Rooftop PV with Battery Storage for Constant Output Power Production Considering Load Characteristics

Nasim Jabalameli, *Student Member, IEEE*, Sara Deilami, *Student Member, IEEE*
Mohammad A.S. Masoum, *Senior Member, IEEE,* Farhad Shahnia*, Member, IEEE*

Department of Electrical and Computer Engineering, Curtin University, Perth, WA, Australia

nasim.jabalameli@postgrad.curtin.edu.au, saramir29@yahoo.com, m.masoum@curtin.edu.au, Farhad.Shahnia@curtin.edu.au

Abstract- **One of the main limitations of rooftop photovoltaic generation systems (rooftop PVs) is the dependency of their output power to environmental factors such as sun radiation, panel temperature, passing clouds and shading, as well as loading level (operating point on v-i characteristics). This dependency may result in sudden output power variations of rooftop PVs particularly during cloudy periods. This paper investigates application and control of battery storage (BS) systems to overcome the sudden output power variations of rooftop PVs. A practical battery storage energy management strategy (BS-EMS) for operating grid-connected rooftop PVs at point of common coupling (PCC) is presented such that the delivered output power to the grid is constant under various operating conditions. The power balance between rooftop PV, BS and grid is considered by dynamic control of the BS converter to achieve constant output power to the grid during daylight. Simulation results for a 24-hour period will be presented and analyzed to investigate the performance of BS-EMS for a system comprising of a single-phase rooftop PV with BS and linear loads connected to power grid.**

I. INTRODUCTION

The demand, consumption and price of electricity are rapidly increasing in many developing countries such as Australia. To meet current and future energy requirements, more electric power plants have to be introduced or the structure of energy production needs to be changed with different approaches such distributed generation (DG) sources at distribution feeders or directly at the consumer (residential) side [1-3]. Among DG technologies, renewable energy resources have found more applications mainly due to the increasing concern about environmental issues and adopted feed-in tariffs for grid-connected PV systems [1]. Among various renewable energy resources, wind power and PV systems have found more applications in distribution and residential networks [2, 3]. However, PV systems still have a payback time and as the electricity price rises steadily; their cost efficiency becomes more attractive particularly for residential applications such as rooftop photovoltaic generation systems (rooftop PVs).

Currently, most PV generators are designed with maximum power point tracking (MPPT) abilities to justify their relatively high investment cost. That is the main task of the PV converter is to extract the maximum possible energy from the sun and deliver it to the power grid to increase the profit. However, due to the stochastic nature of the solar cell power output, large developments of grid-connected PV systems involve large fluctuations of the frequency, power, and voltage in the grid. Utilities are beginning to detect these problems in both the distribution (due to moderate and large PV power plants) and residential networks (caused by large penetrations of rooftop PVs).

The unpredictable and stochastic nature of renewable energy sources such wind and PV is a serious issue that causes grid balance gradually difficult to attain [2, 4]. In this term, energy storage (ES) units such as researchable batteries [4-5], ultra-capacitor and fuel cells [2-3] can be used to balance the lack of power or to store the extra power during the off-peak hours. Anderson presents an economic energy management strategy based on time of use (TOU) rating for grid-connected PV with battery storage (BS) system (BSS) for increasing cost efficiency [3]. Similarly, reference [6] investigates the design of an optimal charge\discharge algorithm for distributed BS systems connected to PV systems that also consider cost analysis. Reference [5] presents grid-connected distributed energy systems in combination with lithium-ion battery as the storage element. Reference [7] explains how batteries interconnected to distributed systems can be utilized to expand the energy production of conventional grid-connected PV power plants, mostly under mismatching operating conditions. Apart from these works, Hector ei al. proposed an energy management strategy (EMS) for large-scale power plants operating with different ES ratings [2]. On the other hand, some researches have considered application of ES in isolated PV systems. In this regard, [8] investigates the performance and energy supplies of different types of battery technology suitable for usage in isolated power systems. While, there are a few literatures in terms of PV sources combined with ES [2], more research is required to evaluate the application and capacity of BS in grid-connected PV systems particularly with consideration of real-time weather and load conditions.

