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Optimization for a Grid-Connected Hybrid PV-Wind-Retired HEV Battery Microgrid System

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Abstract

This paper presents a study on the retired EV(electrical vehicle) battery in hybrid PV-Wind-Retired Battery microgrid system. An optimal control theory based algorithm is proposed to determine the optimal application of the battery pack for a residential house equipped with a roof-top PV system and a wind turbine. The main goal of this algorithm is to low the cost of energy purchased from the main grid and maximize the profits for selling energy generated by photovoltaic arrays and wind turbine.

Keywords: EV, HEV, the Retired EV Battery, Hybrid PV-Wind-Microgird, PV(photovoltaic), Wind-Turbine, Optimization, Microgrid, ESS(Energy Storage Systems)

1. INTRODUCTION

Electric vehicle (EV/HEV) is considered one of the most promising solution towards the decarbonisation of the transportation sector[1]. Li-ion batteries are widely used in EV and HEV. Anyhow, typically Li-ion batteries still preserve about 80% of their initial capacity when retired from EV or HEV use [2]–[3]. Such batteries, no longer useable for EV and HEV applications, are still capable of providing energy storage service in other less-demanding applications, in which battery performance, volume and weight boundaries are not so critical. The topic of battery reuse has been addressed since the appearance of the first commercial EV, and several studies have evaluated the economic viability of the so-called second life battery usage. With the time goes by , there will be a large number of battery packs retired eventually from electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) [1]. Using the retired batteries could greatly increase the total lifetime value of the battery packs and bring economic benefits to both of the power consumer and EV/HEV manufactures. To operate this system efficiently, the optimal usage profile of the battery pack and the size of the PV system need to be investigated.

This paper focus on the retired EV/HEV battery used in the microgrid.

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Microgrid system is an aggregation of distributed energy resources (DER) such as renewable energy sources (RES), loads and energy storage systems (ESS) as controllable entities which may operate in grid-connected or islanded mode.

Optimal battery usage profile have been investigated . [2] studied the usage optimization of the Retired PHEV and HEV, however, the battery model is a simple based model which will not represent battery's actual behavior. [4]-[5] studied the battery usage profile for improved utility grid operations, and in [9], an energy management strategy is designed to gain the maximum economic profit for a residential house with PV system. In these papers, the battery size can be changed continuously. The size of the PV system is fixed and the cost is not considered in the cost function. [10] and [12] consider the optimal sizing of energy storage with renewable energy to minimize the electricity bill, but the electricity price is fixed or based on a Time of Use Rate. However, the scenario discussed in these papers is different. On one hand, the size of the battery pack is fixed since it is directly taken from the EV. Considering that the typical power level of a residential house is in the range of several kilo-Watts, a single battery pack already has a comparable power and energy level for this application. On the other hand, since the price of the PV system is relatively high, the size of PV system needs to be considered to achieve a minimized overall system cost.

Distributed Energy Resource(DER) sizing is highly depending on the annual power consumption level and load profile of target residential microgrid. Simulated or predicted residential load profile is usually applied in large scale residential usage optimization. For example, paper [13] and [14] utilize simulated daily and monthly community load profile for the large scale distributed energy source sizing and energy storage unit sizing. On the other hand, DER sizing algorithm proposed by paper [5] and [15]shows that complete long term historical data of household-level load demand is the prerequisite to obtain overall optimal result for a very small scale residential microgrid. However, those high resolution historical data is not always available. A probabilistic household load demand model is utilized in this study to avoid this information restriction. The proposed model can simulate the load demand of target residential load for entire year based on local temperature data.

Now most of present researches on the retired battery pack is focused on the theoretical study. Though a second use battery field test is performed at University of California, San Diego [10], the experimental integration of the retired battery pack for residential applications has not been thoroughly studied yet. Feng Guo and He Li [2] provided a comprehensive study on the deployment of the retired PHEV battery in residential application with a simple battery model which is not enough for the study.

E.Martinez-Laserna[1] researched on battery second life performance and degradation, however none of the battery was obtained from real-life EV and HEV uses. Adriana Luna[8] optimized optimal power scheduling for a grid-connected hybrid microgrid system but no using retired EV battery.

In this paper, we used a better EV battery model[5] and an algorithm for determining the optimal usage profile of the retired EV battery and optimal size of the PV system for a residential microgrid is presented with the new battery model. Then introduces the data input and optimization strategy of the EMS,. At the same time, it shows how to improve the EMS performance by utilize the household load modeling method. In last, conclusions and the plan for future work are given.

