Energy Control Strategy for Large-Scale Grid Connected PV System with Batteries

Sumayya Al Mazrouei *, Abdul-Kadir Hamid **‡

* Department of Electrical and Computer Engineering, University of Sharjah, Sharjah, United Arab Emirates

** Department of Electrical and Computer Engineering, University of Sharjah, Sharjah, United Arab Emirates

((U00035180@sharjah.ac.ae, akhamid@ sharjah.ac.ae)

‡ Corresponding Author; Abdul-Kadir Hamid, Tel: +97165050932,

Fax: +97150500872

Abstract- Power management and grid stability assurance nowadays are critical tasks in modern grids because of the variables involved in generation and on the demand side. The biggest challenge of the solar energy is the intermittency of the energy produced. Solar photovoltaic (PV) is unpredictable and the generated power from large PV system can be affected by clouds, dust, or other factors. These situations lead to challenges in stabilizing the production of large PV system. This intermittency is a concern for large-scale grid connected photovoltaic (PV) system which require stable and reliable energy production all the time. The importance of energy storage system (ESS) as a solution to stabilize the effects of solar intermittency and as an energy buffer for a grid-connected PV system. Batteries energy storage system (BESS) can potentially solve this intermittency by storing energy and inject power into the grid when needed. Integrating large number of lithium- ion batteries with PV system in large-scale grid will control the energy flow from PV system and make sure to produce stable energy as required.

This paper investigates an energy management mechanism for large-scale grid connected photovoltaic (PV) systems with lithium- ion batteries. The proposed system consists of a 1 MW PV system and 1 MW lithium-ion batteries connected to the grid by DC-DC converters and DC-AC inverters. MATLAB-SIMULINK is used to simulate the PV-batteries system under different circumstances of various irradiance and temperature levels. The proposed energy management strategy is verified by the results of simulation.

.

Keywords Energy Management, Large-Scale, Photovoltaic (PV), Batteries, Simulink.

1. Introduction

Global warming (GW) is threatening the world's delicate ecosystems and to avoid such a disaster, the levels of emissions should be reduced 80% by 2050. The use of renewable emission-free sources of energy offers a feasible solution to this problem [1]. Solar power represents enormous resources which meet the world's needs for low-carbon power generation. According to International Energy Agency (IEA) , the development of affordable, unlimited and clean solar energy technologies will have huge longer-term benefits , it will increase countries' energy security through reliance on import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating global warming, and keep fossil fuel prices lower [3].

Solar energy photovoltaic(PV) technologies have enormous growth over the past years, amounting to a total installed capacity of around 177 GW worldwide by the end of 2014 and it is projected to be 1721GW by 2030 [4]. However, PV energy is unpredictable and the generation of large PV system can be easily affected by different weather factors such as clouds, dust and others. Grid stability and energy management nowadays are important in modern grids [2]. In large scale grid connected PV system, this is considerd a problem for the balance and stability of the power system as a consequence of the variability of the solar

irradiation [15]. Different solutions are already being studied to mitigate this intermittency. One of the potential energy control solutions to mitigate this intermittency is the energy storage system (ESS) Storage system manage the grid to make sure it is fully available by supplying energy based on the availability of PV system and grid requirements [5]. ESS has been considered by the system engineers and operators as a very important tool for several features such as energy time frame shifting, intermittency handling, transmission congestion relief, and power quality improvements [17].

ESS will store energy in low demand and supply back during peak time. As a result, ESS reduce the cost and time of building new PV plants [16]. Among different ESS technologies, batteries are the main storage technologies commonly used in PV systems. Lithium-ion batteries or li-ion batteries used for this system with advantages compared to others, faster charging/discharging cycles, light weight and higher efficiencies up to 99% [6]. Li-ion battery enlarges its area of use from small to large scaled renewable energy storage applications [7].