This paper aims to attain constant-production periods in grid-connected rooftop PVs under different operative and environmental operating conditions by including a BS unit. An EMS is proposed that considers the power balance between rooftop PV, BS, household load and grid to dynamically control BS converter such that the output power to the grid is constant during daylight. Simulation results generated in PSCAD will be presented and analyzed to investigate the performance of BS-EMS for a system consisting of single-phase rooftop PV with BS and linear load connected to power grid.

II. ROOFTOP PV AND BATTERY STORAGE SYSTEM

PV systems are being accepted as suitable alternatives to the conventional energy resources due to environmental concerns, the increasing price of electricity and transmission congestion management issues. PV power currently represents a low percentage of the global electricity production. However, its applications in residential and industrial networks are rapidly growing since the peaks of most industrial and some residential loads usually coincide with the maximum output of the PV modules. Fig. 1 shows typical configuration of a house with linear loads and rooftop PV connected to the power grid at point of common coupling (PCC). The increasing penetration of rooftop PVs in residential networks has encouraged many researchers and electric utilities to investigate their advantages, limitations and impacts on distribution systems.

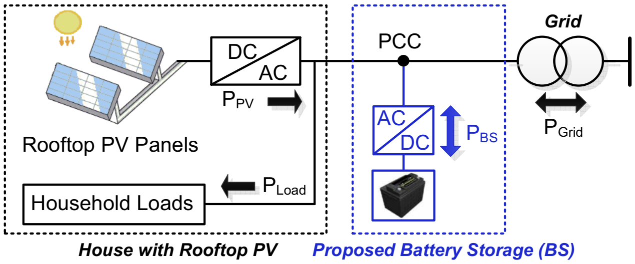

Fig. 1. Typical house with grid-connected rooftop PV and BS system.

One of the main limitations of rooftop PVs is the dependency of their output power to environmental factors such as sun radiation, panel temperature, passing clouds and shading, as well as loading level (operating point on their nonlinear v-i characteristics). This dependency may result in sudden output power variations of rooftop PVs during cloudy periods. Fig. 1 also shows a proposed practical solution to overcome this limitation by including a shunt-connected BS system at PCC to ensure constant output power production to the grid during daylight. This configuration allows the consumer to store the excess generated energy in PV storage elements during off-peak hours and return it back to the grid at appropriate times. This arrangement has a few advantages:

- It can moderately mitigate the stochastic nature of the PV production in real time.
- It can increase the profit by selling the stored energy during peak hours.
- With the proper control of BS system, this configuration can also be utilized to overcome sudden output power changes of rooftop PVs due to variations in environmental factors and load level.

Fig. 2 shows typical (forecasted/measured) household daily load curve and daily average summer rooftop PV generation. The main aim of this paper is to propose, implement and test a BS-EMS for the storage system of Fig. 1 to achieve a constant daily output power to the grid such as the grid reference characteristic shown in Fig. 2.

Inclusion of the load is very important as its variations will have impacts on the performance of BS-EMS. Several factors influence the load in the electrical network including the weather situation (e.g., temperature, cloud coverage, etc.), social activities (such as holidays), standard working hours, etc.

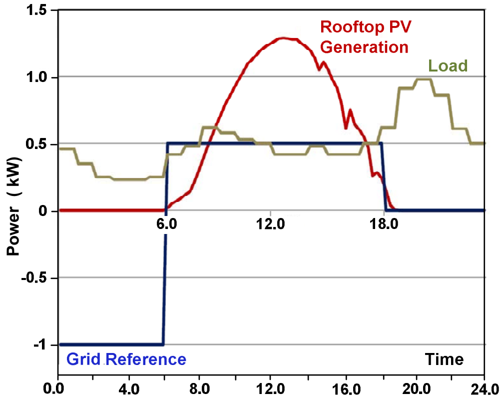

Fig. 2. Household load curve, constant daily output power to grid ($P_{Grid\text{-}ref}$), typical rooftop PV generation for a summer day in Perth, WA [9].