2. Wind Turbine Generating System

The working principles of the wind turbine can be described in two processes, that are carried out by its main components: the rotor which extracts kinetic energy from the wind passing it and converts it into mechanical torque and the generating system, the job of which is to convert this torque into electricity.

A wind turbine operates by extracting kinetic energy from the wind passing through its rotor. The power developed by a wind turbine is given by:

$$P = \frac{1}{2} C_p \rho V_w^3 A \tag{1}$$

where:

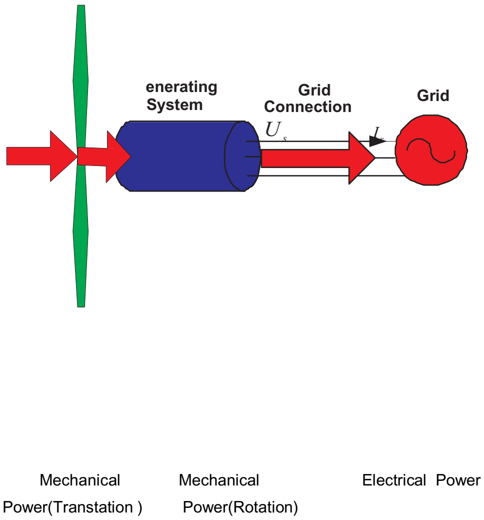


Fig. 1. General working principle of wind power generation

P = Power (W).

C_p = power coefficient.

V_w = Wind velocity (m/s).

A = swept area of rotor disc(m^2).

ρ = density of air (1.225 kg/m^3).

3. BATTERY USAGE PROFILE OPTIMIZATION AND PV SIZING

3.1. Overview of the proposed optimization algorithm

The case study in this paper is a residential house equipped with a retired battery pack and a roof-top PV system and wind turbine. It should be emphasized that the this algorithm is not limited to the particular system but can be applied towards wide circumstances for battery usage profile optimization with different renewable energy resources..

In the proposed optimization algorithm, an EMS(Energy Management System) is first developed to gain the maximum economic profit of the battery energy storage unit at a fixed size of the PV system. It is based on the minimization of the yearly energy cost, which is reflected by the following equation

$$C_{EnergyCost}(S_{PV}) = \sum_{t=0}^{N} \{[P_{Load}(t) - P_{PV}(t) - P_{Battery}(t) - P_{Win}(t)] \times E_{Price}(t, state)\} \quad (2)$$

where S_{PV} is the size of the PV system, measured in kW; N is the total number of sequential time steps, $P_{Load}(t)$, $P_{Battery}(t)$ and P_{Win} (t) represent the power requirement of the load, the power obtained from the PV system, the power extracted from the battery pack as a function of time, and the power of wind turbine respectively;

$E_{Price}(t, state)$ is the electricity price per kilowatt-hour (kWh), which is set by the utility company and assumed to be independent of renewable energy generation.

After the energy cost is minimized by the EMS, the optimization algorithm evaluates the tradeoff between the value that PV and energy storage system create and their capital cost. It searches for the minimum of the following cost function with different sizes of the PV system,

$$C_{TotalCost}(SPV) = C_{PV}(S_{PV}) + C_{Battery} + C_{EnergyCost}(S_{PV}) + C_{Win} \quad (3)$$

where $C_{PV}(P_{PV})$, $C_{Battery}$ and C_{Win} are the yearly prorated installation/maintenance cost of the PV system , battery energy storage unit and installation/maintenance cost of the wind turbine respectively.

In sum, the proposed algorithm contains four steps:

(1) After the profiles of load, irradiance, wind strength, and kWh price are collected, set PV size to be 0 as a starting point and the SOC<80%.

(2) Apply the EMS to minimize (1), which results in a minimized yearly cost for the picked PV size. Basically, the EMS will determine an optimal charging/discharging profile for the battery pack to achieve the minimum electricity purchase from the utility grid, i.e., when the electricity price is high, the battery pack will send power to

