ELECTRICAL STORAGE MODELING: APPLICATION FOR BUILDING ENERGY MANAGEMENT

MÔ HÌNH HOÁ LƯU TRỮ ĐIỆN NĂNG: ỨNG DỤNG QUẢN LÝ NĂNG LƯỢNG TRONG TOÀ NHÀ

Đặng Hoàng Anh[1,*]

ABSTRACT

In building energy management, the electrical storage is important to ensure power supply continuity and reduce cost of electrical consumption. Therefore, an electrochemical battery model is highly recommended for above objectives, which can contribute to simulate the impact of electrical storage in the building. In the framework of MSGBEM project, a Photovoltaic generation, an electrical storage and power grid supply is proposed to be installed for energy management of USTH building. In this paper, toward electrical energy management, an electrical storage modelling is developed for a complete solution for the electrical optimal management, including prediction, optimization, and real-time management of an electrical storage system with photovoltaic generation. This research is applied for a case study of 6th floor energy management of USTH building.

Keywords: *Building energy management; electrical storage; renewable energy; demand response; energy autonomy.*

TÓM TẮT

Đối với quản lý năng lượng toà nhà, hệ thống lưu trữ năng lượng có vai trò quan trọng đảm bảo cung cấp điện liên tục và góp phần giảm thiểu chi phí tiêu thụ điện năng. Vì vậy, mô hình hoá hệ thống lưu trữ năng lượng (điện hoá) rất cần thiết vào đáp ứng các mục tiêu trên, đóng góp lớn vào mô phỏng ảnh hưởng của hệ thống lưu trữ năng lượng đối với toà nhà. Trong khuôn khổ dự án MSGBEM, hệ thống tấm pin mặt trời kết hợp hệ thống lưu trữ năng lượng nối với lưới điện sẽ được lắp đặt phục vụ quản lý năng lượng tại toà nhà USTH. Trong bài báo này, mô hình lưu trữ năng lượng được phát triển hướng tới ứng dụng quản lý tối ưu điện năng, trong đó cho phép dự báo, tối ưu hoá và quản lý thời gian thực hệ thống lưu trữ năng lượng kết hợp với hệ thống pin mặt trời. Nghiên cứu được áp dụng cho quản lý năng lượng khu vực tầng 6 của toà nhà USTH.

Từ khoá: *Quản lý năng lượng; lưu trữ điện năng; năng lượng tái tạo; đáp ứng nhu cầu phụ tải; năng lượng tự dùng.*

[1]Viện Công nghệ HaUI, Trường Đại học Công nghiệp Hà Nội
*Email: danghoanganh@haui.edu.vn
Ngày nhận bài: 05/01/2018
Ngày nhận bài sau phản biện: 29/3/2018
Ngày chấp nhận đăng: 21/8/2018
Phản biện khoa học: TS. Nguyễn Hữu Đức

SYMBOL

Symbol	Unit	Mean
Psp	W	Power set point
Pb	V	Real battery power
SOC	%	State of charge
SOH	%	State of health
Vmax	V	Overvoltage
Ilim	A	Limit current
I_B	A	Battery current
Q	Ah	Battery charge
Q_{max}	Ah	Maximal battery charge

ABBREVIATIONS

HaUI	Hanoi University of Industry
USTH	University of Science and Technology of Hanoi
MSGBEM	Micro Smart Grid for Building Energy Management

1. INTRODUCTION

A smart building is a type of building that, from design, technologies and building products, uses less energy than a conventional building and can be controlled optimally by occupant. Energy management is one of innovate solutions to reach this goal within two main strategies:

- Reduce energy consumption and develop renewable sources
- Optimize power supply that depends on production, distribution and storage.

To assess the potential gains from these solutions, one of priorities is the development of simulation models, which could be used for global simulation, optimization and prediction for energy management in buildings [1].

In the MSGBEM project, we have a platform powered from a Photovoltaic generation, an electrical storage (battery bank of 15kWh) and power grid (220/400V). In this paper, toward electrical energy management, we develop an electrical storage modelling for a complete solution for the electrical optimal management, including prediction, optimization, and real-time management of an electrical storage system with photovoltaic generation. This research is applied for a case study of 6th floor energy management of USTH building. It is also applied to real-system in next year, when all materials are available in USTH.