Many literatures have been published related to drive PV power plants with energy storage (ES) to manage and stabilize the production of PV power plants. However, a large and growing body of literature is related to the investigation of the possible use of ESSs to reduce the significant impact of PV generation on distribution networks (residential) and standalone (off grid) small scale KW photovoltaic systems. The main objective of this paper is to present energy control strategy using lithium ion batteries for large scale of PV system connected to grid. The batteries act as energy buffer and inject electricity into the grid based on requirement to manage the production of the PV system. In this paper, the concept of energy storage management used is an extension of the approach implemented for low voltage and low energy storage system applied in [8]. The proposed model consist of 1MW of PV system along with 1MW batteries and the grid which are connected by DC-DC boost converters and three phase DC-AC inverters as shown in Fig.1. Maximum power point tracking (MPPT) perturb and observe (P&O) method is used as known of its ability to significantly increase the efficiency of the PV system during the rapid change in irradiance [9]. The batteries manage the power flow through grid using bidirectional converter and controller. The results of simulation confirm the effectiveness of the strategy of energy storage management.
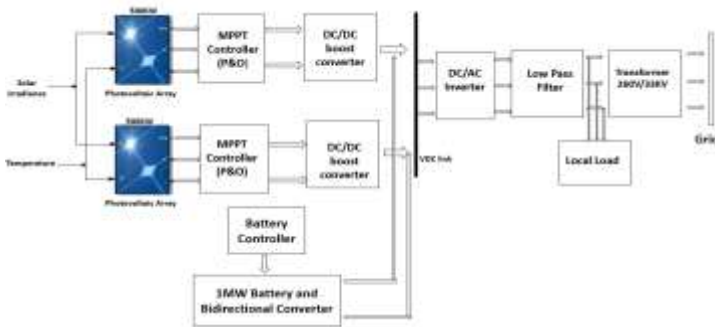
Section 2 describes the basic components of the proposed model. Section 3 explains the energy management strategy used to control the energy flow through the whole system. Section 4 displays the simulation results by Matlab and finally section 5 presents the conclusion.

2. Grid connected PV-Batteries System Design

The PV-Batteries grid connected system design is based on type of the system, location, required area, solar irradiance etc. The basic components of PV system are PV modules, maximum power point tracking (MPPT), DC-DC converter, VSI inverter and batteries. [18]. To design a grid connected solar PV system for the commercial use, the following steps are required

2.1 Photovoltaic cell

A typical circuit of photovoltaic cell is shown in Fig.2 presented by a mathematical model of inputs and output. I-V characteristics are frequently measured under standard test conditions (STC) of 1000 W/m2 irradiance, Air Mass (AM) 1.5 and ambient temperature 25 °C as per IEC 60904-1. The following equations describe the I-V characteristic of the PV solar cell [10]:

$$I_{ph} = I_D - I_{PV} - (\frac{V_{PV} + R_s . I_{PV}}{R_p}) \tag{1}$$

$$I_D = I_0 . \left(e^{\frac{V_D}{V_T}} - 1 \right) \tag{2}$$

$$V_D = V_{PV} + I_{pv} . R_s \tag{3}$$

$$V_T = \frac{n . K . T}{q} \tag{4}$$

where I_{pv} is cell current (A) , I_{ph} is light generated current (A) , I_D is Shockley diode equation (A) , I_O is diode saturation current (A) , R_S is cell series resistance (Ohms) , R_P is cell shunt resistance (Ohms) , V_D is diode voltage (V) , V_T is temperature voltage (V) , V_{PV} is cell voltage (V) , n is dimensionless junction material factor , K is Boltzmann constant 1.38*10-23 J/K , T temperature measured by Celsius, q is electron charge 1.602*10-19 C.

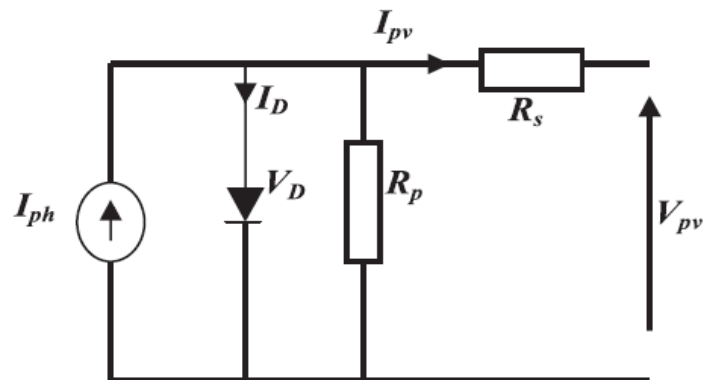**Fig. 1.** Block diagram of PV-Batteries system.

Fig. 2. Typical circuit of PV solar cell.