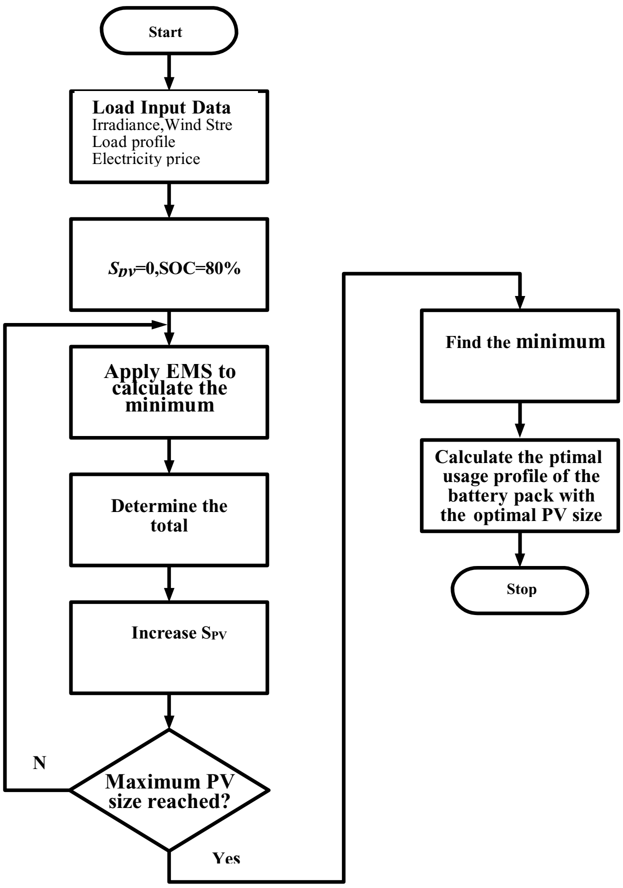


Fig.2 . Calculation flow chart of the proposed optimization

the grid, whereas when the electricity price is low, the battery pack will absorb power from the grid.

(3) Linearly increase the PV size, wind turbine, and repeat step (2) to form a curve that shows the relationship between the size of the PV system and total yearly cost. An optimal PV size will be identified as the minimum in this curve.

(4) At the optimal PV size, run (2) again to obtain the optimal usage profile of the battery.

The calculation flow chart of the proposed optimization algorithm is shown in Figure 2.

3.2. The developed Energy Management Strategy

The objective of the proposed EMS is to minimize the cost of energy purchased from the main grid and maxmize the profits for selling energy generated by the photovoltaic and wind turbine over a period of one calendar year. It utilizes a non-linear optimal control tool (BLOM) [11] to minimize the cost function shown in (1). Models of the battery energy storage unit and PV system are incorporated in the EMS; irradiance, load profile, and electricity price information are utilized as the model input.

(1) Battery energy storage unit model

The battery energy storage unit is one of the core parts of the system. The PHEV initial energy capacity is ECBattery=7.6 kWh. At the time of retirement from the vehicle, it still has 80 % of the capacity left. In order to optimize the battery's charge and discharge state during the energy conversion, the following constrains are taken into consideration in the proposed method in this paper:

a) the battery's state of charge（SOC）can not be less than SOC_{min};

b) the charge rate r_{ch} and the discharge rate r_{dch} cannot exceed the limited value;

c)the charge and discharge current I_{ch} and I_{dch} can not exceed the maximum value I_{chmax} and I_{dchmax}, respectively;

d) the charge and discharge power P_{ch} and P_{dch} are within the maximum value;

e)the battery's charge/discharge cycles Nc can not exceed the limited value Ncmax, in a scheduling period, where Nc is defined as follows: Nc will add once when the battery is charged from one state(i.e., SOC=x, SOCmin≤x≤100%) to full state(i.e. SOC=100%) and then discharged to the same state(i.e., SOC: x→100%→x).

According to the principles above, the battery's charge and discharge state is constrained as follows:

$$SoC_{min} \le SoC(t) \le SoC_{max} \tag{4}$$

$$r_{ch} \le r_{ch\_R}, r_{dch} \le r_{dch\_R} \tag{5}$$

$$I_{ch} \le I_{ch\max}, I_{dch} \le I_{dch\max} \tag{6}$$

$$0 \le P_{bs\_ch} \le P_{bs\_ch\max} \tag{7}$$

$$0 \le P_{bs\_dch} \le P_{bs\_dch\max} \tag{8}$$

$$N_C \le N_{C\max} \tag{9}$$

The power loss during battery charging/discharging is considered in the model, which can be expressed by the following relationship[5,6,7]

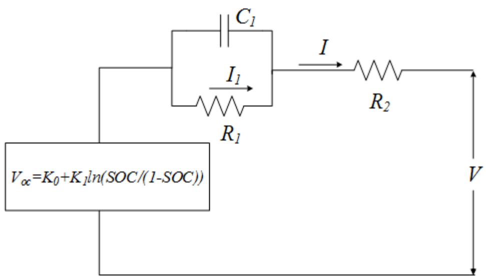


Fig. 3. Battery Model

$$VOC = K0 + K1ln(\frac{SOC}{1-SOC}) \tag{10}$$

A retired EV battery pack is utilized in this study. The initial energy capacity is ECBattery=7.6 kWh. At the time of retirement from the vehicle, it still has 80 % of the capacity left.