2. ELECTRICAL STORAGE MODELLING

In simulation and application of electrical storage, the preferred electrical model of battery is electrical capacity, which is simple and describes energy balance in charging and discharging process. However, this model cannot describe accurately the functional states of the battery at each moment (state of charge, state of health) and some functional conditions (overvoltage, overcurrent) for predictive and feedback control.

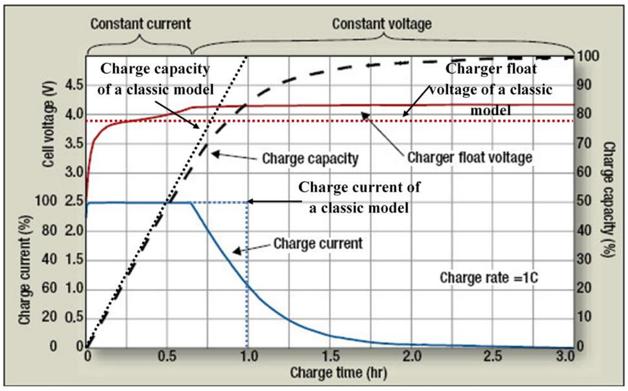


Figure 1. Charge profile of a Li-ion battery

For example (Figure 1), in the constant voltage stage, charge current depends highly on battery property, and real charge time is much longer than estimated charge time by using an electrical capacity model. To reach these proposed goals and consider the battery typical characteristics, a physical model is required but must be as simple as possible.

2.1. Electrical equivalent model

Various models are available in the literature [2, 3, 4, 5, 6, 7] to reach fine and fast simulation. In our framework, a simple model is preferred to describe charging and discharging process.

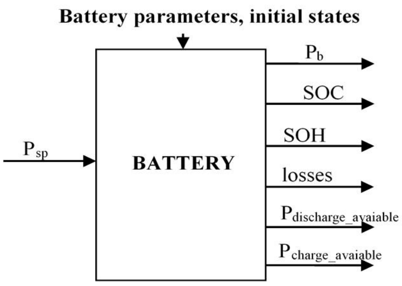


Figure 2. Battery model specification

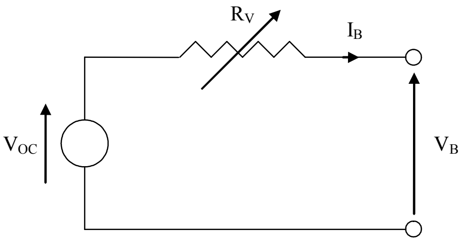


Figure 3. Electrical equivalent circuit

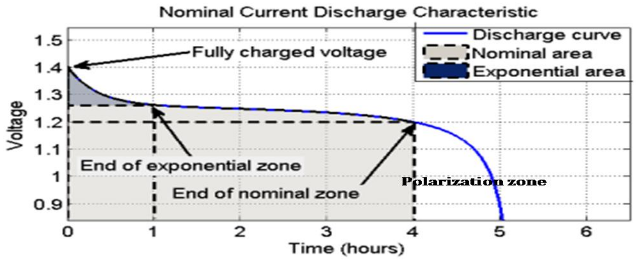


Figure 4. Typical Discharge Curve Characteristics

This is the reason why we have chosen Shepherd's hypothesis [2] as the basis content of this model. These hypotheses are based on a simple equivalent circuit: a voltage source is connected with a variable resistor (Figure 3).

This model must consider the variation of battery voltage depending on battery state of charge. Indeed, the curve consists of three operating zones: exponential zone, nominal zone and polarization zone (Figure 4).

By synthesizing the three discharge phenomena and Shepherd's hypothesis, we can re-establish power discharging and charging equations [3].

For the discharge mode ($I_B \geq 0$), the battery power equation across the battery can be defined as below:

$$P_B = V_0 I_B - R_I I_B^2 - K\frac{Q_{max}}{Q} I_B^2 + A I_B e^{B(Q-Q_{max})} \tag{1}$$

In charge mode ($I_B \leq 0$), the polarization resistor is modified to approach the operation of the battery. So the power equation is rewritten:

$$P_B = V_0 I_B - R_I I_B^2 - K\frac{Q_{max}}{Q_{max}-Q} I_B^2 + A I_B e^{B(Q-Q_{max})} \tag{2}$$

These equations allow determining the state of charge (SOC), the available powers (charge and discharge) and Joule losses.