III. BATTERY STORAGE ENERGY MANAGEMENT STRATEGY (BS-EMS) FOR CONSTANT OUTPUT POWER PRODUCTION

An EMS in conjunction with a BS system will be implemented to support the rooftop PV (Fig. 1) in providing constant power production during different periods throughout the day. The entire PV system will work according to the BS-EMS. Constant output PV power will be produced as a result of dynamically controlling the BS converter under various operating conditions. In this sense, the control scheme of the total system (rooftop PV, BS, household load and grid) is based on the following power balance equation:

$$\sum_t P_{Grid\text{-}ref}(t)=\sum_t [P_{PV}(t)+P_{BS}(t)-P_L(t)], \qquad (1)$$

where $t=\Delta t, 2\Delta t, \ldots 24\,hours$ and Δt is the time interval. $P_{Grid\text{-}ref}$, P_{PV}, P_{BS} and P_L are the instantaneous desired (requested) constant power to be injected into the grid, the instantaneous power provided by rooftop PV panels (which mainly depends on the site location and weather conditions), the current power exchanged by the BS and the instantaneous household load, respectively (Fig. 2).

The operation of BS system will be dynamically controlled based on the following charge and discharge characteristics:

$$Charge:\ If\ P_{BS}<0 \Rightarrow \frac{d\,E_{BS}(t)}{dt}=-P_{BS}(\varepsilon c) \qquad (2)$$

$$Discharge:\ If\ P_{BS}>0 \Rightarrow \frac{d\,E_{BS}(t)}{dt}=\frac{-P_{BS}}{\varepsilon d} \qquad (3)$$

where BES, εc and εd are the current stored (available) energy of BS system, charging efficiency and discharging efficiency, respectively.

According to Eq. 1, the desired constant output power level to the grid ($P_{Grid\text{-}ref}$) can be changed for each time interval (Δt). In this paper Δt is assumed to be 15 min. Therefore, the power production patters can have up to 24x4=96 different durations $P_{pattern}=\{p_1,\ p_2,\ \ldots,\ p_{96}\}$. However, in this paper a single constant output power level is considered during daylight (e.g., 0600h-18:00h) as by the $P_{Grid\text{-}ref}$ waveform in Fig. 2.

The PV, load and BS energy profiles during the 24 hour period can be calculated as follows:

$$\tilde{E}_{PV}(t)=\sum_{k=0}^{95}[\tilde{E}_{PV,k\Delta t}=\int_{t=k\Delta t}^{(k+1)\Delta t}P_{PV}(t)dt=\Delta t(P_{PV,k\Delta t,max})]. \quad (4)$$

$$\tilde{E}_{L}(t)=\sum_{k=0}^{95}[\tilde{E}_{L,k\Delta t}=\int_{t=k\Delta t}^{(k+1)\Delta t}P_{L}(t)dt=\Delta t(P_{L,k\Delta t,max})]. \quad (5)$$

$$\tilde{E}_{BS}(t)=\sum_{k=0}^{95}[\tilde{E}_{BS,k\Delta t}=\int_{t=k\Delta t}^{(k+1)\Delta t}P_{BS}(t)dt=\Delta t(P_{BS,k\Delta t,max})]. \quad (6)$$

where $P_{PV,k\Delta t,max}$, $P_{L,k\Delta t,max}$ and $P_{BS,k\Delta t,max}$ are the maximum values of PV, load and BS power during time interval $k\Delta t$, respectively.

IV. FLOW CHART OF THE PROPOSED BS-EMS

Fig. 3 shows flowchart of the proposed algorithm for battery storage energy management strategy (BS-EMS) that will dynamically control the battery charge/discharge process according to Eqs. 1-3.