2.2 MPPT and DC-DC boost converter

Maximum power point tracking (MPPT) is a control method used in grid connected PV system to extract the maximum power from PV system. MPPT works together with DC-DC boost converter by controlling the duty cycle of the DC-DC boost converter to track the maximum voltage of PV array. In this paper, MPPT perturb and observe (P&O) method is used as known for enhancing the solar energy conversion efficiency under different temperature and irradiation levels [9-11]. P&O flow chart as shown in Fig.3 depend on the duty cycle (D) of a DC-DC converter to adjust the voltage output of PV array at the maximum power point [11]. The PV array power in every cycle is being monitored and compared to a reference value before each perturbation made. If a positive or negative change in duty cycle of DC-DC converter, the output power to increase or decrease according to the duty cycle change. The performance of the P&O algorithm depends on the converter switching duty cycle (D) and perturbation magnitudes (ΔD) [9]. Below equation describes the output voltage of boost converter [11]:

$$V_{out} = \frac{Vin}{1 - D} \qquad (5)$$

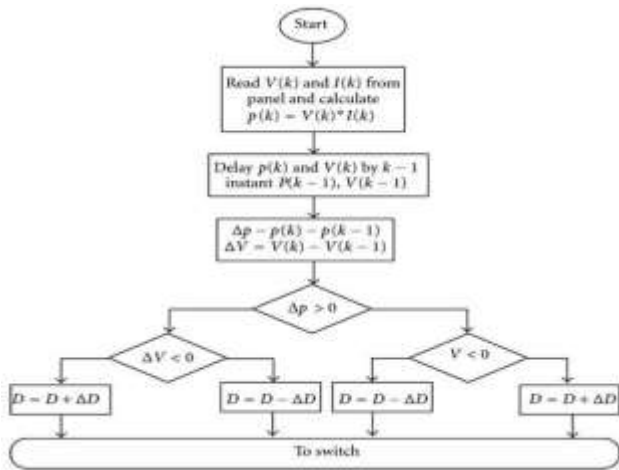where V_{out} is the output voltage, Vin is the input voltage and D is duty cycle.

Fig. 3. Perturb and observe (P&O) flow chart.

2.3 Voltage source inverter (VSI)

Three phase voltage Source Inverters (VSI) is used to convert the DC bus voltage regulated by the capacitor into three-phase AC voltages with variable magnitude and frequency [11]. The inverter circuit is represented in Fig.4, it contains insulated gate bipolar transistors (IGBTs) which rely on the reference voltage and the switching method to provide variable frequency. VSI is efficient, cost effective, require small space, and faster dynamic response. Two control loops used in VSC: internal control loop to regulate Id (direct axis current) and external loop Iq (quadrature axis current) to control the active and reactive power flow of three phase inverters connected to grid. Phase locked loop (PLL) is applied to control the grid voltage and current to maintain the

same frequency and phase [12]. PLL provide a stable reference synchronization signal for the inverter by minimizing the error between actual current and the reference current gained from the DC link controller [11]. Iq current is set to zero to keep unity power factor while Vd and Vq are the outputs voltage of the current controller which converted by the three-level pulse width modulation (PWM) to three modulating signals Uref_abc. The working principle of PWM includes the followings [11]:

- Frequency of PWM

- Fundamental frequency

- Amplitude

- Modulation Index is defined by:

$$m = \frac{V_{control}}{Vd/2} \qquad (6)$$

The output of the VSI is connected to RL low pass filter to attenuate the high frequency harmonics and prevent them passing into the power system grid [11]. A balanced three phase load is represented in the model parallel with RL filter. The active and reactive powers absorbed by the load at constant impedance which is proportional to the square applied voltage [13].

Fig. 4. Voltage source inverter circuit.
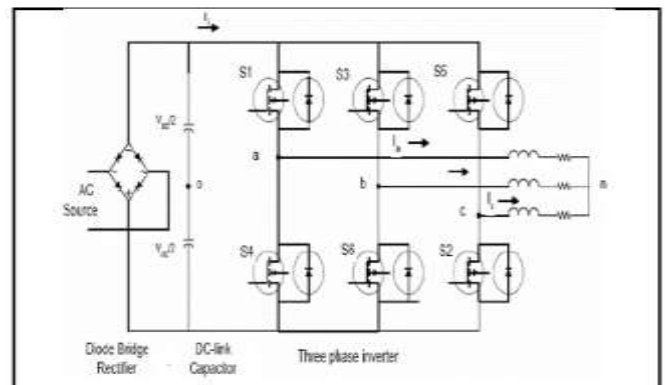
2.4 Batteries

Lithium- ion battery model with controller is presented in Fig.5. Batteries can be connected in series and/or parallel to increase voltage and/or current output for larger storage applications is known as battery bank. Available battery bank in PV system tied to grid depend on capacity at a time t (h) during charging and discharging are given by below equations respectively [14]:

$$C_{batt}(t) = (t - 1)(1 - \sigma)C_{batt} - \eta_{bat}\left[P_{PV}(t) - \frac{P_L(t)}{\eta_{inv}}\right] \qquad (7)$$

$$C_{batt}(t) = (t - 1)(1 - \sigma)C_{batt} - \left[\frac{P_L(t)}{\eta_{inv}} - P_{PV}(t)\right] \qquad (8)$$

Where $C_{batt}(t)$ and $C_{batt}(t - 1)$ are available capacities (Wh) at times t and t -1, respectively, σ is the self-

discharge rate, $P_{PV}(t)$ is the energy generated by the PV system. $P_L(t)$ is the load demand at time t, η_{inv} is the inverter efficiency and η_{bat} is the battery charging/discharging efficiency.