State of charge:

$$SOC = \frac{Q}{Q_{nom}}.100\% \tag{3}$$

Joule losses in discharge mode:

$$Joulelosses = R_I I_B^2 + K\frac{Q_{max}}{Q} I_B^2 \tag{4}$$

Joule losses in charge mode:

$$Joulelosses = R_I I_B^2 + K\frac{Q_{max}}{Q_{max}-Q} I_B^2 \tag{5}$$

Available discharge power:

$$P_{discharge\_avaiable} = \frac{[V_0 + A I_B e^{B(Q-Q_{max})}]^2}{4(RI + KQ_{max}/Q)} \tag{6}$$

Available charge power at constant current stage:

$$P_{charge\_avaiable} = V_0 I_{lim} - R_I I_{lim}^2 - K\frac{Q_{max}}{Q_{max}-Q} I_{lim}^2 + A I_{lim} e^{B(Q-Q_{max})} \tag{7}$$

Available charge power at constant voltage stage:

$$P_{charge\_avaiable} = -\frac{V_{max}^2 - V_{max}V_0 - V_{max}Ae^{B(Q-Q_{max})}}{R_I + KQ_{max}/(Q_{max}-Q)} \tag{8}$$

Besides, the state of health (SOH) is estimated by "additive law" [7]:

$$SOH = \left[1 - \frac{\int |I_B| dt}{N_C . Q_{max}}\right].100\% \quad (9)$$

The model can accurately simulate the behavior of an electric battery by using identified parameters from typical battery characteristics.

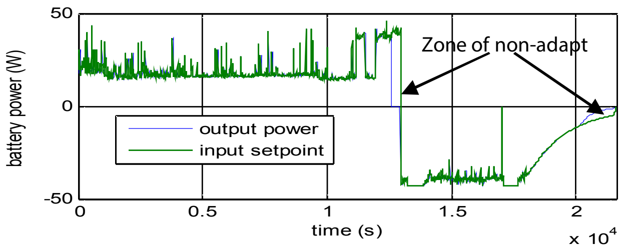
In our framework, we have to keep a compromise between accuracy and ease of use. In particular, model parameters can be considered constant in charge mode and discharge mode, thus facilitating the implementation of the model. Our model integrates the parameters for four famous kind of battery (Lead-acid, Ni-Cd, Ni-Mh, Li-ion).

2.2. Model validation

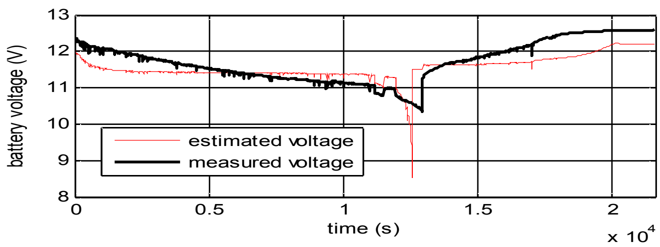
This model is validated by a test on a Laptop DELL Latitude E6400 including a Li-ion battery (rated voltage: 11.1 V, rated capacity: 6100 mAh, cycle durability: 1200, initial state of charges 100%).

In Figure 5, the simulation is well reproducing the measured power set point and the measured state of charge. Because of using average parameters for Li-ion battery, the model cannot reproduce exactly the battery voltage which is sensible with different parameter values. This has an influence for calculating the state of charge which is sometimes a little bit higher or lower than measurement data. This is also the case for the output power which cannot reproduce exact values at the end of discharge mode or charge mode as shown on Figure 5a.

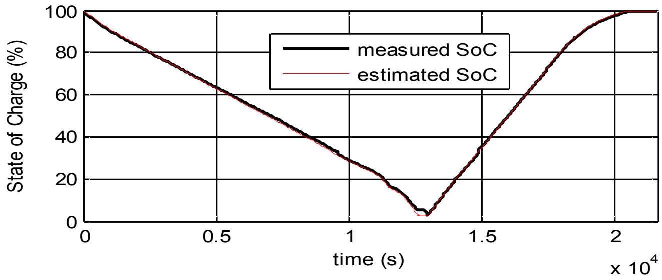
For health protection, the battery should not be used until the end of its charge like it was done in this test case. Thus the peak estimated voltage at the end of battery charge (see Figure 5.b) would not exist in almost operation modes. Thus, if we exclude this peak value, Figure 5.b shows that the difference between simulations and measurements is lower than 10% which is the level of accuracy that we can accept.