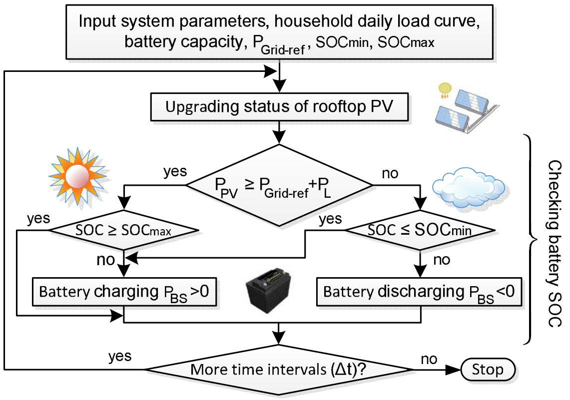

Fig. 3. Flowchart of the proposed BS-EMS algorithm for battery charge/discharge management to attain constant output power to grid.

At each time interval (e.g., Δt=15 min in this paper), BS-EMS will upgrade the status of rooftop PV based on solar radiation, feed the household loads and based on the weather condition (sunny, cloudy) decides to either charge or discharge the battery. This process will continue for 24 hours until the final time interval (t_{final}= 96Δt=96(15 min) = 24 hours) is reached.

In order to protect the battery and increase its lifetime, BS-EMS is designed to limit the minimum and maximum levels of the battery state-of-charge (SOC) to SOC_{min} and SOC_{max}, respectively. The battery SOC can be defined from the perspective of energy as follows [10]:

$$SOC=W_{remain}/W_{initial} \quad (7)$$

where W_{remain} and $W_{initial}$ are the remaining and initial power of the battery, respectively. In practice, the definition and determination of SOC is more complex. There are few established approaches to estimate SOC based on discharge test, ampere hour measurement, open circuit voltage, constant current voltage, internal resistance, linear model, neural networks, Kalman filter etc. [10].

In order to utilize the battery more efficiently, BS-EMS will also try to utilize it to supply the household loads during peak load hours when the price of electricity is high (e.g., 19:00-24:00) and will buy cheap electricity from the grid during off-peak hours (00:00-7:00) to recharge it for the next day. This is done by considering the battery capacity ($BCAP$) and selecting a relatively small value for $P_{Grid\text{-}ref}$ during peak load hours and a relatively large value during off-peak load hours as shown in Fig. 2.

A PSCAD computer program is developed to model the grid-connected rooftop PV and household linear load combined with the shunt connected BS system which is dynamically controlled over a 24 hour period based on the proposed BS-EMS algorithm (Fig. 3). The complete PSCAD system model including the dynamic control of the battery status and output voltage condition is shown in Fig. 4. For calculation of voltage reference (V_{ref}), the following load flow equations are used (Fig. 4):

$$P_{BS}=(V_1V_2/X)sin(\theta_1-\theta_2) \quad (8)$$

$$Q_{BS}=(V_1V_2/X)cos(\theta_1-\theta_2) \quad (9)$$

$$V_{ref}(t)=V_1 sin(\omega t+\theta_1) \quad (10)$$

where P_{BS} and Q_{BS} are the active and reactive output power of the BS; V_1 and V_2 are the capacitor and PCC voltages while θ_1 and θ_2 are the corresponding phase angle.

The aim of BS converter control is to generate a switching function (U) that can take on +1 or -1 values depending on the status of the (IGBT) switches.

A state space approach is used to implement the converter control: The input state vector is:

$$X^T=[V_{cf}\quad i_f] \quad (11)$$

$$\dot{x}=Ax+Bu_c \quad (12)$$

$$y=V_{cf}=[1\ \ 0]x \quad (13)$$

where x, y and u_c are input state vector, output state vector and the continuous time version of the switching function U, respectively; while A and B are state matrix and input matrix, respectively. A hysteresis band approach is used to turn on/off the (IGBT) switches. The switching logic is

$$\begin{cases} if\quad u_c>h\quad then\quad u=+1 \\ if\quad u_c\le h\quad then\quad u=-1 \end{cases} \quad (14)$$

where h is a small positive constant that defines the hysteresis band.