During operation, the Sate of Charge (SOC) of the battery pack should be within certain limit at any time, which can be expressed as

$$SoC_{min} \le SoC(t) \le SoC_{max} \tag{11}$$

where SoC_{min} and SoC_{max} are the lower and upper SOC limit, and set to be 30% and 80%, respectively.

The power loss during battery charging/discharging is considered in the model, which can be expressed by the following relationship

$$P_{Battery} = V_{OC} \text{x} I(t) - I^2 R_2 - I_1^{\,2} R_1 \tag{12}$$

where V_{OC} is the open circuit voltage, $I(t)$ is the current and R_2 is the internal resistance of the battery pack. By the experiment, V_{OC} and R_2 are chosen as 334 V and 0.1 Ω, respectively.

The estimated installation/maintenance cost of the battery energy storage unit consists of the retired battery pack and the power electronics circuit. The cost of the retired battery pack is proportional to the energy capacity, while the cost of the power electronics circuit is proportional to the maximum power level. The yearly prorated installation/maintenance cost of the unit can be calculated as

$$C_{Battery} = \frac{CT_{Battery} \cdot EC_{Battery} + CT_{PE} \cdot P_{Battery\_max}}{LT_{Battery\_max}} \tag{13}$$

where $CT_{Battery}$ is the cost of the retired battery pack per kWh, and CT_{PE} is the cost of the power electronics circuit per kW. They are assumed to be \$100/kWh and \$260/kW, respectively. $LT_{Battery}$ is the life time of the unit, and is assumed to be 10 years [1].

(2) PV system model

A simplified PV system model is utilized in the proposed EMS. It is assumed that the output power of the PV system is only determined by the irradiance and not influenced by the temperature,

$$P_{PV}(t) = \begin{cases} \frac{I_{rr}(t)}{Irr\_max} S_{PV}, when I_{rr}(t) < I_{rr\_max} \\ S_{PV}, when I_{rr}(t) \geq I_{rr\_max} \end{cases} \quad (14)$$

where Irr(t) is the irradiance at time t. I_{rr_max} is the saturate irradiance, and is set to be 1000 W/m2; and S_{PV} is the size of the PV system, which is measured in kW and varying during each calculation step. The maximum size of the PV system is set as S_{PV_max}x=10 kW.

The estimated installation/maintenance cost of the PV system consists of the PV panels and the power inverter, which are both proportional to the size of the PV system. Therefore, the yearly prorated cost can be calculated as

$$C_{PV} = \frac{(CT_{PV} + CT_{Inverter}) \times S_{PV}}{LT_{PV}} \quad (15)$$

where CT_{PV} is the cost of the PV panel per kW, and $CT_{Inverter}$ is the cost of the PV inverter per kW. They are assumed to be $ 1.85/W in total (with government incentive). LT_{PV} is the life time of the PV system, and is assumed to be 25 years.

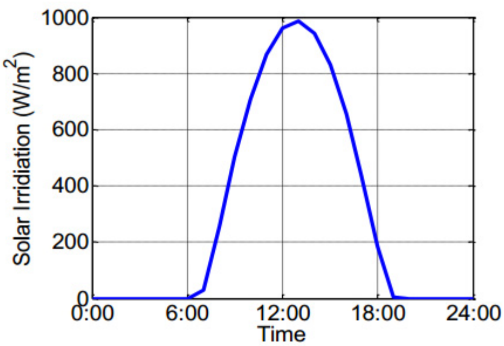


Fig. 4. Example of the irradiance profile

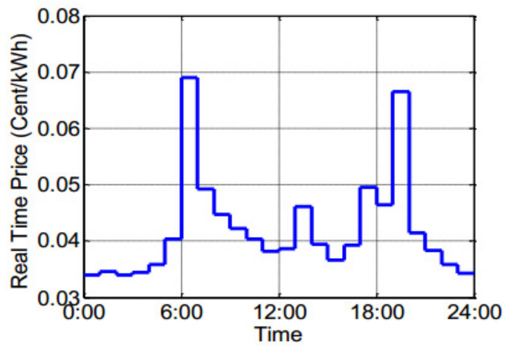


Fig. 5. Example of the retail electricity price

The irradiance profile is needed to decide the output power of the PV system at any given time. One-year irradiance data are collected with a time interval of 1 hour [16]. As an example, the irradiance profile of May 1st is plotted in Figure 3.