(a)



(b)



(c)

Figure 5. Simulations vs measures for power, voltage and SOC

Actually, the power set-point in charge mode of a laptop is not clearly defined. In fact, in almost cases, we usually estimate charge power of battery between the maximum power value of adapter and power consumption of the PC, while the real value depends completely on its properties (type of battery and technical parameters).

In order to validate battery model function in this condition, we made a test of charge mode (without using the PC) of a Li-ion battery from a computer: DELL PRECISION module KY265 11.1V, battery capacity: 85Wh, design charge power: 130.65W (19.5V × 6.7A), the initial state of charge $SOC_0 = SOC_{min} = 5\%$, maximum charge current $I_{lim} = -0.7Q_{rat}$ and maximum voltage $V_{max} = 1.13V_{rat}$.

In Figure 6, the estimated power curve during charging is close to the battery characteristic curve. In constant current stage, the model calculation could well reproduce the measured power. But, in constant voltage stage, battery model start to make errors in calculation and they will be accumulated and lead to a different at end of charge process with an order of 7%. In our framework, these errors of charge power and charge state are acceptable for the purpose of prediction.

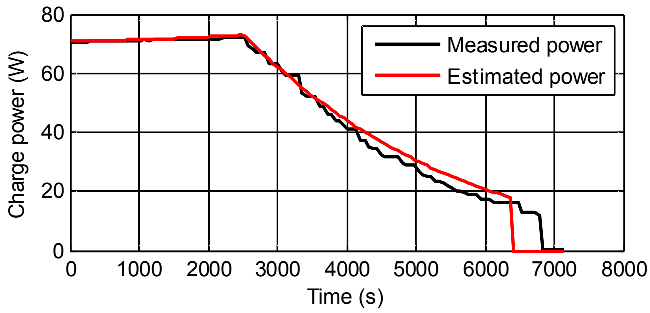


Figure 6. Model validation for power in charge mode

3. CASE STUDY: ELECTRICAL ENERGY MANAGEMENT IN 6TH FLOOR OF USTH BUILDING

The MSGBEM project focuses on the "micro smart grid" development at the building level. The power supply system for platform is from a Photovoltaic generation, an electrical storage (battery bank of 15kWh) and low voltage power grid. The PV system at power scale of 15kWp including an inverter and solar panels will be installed on the rooftop of USTH building. This system extracts the maximum power obtainable from the PV array under different working conditions to provide a portion of the building power demand. In fact, storage can "smooth" the delivery of power generated from solar technologies, in effect, increasing the power of PV sources. The load includes lighting systems, ventilation and air-conditioning systems, and elevator. Besides, the monitoring system allows collecting data that can be analyzed providing information for the optimal operation. The energy controller reads all the data measured by the transducers for managing and running the equipment following the different selected modes. The energy manager controls the delivery of energy, the run of charges and discharges batteries. Therefore, the electrical storage or battery model is necessary for electrical energy management [10].

In this section, we illustrate the power system of 6th floor of USTH building as a "micro smart grid". Indeed, it is supposed to be supplied from 15kWp PV panels, power grid 380/220V and room UPS (uninterrupted power supply) devices. Due to the lack of experimental materials and supervisor system, we simulate the energy consumption by EnergyPlus, size the UPS devices for room and simulate prediction and real-time control for electrical energy management.