V. ANALYSES OF SIMULATION RESULTS

The grid-connected rooftop PV and BS system of Fig. 1 is simulated to investigate the performance of the proposed BS-EMS (Fig. 3). The PV rating and battery capacity are 1.59kW and 5.7kWh, respectively. The output power profile of rooftop PV and household daily load curve are shown in Fig. 2. The system is required to keep the power delivered to the grid during the daylight (0600h-18:00h) at a constant level of 0.5kW (Fig. 2, $P_{Grid\text{-}ref}$). Detailed simulations are performed and shown in Figs. 5-9 for the three operating conditions of Table I to demonstrate the performance of BS-EMS with the selected parameters, as well as the impacts of battery capacity and constant output power level.

TABLE I
SIMULATED CASE STUDIES

Case	Description	Simulations
1	Base case, demonstrating system ability to deliver constant output power.	Fig. 5
2	Exploring impacts of changing battery capacity on system performance.	Figs. 6-7
3	Investigating impact of changing the reference constant output power level.	Figs. 8-9

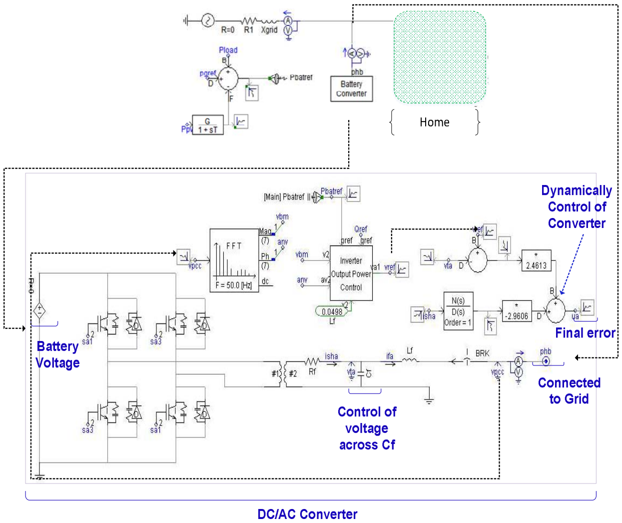

Fig. 4. Flowchart of the proposed algorithm for battery charge/discharge management (BS-EMS).

A. Case 1: Performance of BS-EMS

Fig. 5 shows simulation results for normal operation of the system with the PV, load and reference output power characteristics of Fig. 2. Comparison of the simulated grid power and the requested reference power ($P_{Grid\text{-}ref}$) indicates fine performance of BS-EMS in keeping the output power at 0.5kW during daylight. Note that the grid is feeding the load and partially charging the battery during early morning (0000h-0600h). This is justifies as the price of electricity will be cheap during these off-peak load hours.

Examination of the battery energy profile indicates that when necessary, the stores energy will be released to the grid through the day (0600h-1030h and 1530h-1800h) to achieve the requested constant output power. However, the excess PV power during high sun radiation hours (1030h-1530h) will be used to recharge the batter. For the situation of Fig. 5, the battery is not fully discharged during the day at 1800h (SOC=3.2kWh/5.7kWh=0.56); therefore it will continue feeding the load until reaching SOC_{min} at 2000h.

B. Case 2: Impact of Battery Capacity

To explore the impacts of BS capacity on the performance of BS-EMS, simulations are repeated with large (10kWh) and small (3kWh) battery sizes and presented in Figs. 6 and 7, respectively. The negative impact of small battery capacity is clear from the grid power characteristic of Fig. 6 which is not constant from 0830h to 1045h. The battery stops supporting the grid as its SOC drops to SOC_{min}=0.2 at 0830h. Clearly, the battery will not also be able to support the load after 1800h.