2.4.1 DC-DC bidirectional converter

A non-isolated DC-DC Bidirectional Buck/Boost converter is used as a controller to the batteries as described in Fig.6. The bidirectional converter is set to charge and discharge based on the grid requirements. The Buck converter operates in a continuous mode with the following duty cycle [8]:

$$\text{Vout} = \frac{Vin}{(1 - Dboost)} \qquad (9)$$
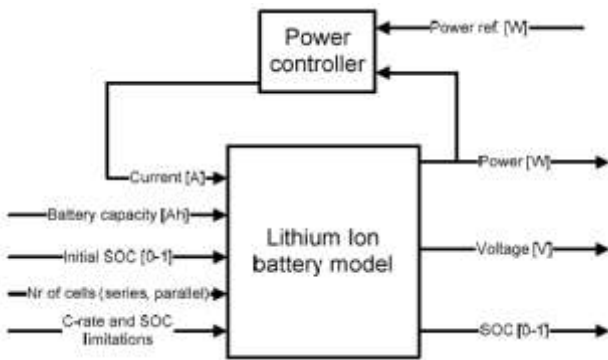

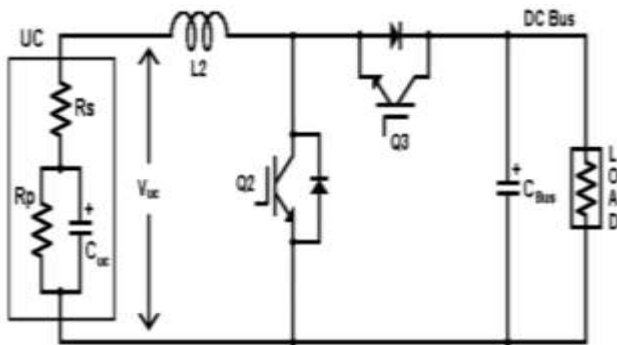**Fig. 5.** Block diagram of the Li-ion battery system.

Fig. 6. DC-DC Bidirectional Buck/Boost converter.

3. Energy Management Strategy

The system operates as an energy management using large scale of series and parallel batteries connected to the grid to inject power when needed, below equation represents the operation of the system [8]:

$$P_{Grid} = P_{PV} + P_{bat} \qquad (10)$$

Where P_{Grid} is the grid power, P_{PV} is the output power from PV system and P_{bat} is the total batteries power.

Batteries controller is the main controller that manages the energy flow in the entire system. Fig.7 shows the batteries controller algorithm used in this system. In this system, four operation modes of energy flow analysed as shown in Fig.8.

Case 1: PV system supply power to the grid and the extra power used to charge batteries.

Case 2: PV-batteries system both injecting power to the grid.

Case 3: Batteries only available and used to supply energy to the grid.

Case 4: PV system supply power to the grid and batteries start charging.
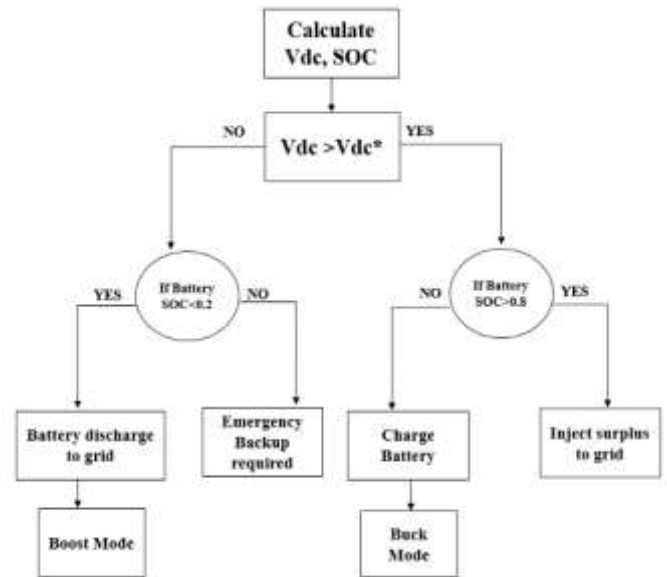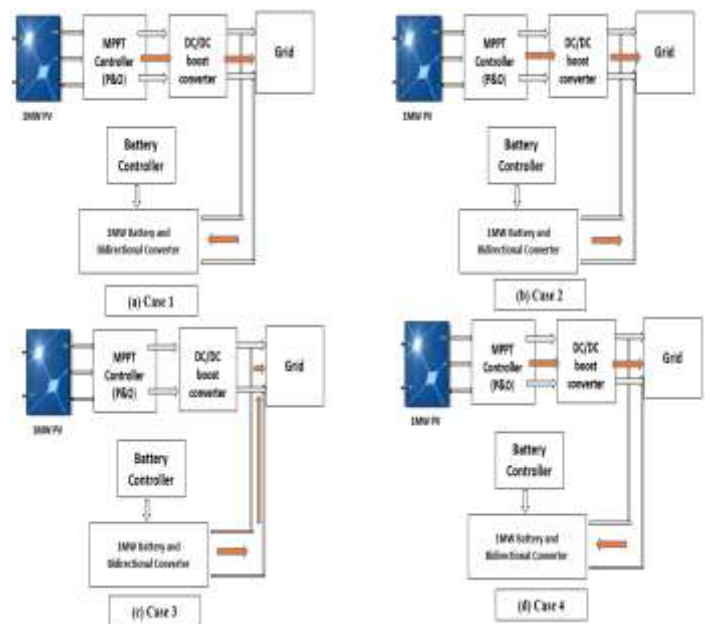