3.1. Calculation of energy consumption

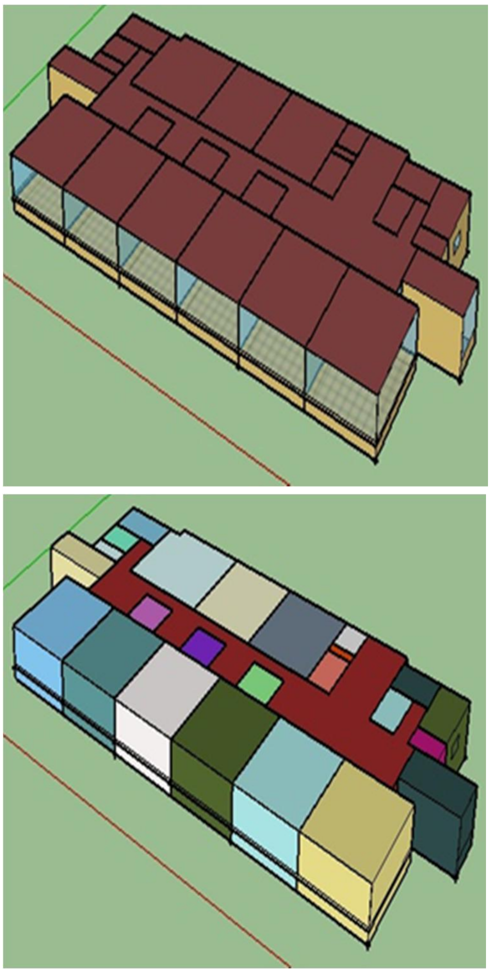


Figure 7. 3D overview of 6th floor USTH's building by SketchUp

OpenStudio, the energy simulation software is used very effectively in energy management of buildings. It is used in combination with a SketchUp design software allows creating 3D model of a specific research subjects and then proceed to simulate energy on the OpenStudio interface. In this section, we heritage the building energy model of 6th floor, which is also used for thermal envelope modeling, to calculate energy consumption profile. In fact, based on the provided drawing and through the actual survey, a 3D model has been designed for 6th floor of USTH building with different temperature zones expressed by different colors in the Figure 7.

The setting of object envelope characteristic, loads of energy consumption such as air conditioners, lightings, as well as schedules are carried out on the OpenStudio interface. With a year of most updates weather data in Hanoi included in the model, the 6th floor USTH building was simulated by OpenStudio. The simulation results allow to obtain data of the energy consumption of each space. Besides, the profile of PV production is given by our work of PV modelling in the framework of MSGBEM project.

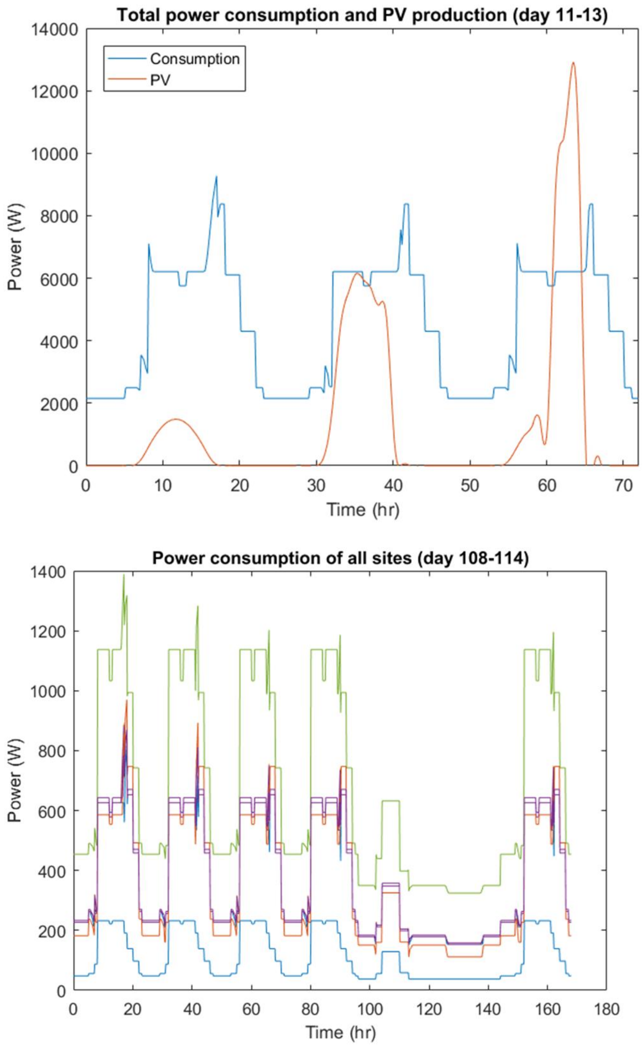


Figure 8. Sample of total power consumption, site's consumption and PV production

