “Dynamic Operation and Control of a Hybrid Wind-Diesel Stand Alone Power Systems”, Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC’10), pp. 162-169, February 2010.

[21] S. Das, A. Lodha, A. Anand, S.S. Priya and M.M. Manohara Pai, “Studies on Solar Radiation Estimation, Modeling and Analysis for Manipal”, Engineering Science and Technology: An International Journal (ESTIJ), vol. 3, no. 3, pp. 492-496, June 2013.