Fig. 7. Batteries controller algorithm.

Fig. 8. Energy flow of the system.

4. PV-Batteries System Simulation Results

4.1 System Simulation

Fig.9 shows the Simulink block diagram of the studied design 1 MW PV system along with 1MW li-ion batteries storage systems. The Solar PV Module used in this paper is two thin-film modules connected in series with a capacity each of 500 KW as shown in Fig. 10 (a) and its parameters are shown in Table 1. The PV Module operates at constant irradiation level of 1000 W/m^{2}and ambient temperature of 25°C. The output plot of the PV Module is shown in Fig.10 (b).
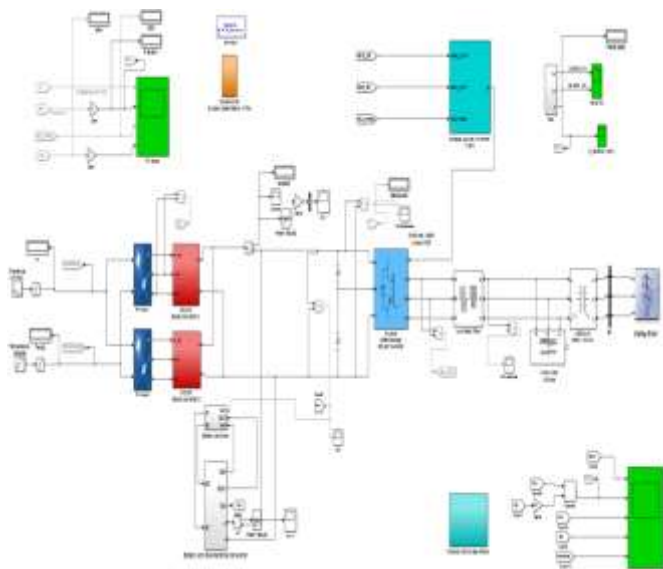

Fig. 9. Simulation representation of Proposed System.

Fig. 10. (a) Simulink model of the PV Module; (b) Voltage and current plots of PV Module.

The maximum voltage from PV array by P&O algorithm is 207V. The boost converter boosts maximum DC voltage of PV array from 207V to 500V using 0.5 duty cycle. The output voltage from the Boost converter is always close to the reference value 500 V set in this system. Parameters of boost converter used in simulation is shown in Table 2. The VSC regulates the DC bus voltage at 500 V and maintain unity power factor. The control system uses a sample time of 50 μs for voltage and current controllers and for the PLL. PWM generators of Boost and VSC converters use 5μs sample time to get a suitable resolution of PWM waveforms. The parameters used in the simulink model for the batteries are shown in Table 3.

Table 1. PV module parameters.

Short Circuit Current (Isc)	1.74 A
Open Circuit Voltage(Voc)	86 V
Voltage at maximum power point (Vmp)	67.8 V
Current at maximum power point (Imp)	1.55 A
Maximum Power (Pm)	105 W
Series Resistance (Rs)	6.0192 Ω
Parallel Resistance (Rsh)	555.358 Ω
Diode Saturation Current (I0)	1.0402e-13 (A)

Table 2. Boost DC/DC converter parameters.