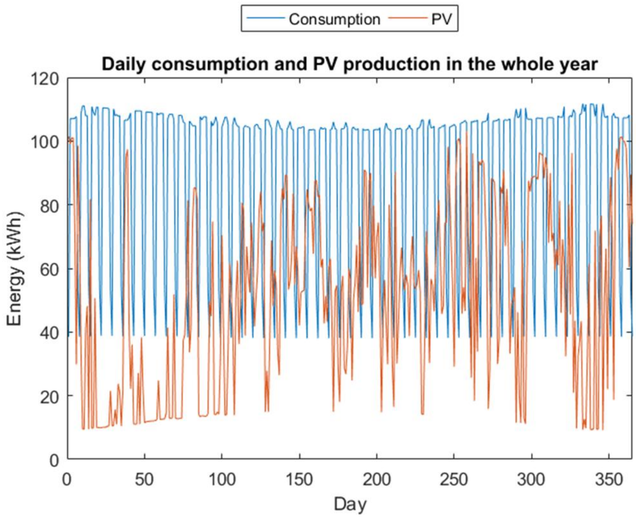


Figure 9. Daily energy consumption and PV production in 1 year

Because the PV power is apparently not enough for total power consumption of 6th floor, due from Heating, Ventilation and Air Conditioning (HVAC), electric appliances and lighting (Figure 9). Therefore, we suppose that PV arrays supply only for electric appliances and lighting of classrooms, lab rooms and offices (11 main rooms).

3.2. UPS sizing

11 UPS were assigned to 11 main rooms of the 6th floor consisting of laboratories, computer rooms and offices (Table 1). The corridor and less frequented areas (toilets and storages) were excluded from the consideration, as well as the HVAC consumption of all sites. Based on the average energy balance and consumption of the sites in one year, the UPS were sized, giving 3 typical sizes (Table 1).

Table 1. Size of the UPS assigned to each site

Name in model	Function	UPS size (Wh)
Space 101	SA lab 612	5000
Space 102	CleanED Lab 610	5000
Space 103	CleanED Lab 608	5000
Space 104	NENS lab 606	5000
Space 105	2 computer rooms	9000
Space 107	Cabine 06	1000
Space 108	Cabine 05	1000
Space 109	Cabine 04	1000
Space 113	Classroom 605	5000
Space 114	Office Energy dept.	5000
Space 115	Office WEO dept.	5000

The sizing decision is based on the daily energy balance of each site, calculated by the difference between the total PV energy supplied to the site and its energy consumption in the same day. Since the PV power that the UPS receive differs according to their consumption, to approximate the annual amount of generated energy delivered to each UPS, a priority factor is assigned to each UPS based on their total energy consumption. The sum of the factors is 1. PV power delivered to a site is therefore taken to be the total PV power multiplied by the priority factor corresponding to the site.

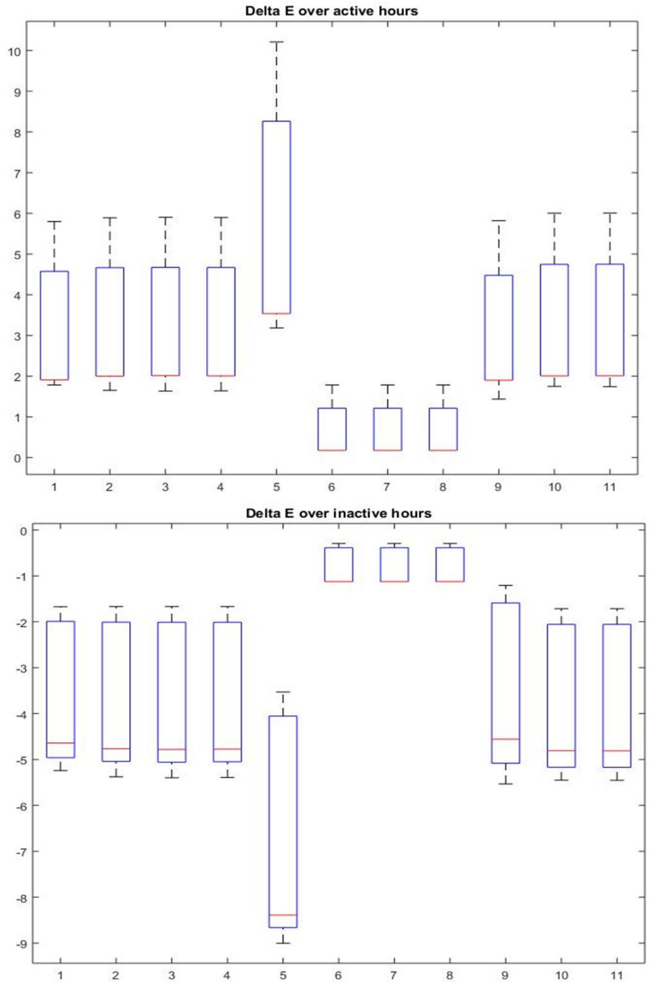


Figure 10. Energy balance over active and inactive period

We examined the energy balance over active, and inactive period since these 2 cases have different characteristics: during the active period, taken from around 8:30 AM to 4:30 PM, PV production is usually present together with high consumption, while in the inactive period, the background consumption is dominant. The results for every day in the year are summarized in box plots to aid sizing decision. From the results, we determined 3 sizes of UPS to be used: 5kWh, 1kWh, 9kWh.