(3) Electricity price

Real-time electricity pricing strategy is utilized in this study. The price information is collected from a utility company [17] and updated every hour. In addition, it is assumed that the utility company will pay the customers for the energy feedback to the grid, when the output power of PV system and energy storage unit are higher than the load power. However, the retail price, which is the price that the utility company sells the electricity to the customers, is twice the purchase price, which is the price that the utility company buys the electricity from the customers, as reflected in the cost function

$$\begin{cases} E_{Price}(\mathbf{t},\mathbf{0}) = \mathrm{E}_{RetailPrice}(\mathbf{t}) \\ E_{Price}(\mathbf{t},\mathbf{1}) = \mathrm{E}_{PurchasePrice}(\mathbf{t}) \end{cases} \tag{16}$$

Where

$$\text{state} = \begin{cases} 0, when P_{Load}(\mathrm{t}) - \mathrm{P}_{PV}(\mathrm{t}) - \mathrm{P}_{Battery}(\mathrm{t}) > 0 \\ 1, when P_{Load}(\mathrm{t}) - \mathrm{P}_{PV}(\mathrm{t}) - \mathrm{P}_{Battery}(\mathrm{t}) < 0 \end{cases} \tag{17}$$

And

$$E_{RetailPrice}(t) = 2E_{PurchasePrice}(t) \tag{18}$$

As an example, the daily retail price in March 1st is plotted in Figure 4.

(4) Residential load

The historical residential load demand in one year is obtained from a utility company. It is collected from an anonymous customer and updated every hour. At the same time, a novel probabilistic load demand forecasting procedure has been developed to extend the applicable range of proposed EMS. As an example, a single day (May 1st) load demand predication for a typical household in Middle

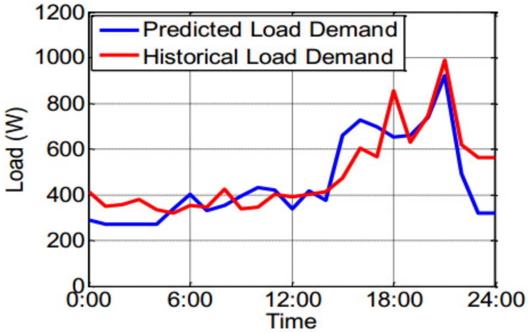
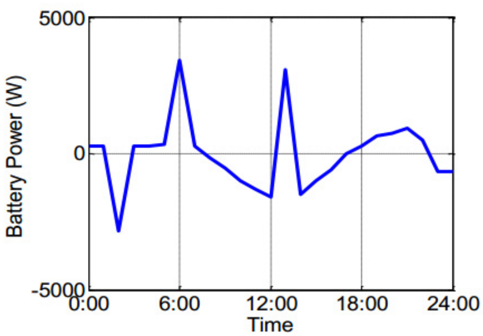


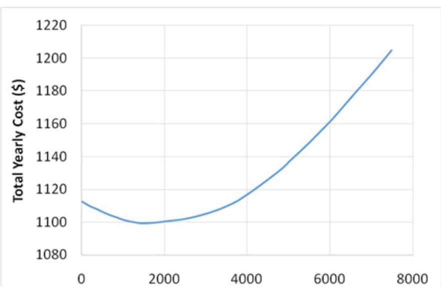
Fig. 6. Example of predicted and historical load demand

By extract target house's power consumption event distribution pattern from historical data, future load demand of the target house can be forecasted. Firstly, data collection is performed and data is pre-processed. Secondly, the inputs of the forecasting including local temperature information are defined. Finally, based on the load data, two household load demand forecasting models of the target house will be identified for weekdays and non- workdays, respectively.

3.3. Optimization results

The simulation result to determine the optimal size of the PV system is shown in Figure 6. It can be





noted that when PV size is 1.58 kW and the wind turbine power is 0.42kW, the yearly cost is minimized.

Fig. 7. Total yearly cost with different PV sizes Fig. 8. Example of the battery pack's optimal usage profile

With all the aforementioned information, the optimal battery pack usage profile can be determined. The calculation step is set to be 1 hour. An example of the optimal usage profile of the battery pack in March 1st is shown in Figure. 7. Compared with the electricity price information shown in Figure 4, it can be seen that when the electricity price is low, the battery is charged, while when the electricity price is high, the battery is discharged. These cycles are repeated multiple times in one day to gain the maximum economic profit.