Lboost	5e-6 H
Cboost	100e-5 F
Rboost	6e-7 Ω
Ts_control	50 μs
Ts_power	5 μs
Duty cycle	0.5

Table 3. Batteries parameters.

Nominal Voltage (V)	48 V
Rated capacity(Ah)	11 Ah
SOC(%)	60 %

No of series	11
No of parallel	20

4.2 Results

The PV-Batteries system simulated for 4 seconds with different irradiance levels and different temperatures. Batteries charging and discharging operations is presented in Fig.11. The system operates under six scenarios, the first four cases are simulated under different irradiance levels and at 25°C temperature as shown in Fig.12.

- *Case 1:* from 0 to 1 second at 1000 W/m^2, PV system supply power to the grid and the surplus to charge the battery.

- *Case 2:* from 1 to 2 seconds at 500 W/m^2, PV system and batteries together inject power to grid.

- *Case 3*: from 2 to 3 seconds at 300 W/m^2, PV power reaches the minimum conditions and cannot support the grid anymore; batteries only inject all its power to the grid.

- *Case 4:* from 3 to 4 seconds at 1000 W/m^2, battery will start charging with the full availability of PV system to supply the grid.

Fig.13 shows the results of the other two cases simulated at 1000 W/m^2 with two high temperatures as below:

- *Case 5:* from 0 to 4 seconds at 45°C, 800 KW output power from the grid, when PV system produced 1 MW and 200 KW are taken by battery.

- *Case 6:* from 0 to 4 seconds at 60°C, 600 KW output power from the grid, when PV power output is reduced to 890 KW and 200 KW are taken by battery.

The total power of the grid after integrating both the batteries and PV system in the different scenarios are represented in Fig.14. It shows clearly how batteries are effective in keeping the grid services available all the time and in stable regard the absence of PV system.
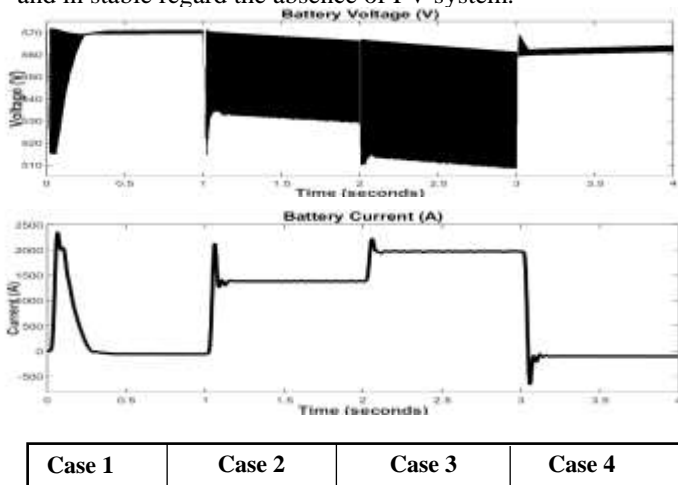

| Case 1 | Case 2 | Case 3 | Case 4 |

Fig. 11. Battery voltage and current charging and discharging conditions.