3.3. Electrical energy management

The main algorithm is written in a MATLAB function which was used to iterate over every day in the year.

Table 2. Variables of objective function

Input	Intermediate variables	Output
• Predicted PV production • Predicted power usage (every site) • Initial SOC, SOH	• Load priority (within day) • Total required energy (E_stock)	• Optimized power usage • Optimized UPS power usage

• Battery capacity • Electricity price • Timestamp of each value • Other parameters	• Required SOC (every UPS) • Energy flux • Power from grid	• SOC, SOH (within day) Indices: global efficiency, energy from grid, utility cost, excess PV

After parsing the input variables and initializing the parameters, the algorithm evaluates the given scenario to optimize the required energy level of each UPS and charge starting time in order to minimize electricity cost within the day. Once the required energy is calculated, this is distributed to each UPS according to its pre-calculated priority then translated into the required SOC. The priority is determined by the fraction of the site's consumption with respect to the total consumption within the day.

The simulation with reactive control is then run to simulate the optimal operation of the platform in the whole day. Prior to the set reactive time, the UPS will be charged to the required SOC level based on the charge start time and charge duration which are determined from the previous step. Starting from the reactive time, the algorithm controls the UPS by its usage, SOC and by the PV production power: UPS will be discharged when the PV production is insufficient compared to demand, disconnected from the load when its SOC falls below the limit value, and charged when there is excess power production. Since the amount of excess PV power is usually not large enough to charge all batteries, the charging is prioritized by selecting the UPS with smallest SOCs. When the UPS is exhausted, electricity will be bought from the grid to charge the UPS and power the connected load. When the simulation finishes, the program evaluates the efficiency of the algorithm by calculating the total cost of electricity bought from the grid in the same day. The program can also calculate and compare the excess PV energy wasted, the electricity price and the grid energy usage between two cases: with and without the pre-charging. These results are parsed to the output for saving and subsequent analyses.

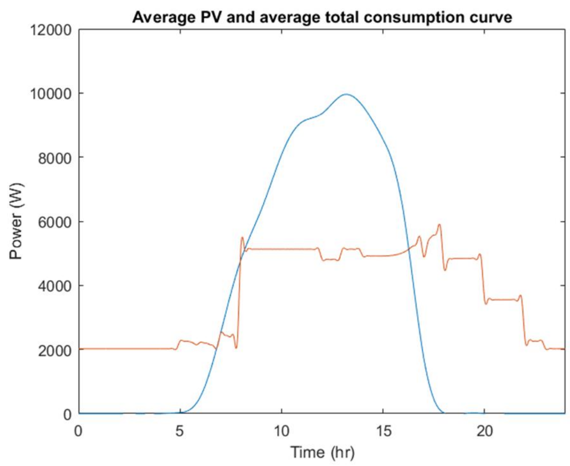


Figure 11. Average power consumption and average PV production for one day

The case of 6th floor electrical energy management is considered, with a PV array of 15kWp and UPS sizing as presented before. At this stage, the simulation is carried out on a hypothetical typical day, obtained by averaging the power consumption and production of the whole year (Figure 11). Initial SOCs of the UPS were chose to range from 0% to 100%. For analyzing robust of optimal control algorithm, we choice electric price depending on time. Simulation time step is 1 minute.

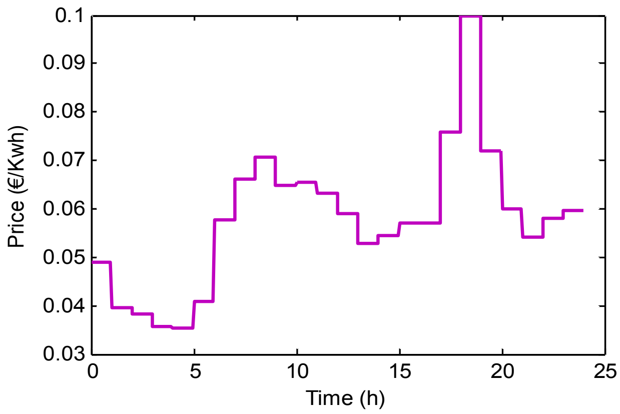


Figure 12. Electric price

Figure 13 shows total power consumption which is balanced with the photovoltaic production. By using UPS and an optimal control, the power consumption profile can benefit as much as possible from the generated power of the photovoltaic panel maximizing by this way the photovoltaic autonomy. Because the energy consumption in this case is more than the generated energy, this system need still to buy energy from electrical grid which is stored on UPS. Besides, the necessary power is bought at the cheapest moment minimize costs.