On the other hand, a large battery will increase system cost and may not have a significant advantage. Comparing Figs. 5 and 7, the only advantage of increasing battery capacity by 10kWh/5.7kWh=%154 is expanding battery support during peak loaf hours from 2000h to 2045h.

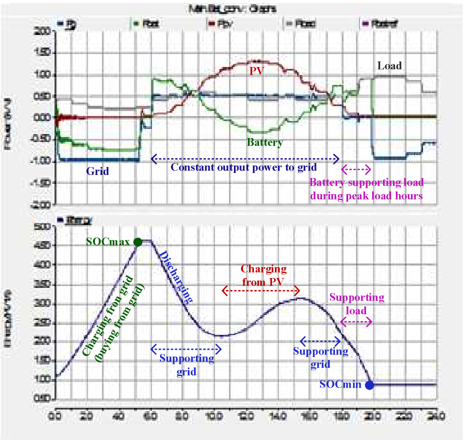

Fig. 5. Case 1: Simulation results with battery capacity of 5.7kWh and constant output power of 0.5kW from 6:00 to 18:00.

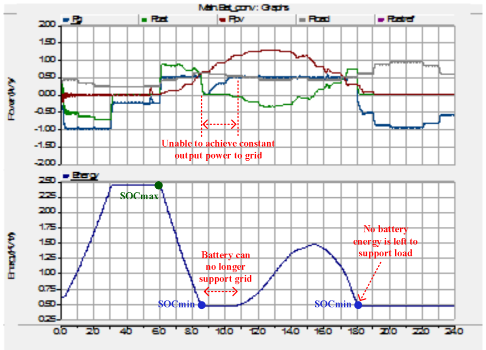

Fig. 6. Case 2: Impact of small battery capacity (3kWh).

C. Case 3: Changing Constant Output Power Level

PV owners would like to have high output power levels to increase their profit by selling more electricity to the grid.

However, the maximum constant output power depends on PV daily output power and battery capacity. Figs. 8 and 9 show simulations with the constant output power level changed from 0.5kW to 0.8kw and 0.3kW, respectively.

According to Fig. 8 (with a high constant output power), BS system is not able to continue supporting the grid for the entire day as it reaches SOC_{min} at 1015h. After this time, the output power will keep dropping in accordance with the diminishing sun radiation. According to Fig. 9, the system will work properly for a small output power level; however, the battery capacity is not fully utilized during daylight. The advantage of this configuration is that BS system can fully support the load during peak load hours (in this case 1800h-2145h) without any grid support.

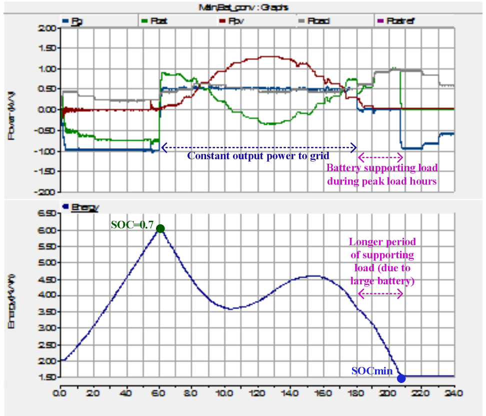

Fig. 7. Case 2: Impact of small battery capacity (10kWh).

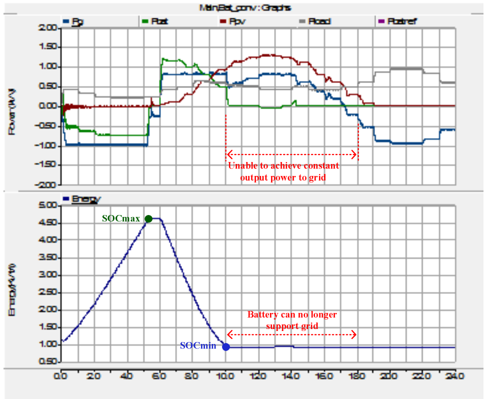

Fig. 8. Case 3: Impact of large output power level (0.8kW).