4. *CONCLUSIONS AND FUTURE WORK*

In this paper, an algorithm for determining the optimal usage profile of the battery pack and PVs in a residential house is proposed. It can minimize cost of buying energy from the grid and maximize profits for selling energy generated by PVs and wind turbine. In the future a hybrid microgrid testbed should be configured to test the algorithm. The proposed EMS and the testbed could be utilized to evaluate the performance of retired EV batteries in residential applications as well as different microgrid control strategies. The life cycle evaluation of retired EV battery in residential applications will be performed in the platform.

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References

[1] E. Martinez-Laserna, E. Sarasketa-Zabala, D.-I. Stroe, M. Swierczynski, A. Warnecke, Evaluation of Lithium-ion Battery Second Life Performance and Degradation, IEEE ENERGY CONVERSION CONGRESS & EXPO, United States, 2016

[2] He Li, Feng Guo, Shaobing Yang. Lingyu Zhu, Chengcheng Yao, Jin Wang. Usage Profile Optimization of the Retired PHEV，ITEC Asia-Pacific 2014

[3] Shuchun Li, Hongwen He,Yong Chen, Optimization Between the PV and the Retired EV Battery For the Residential Microgrid Application, ICAE 2015

[4] D. Menniti, A. Pinnarelli, and N. Sorrentino. A method to improve microgrid reliability by optimal sizing PV/Wind plants and storage systems. *20th International Conference and Exhibition on Electricity Distribution*; 2009, p. 1-4.

[5] HU Xiao-song, SUN Feng-chun, ZOU Yuan. Online model identification of lithium-ion battery for electric vehicles, *J. Cent. South Univ. Technol.* ; 2011, p. 1525−1531

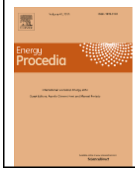
[6] Hongwen He, Rui Xiong, Hongqiang Guo, Shuchun Li. Comparison study on the battery models used for the energy management of batteries in electric vehicles,

[7] Fengchun Sun, Rui Xiong, Hongwen He, Weiqing Li, Johan Eric Emmanuel Aussems. Model-based dynamic multi-parameter method for peak power estimation of lithium–ion batteries, *Applied Energy*; 1996, p. 378-386

[8] Adriana Luna Nelson Diaz Mehdi Savaghebi Juan C. Vasquez, Optimal Power Scheduling for a Grid-Connected Hybrid PV-Wind-Battery Microgrid System, Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE

[9] A. Aichhorn, M. Greenleaf, H. Li, and J. Zheng. A cost effective battery sizing strategy based on a detailed battery lifetime

model and an economic energy management strategy, *Proc. IEEE Power and Energy Society General Meeting*; 2012, p. 1-8.
[10] A. Pesaran, et. Al. *NREL Energy Storage Projects –FY2012 Annual Report,*
[11] Kelman, Anthony, Sergey Vichik, and Francesco Borrelli. BLOM: The Berkeley Library for Optimization Modeling and *Nonlinear Model Predictive Control, Berkeley, CA.*
[12] Garg, M.A. Patterson, W. Hager, A.V. Rao, D.A. Benson, and G.T. Huntington. A unified framework for the numerical solution of optimal control problems using Pseudospectral methods, *Automatica*; 2010, p. 1843-1851.
[13] Tanaka, K.; Maeda, K.; Imanishi, Y.. Dynamic energy management method for power systems with large-scale storage batteries and photovoltaic cells, *Clean Electrical Power (ICCEP)*; 2013, p.268,274.
[14] Shadmand, M.B.; Balog, R.S.. Optimization of photovoltaic-wind hybrid system for apartment complexes and other community living environments by minimizing excess capacity, *Photovoltaic Specialists Conference (PVSC)*; 2012, p.531
[15] Kahrobaee, S.; Asgarpoor, S.; Wei Qiao. Optimum Sizing of Distributed Generation and Storage Capacity in Smart Households, *Smart Grid*; 2013, p.1791-1801.
[16] National Solar Radiation Database [online]. Avaiable: http://rredc.nrel.gov/solar/old_data/nsrdb
[17] Commonwealth Edison Company [online]. Avaiable: http://rrtp.comed.com/live-prices
[18] An Economic Analysis of Used Electric Vehicle Batteries Intergrated Into Commerical Building Microgrids



Biography

Shuchun Li is a visiting scholar at the Ohio State University. His research focuses on the EV(Electric Vehicle) , EV battery and microgrid.