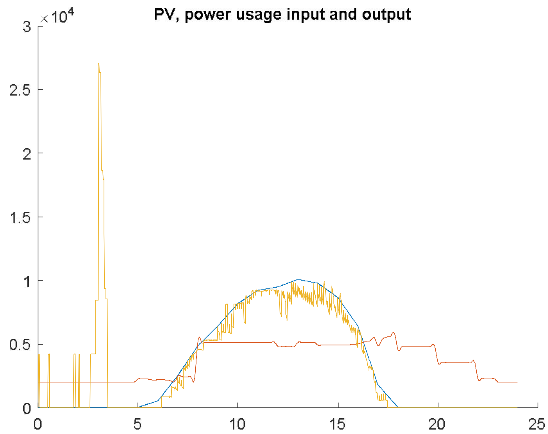


Figure 13. Results of electrical energy management

4. CONCLUSIONS

From this research, an electrical storage modelling has been developed for a electrical optimal management, including prediction, optimization, and real-time management of an electrical storage system with photovoltaic generation. This model is used to model the

UPS and we applied also for a case study of 6th floor energy management of USTH building. For next stage of MSGBEM project, after receiving all necessary materials, this research will be developed and applied on real-system. In fact, the real electrical storage will be modeled by this methodology and our case study will not only in simulation, but also a real optimal energy management.

REFERENCES

[1]. Celik, A.N. Dec 2002. *Optimization and techno-economic analysis of autonomous photovoltaic–wind hybrid energy systems in comparison to single photovoltaic and wind systems*. ScienceDirect, volume 43, issue 18, pages 2453-2468.

[2]. Shepherd, C.M. May 2 1963. *Theoretical design of primary and secondary cells, part III - battery discharge equation*. internal report, U. S. naval research laboratory.

[3]. Tremblay, O., Dessaint, L.A., Dekkiche, A.I. Sept 9-12 2007. *A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicle*s. IEEE VPPC 2007, pages 284 – 289.

[4]. Tremblay, O., Dessaint, L.A May 13-16 2009. *Experimental Validation of a Battery Dynamic Model for EV*. World Electric Vehicle Journal, volume 3, SSN 2032-6653.

[5]. Guasch, D., Silvestre, S. May 2003. *Dynamic Battery Model for Photovoltaic Applications*. Progress in Photovoltaic: Research and Applications, Volume 11, Issue 3, pages 193–206.

[6]. Valøen, L.O., Shoesmith, M.I., Nov 2007. *The effect of PHEV and HEV duty cycles on battery and Battery Park performance*. PHEV 2007 Conference, Winnipeg, Manitoba Canada.

[7]. Long L. Aug 23 2011. A Practical Circuit based Model for State of Health Estimation of Li-ion Battery Cells in Electric Vehicles, Master of Science thesis, TU Delft, Netherlands.

[8]. Picciano N. 2007. *Battery Aging and Characterization of Nickel Metal Hydride and Lead Acid*. The Ohio State University, USA.

[9]. Kazema H. A., Khatiba T., Sopianb K., June 2013. *Sizing of a standalone photovoltaic/battery system at minimum cost for remote housing electrification in Sohar, Oman*. Energy and Buildings, Vol. 61, pp 108–115.

[10]. Delinchant B., Nguyen X.T., Nguyen D.Q., Dang H.A., Wurtz F., June 2015. *Micro Smart Grid Development and Application for Building Energy Management*. 2015 USTH Research project description.

[11]. Đặng Hoàng Anh, Nguyễn Đình Quang, Đinh Văn Bình, Benoit Delinchant, Frederic Wurtz, Nguyễn Xuân Trường, 2015. *Renewable energy supply (PV) integration with building energy management: modeling and intelligent control of electrical storage*. Journal of Science and Technology, Vietnam Academy of Science and Technology, Vol 53, No. 6A.