VI. CONCLUSION

This paper investigates inclusion of battery storage across an existing rooftop PV system to deliver constant output power level to grid during daylight hours after feeding the household loads. This is performed by implementing a BS-EMS to dynamically control the battery charge/discharge and SOC while considering sun radiation and load variations. The main conclusions are:

- The proposed BS-EMS can effectively control the charge/discharge characteristics of the BS system to deliver constant output power to the grid.

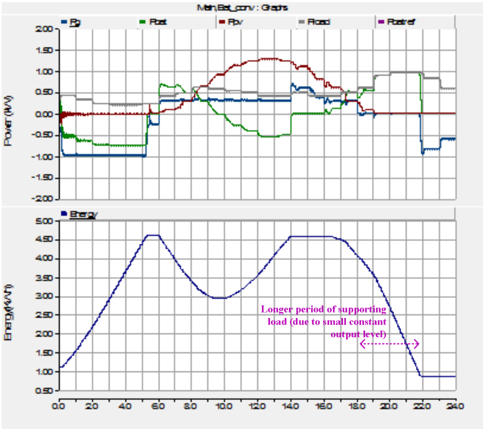

Fig. 9. Case 3: Impact of small output power level (0.3kW).

- The maximum possible level of constant output power will significantly depend on the amount of available daily PV power and to some extent the size of the battery.
- With large output power levels and/or small battery capacities, BS-EMS will not work properly for the entire day as the battery will quickly reaches SOC_{min}.
- With small output power levels and/or large battery capacities, BS-EMS will work properly; however, the available battery capacity is not fully utilized. This configuration is suitable if the intention is to also purchase cheap electricity during off-peak load hours and sell it at a higher price during peak load periods.

REFERENCES

[1] P.G. Barbosa, L.G.B. Rolim, E.H. Watanabe, R. Hanitsch, "Control strategy for grid-connected DC-AC converters with load power factor," *IEE Proc. Gener., Transm., Distrib.,* vol. 145, pp. 487-491, 1998.

[2] H. Beltran, E. Bilbao, E. Belenguer, I. Etxeberria-Otadui, P. Rodriguez, "Evaluation of storage energy requirements for constant production in PV power plants," *IEEE Trans. Industrial Elect.,* vol. 60, pp. 1225-1234, 2013.

[3] A. Aichhorn, M. Greenleaf, H. Li, J. Zheng, "A cost effective battery sizing strategy based on a detailed battery lifetime model and an economic energy management strategy," *IEEE Power and Energy Society General Meeting*, pp. 1-8, 2012.

[4] H. Fakham, L. Di, B. Francois, "Power Control Design of a Battery Charger in a Hybrid Active PV Generator for Load-Following Applications," *IEEE Trans. Industrial Electronic*, vol. 58, pp. 85-94, 2011.

[5] Q. Hao, Z. Jianhui, L. Jih-Sheng, and Y. Wensong, "A high-efficiency grid-tie battery energy storage System," *IEEE Trans. Power Electronics*, vol. 26, pp. 886-896, 2011.

[6] J. H. Teng, S. W. Luan, D. J. Lee, and Y. Q. Huang, "Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable PV generation systems," *IEEE Trans. Power Systems,* vol. PP, pp. 1-1, 2012.

[7] R. Carbone, "Grid-connected photovoltaic systems with energy storage," *International Conference on Clean Electrical Power*, pp. 760-767, 2009.

[8] M. Lafoz, L. Garcia-Tabares, M. Blanco, "Energy management in solar photovoltaic plants based on ESS,"*13th Conference on Power Electronics and Motion Control, EPE-PEMC*, pp. 2481-2486, 2008.

[9] http://perthsolarcity.com.au/holdingpage/

[10] W. Marwali, Q. Yan, "Research on state of charge estimation of batteries used in electric vehicle," *Asia-Pacific Power and Energy Engineering Conference (APPEEC),* pp. 1-4, 2011.