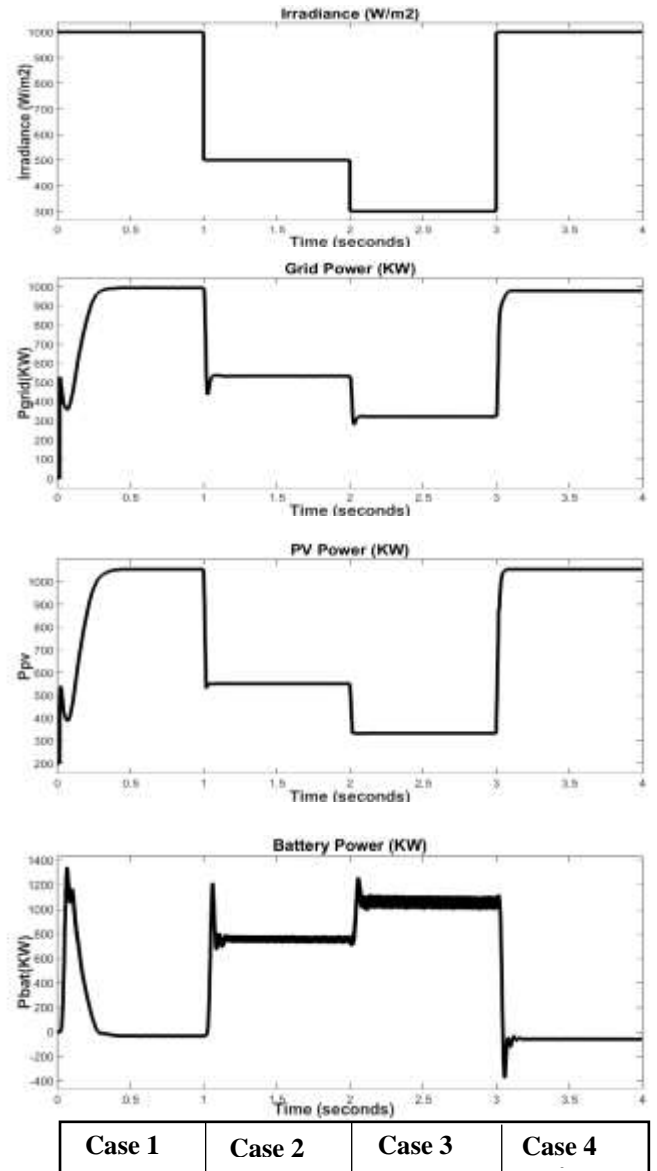| Case 1 | Case 2 | Case 3 | Case 4 |

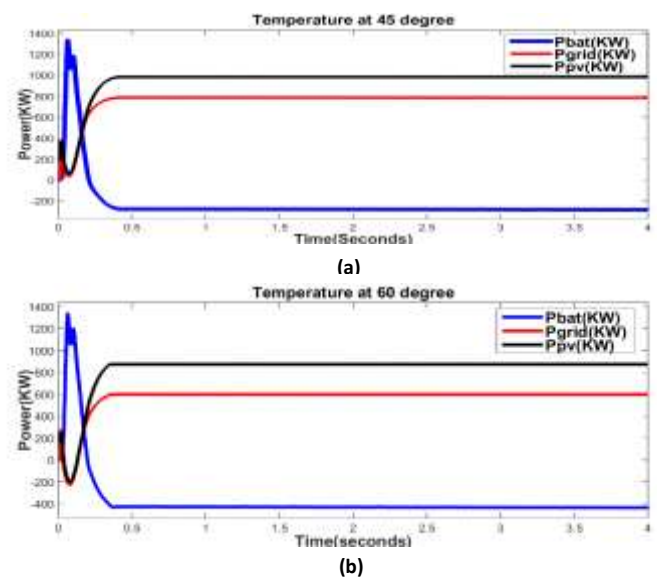**Fig. 12.** PV-Batteries system simulation results.

(a)

(b)

Fig. 13. (a) Case 5 system simulation results at 45°; (b) case 6 system simulation results at 60°.
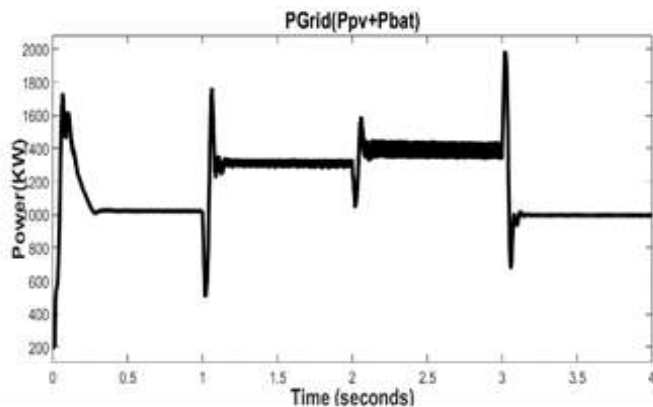
Fig. 14. Total power of grid with PV-battery system.

5. Conclusion

The paper studied energy storage management approach using batteries for large-scale grid connected PV system. The system includes a 1MW PV system and 1MW li-ion batteries connected to the grid by DC-DC converter and three phase DC-AC inverter. The entire system is simulated using MATLAB- SIMULINK for 4 seconds. The system runs for different scenarios and in each case results of PV power, batteries power and grid power was plotted and analyzed. The system was tested for six cases to see how PV-batteries system response during different irradiance levels and different temperature. Four cases are simulated under different irradiance level and fixed temperature 25°C. Case 1 at $1000 \, W/m^2$ PV power supply to the grid and the surplus to the batteries. Case 2 at $500 \, W/m^2$ PV power and batteries together to inject power to the grid due to the lower power produced from PV system. Case 3 at $300 \, W/m^2$ PV power reached the minimum conditions and cannot support the grid anymore; the batteries supply all its power to the grid. Case 4 at $1000 \, W/m^2$ batteries will start charging with the full availability of PV to supply the grid. Cases 5 and 6 were simulated with hot temperature at 45°C and 60°C and results show how PV system and batteries react and affect the total power produced to the grid. Results show how integrated PV-batteries system increases the reliability and flexibility in the entire system by keeping the balance between grid demand and PV-Batteries production.

Acknowledgements

References

[1] M.S. ElNozahya, T.K Abdel-Galila, and M.M.A Salamaaa, "Probabilistic ESS sizing and scheduling for improved integration of PHEVs and PV systems in residential distribution systems," *Electric Power Systems Research*, vol. 125, pp. 55–66, 2015.

[2] O. Palizban, and K. Kauhaniemi, "Energy storage systems in modern grids-Matrix of technologies and applications, " *Journal of Energy Storage* , vol.6, pp. 248-259, 2016.

[3] Solar Energy (n.d.). Retrieved from https://en.wikipedia.org/wiki/Solar_energy

[4] I. Colak ,M. Yesilbudak, N. Genc and R.Bayindir ,"Multi-Period Prediction of Solar Radiation Using ARMA and ARIMA Models," *IEEE 14th International Conference on Machine Learning and Applications* , vol.14, 2015.

[5] M. ElNozahya, T.Abdel-Galila ,and M.Probabilistic, "ESS sizing and scheduling for improved integration of PHEVs and PV systems in residential distribution systems, " *Electric Power Systems Research,* vol.125, pp.55–66,2015.

[6] N. Opiyo , "Energy storage systems for PV-based communal grids, " *Journal of Energy Storage* , vol.7, pp 1-12,2016.

[7] Y. Mendi, "Flexible Energy Saving Solution: An Assessment of Energy Storage Systems for Photovoltaics & Benefits to the Grid-Connected Systems," *Environment and Electrical Engineering (EEEIC), 2016 IEEE 16th International Conference* ,pp.5090-2320, 2016.

[8] S. Gaurava, C.Birlaa , A.Lambaa , S.Umashankara and S.Ganesanb , "Energy management of PV-Battery based Microgrid System, "*Procedia Technology*, vol.21, pp.103–111,2015.

[9] R. Prakash, B.Meenakshipriya, and R.Kumaravelan , "Design of MPPT Controller Using Stepped P&O Algorithm in Solar Photovoltaic System," *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering* ,vol. 8,2014.

[10] M. Bechouat, Y.Soufi , M.Sedraoui , and S.Kahla , "Energy storage based on maximum power point tracking in photovoltaic systems: A comparison between GAs and PSO approaches," *International journal of hydrogen energy* ,vol.40,pp.13737-13748,2015.

[11] A. Mollah , G. Panda, and P.Saha , "Three Phase Grid Connected Photovoltaic System with Maximum Power Point Tracking, " *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering* ,vol. 4 pp. 2278-8875, 2015.

[12] D. Kumar, "Modeling, simulation and performance analysis of a grid-tied voltage source inverter based photovoltaic system under balanced and non-linear load conditions," *Electrical, Computer and Communication Technologies (ICECCT), 2015 IEEE International Conference* , pp.4799-6085,2015.

[13] M.Wanik, A. Bousselham ,and A. Elrayyah , "Real-Time Simulation Modeling for PV-Battery based Microgrid System," *Power System Technology (POWERCON), 2016 IEEE International Conference,*pp.4673-8848, 2016.

[14] H. Beltran H, M.Swierczynski , A. Luna ,G. Vazquez , and E. Belenguer "Photovoltaic Plants Generation Improvement Using Li-Ion Batteries as Energy Buffer, "

Industrial Electronics (ISIE), 2011 IEEE International Symposium, pp.4244-9312, 2011.

[15] Y.M Mendi, *"*Flexible Energy Saving Solution: An Assessment of Energy Storage Systems for Photovoltaics & Benefits to the Grid-Connected Systems *,"* *Environment and Electrical Engineering (EEEIC), 2016 IEEE 16th International Conference* , pp. 5090-2320, 2016.

[16] A. Jamali, N. Nor, and T. Ibrahim, "Energy storage systems and their sizing techniques in power system- A review, "*Energy Conversion (CENCON), 2015 IEEE Conference* , pp. 4799-8598, 2015.

[17] H. Eklas, P.Ron, and B. Ramazan ,*"* Implementation of Hybrid Energy Storage Systems to Compensate Microgrid Instability in the Presence of Constant Power Loads ,*"* *International Journal of Renewable Energy Research*, vol.7, no.2, 2017.

[18] K.Sheeraz, J,Majid, and A.Iram , *"*Effective low cost Grid-Connected Solar Photovoltaic System to Electrify the Small Scale industry/Commercial Building,*"* *International Journal of Renewable Energy Research*, vol.7, no.2, 2017.