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Sizing Analysis of PV System with VRB Storage

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Introduction

The absence of an electrical network in remote regions and the prohibitively high connection cost due to large distances and irregular topography lead the various organizations to explore alternative solutions. And with the development of renewable energy stand-alone solar or wind power systems have turned into one of the most promising ways to handle the electrification requirements of these regions [1–4]. However, common drawback with photovoltaic (PV) or wind energy is their unpredictable nature and standalone PV or wind power systems don't produce usable energy for considerable portion of time during the year. Therefore, energy storage devices are essential to store electricity for use when the solar or wind is absent [5, 6].

Traditionally, lead-acid battery (LAB) was used in PV systems as an energy storage device. However, because of its long charge and discharge cycle, short life as well as environmental pollution problems, LAB was not always suited for the application in PV systems. At present relevant agencies have been conducting other storage technology used in PV systems [6]. In [7] fuel cells in combination with an electrolyser and hydrogen storage tanks have been used in hybrid power systems. However, their high cost and slow dynamic response still persist as the main hurdles for wider applications. The super capacitor was also applied to PV systems in [8], but its power density is lower and capacity influenced by temperature severely.

Now a new energy storage technology of Vanadium redox batteries (VRB) is considered being used in PV systems [9, 10]. VRB have many advantages compared with other storage technologies, including operation over a wide range of power outputs, high storage efficiency, rapid response, low maintenance cost and long lifecycle [11]. Also VRB system can be used for power smoothing and load leveling applications [12]. This paper mainly pays attention to sizing combination and techno-economic analysis of PV system with VRB storage, contrast to traditional LAB storage.

Sizing of the PV modules and storage batteries for stand-alone PV systems is a key chain in system design, which in turn requires the data on solar radiation and load demand. Often traditional sizing methods for PV systems are based on the concept of power supply during a number of autonomous days. And the PV capacity has been determined based on the worst month solar radiation whereas energy storage capacity on the number of days of autonomy. These methods are simple and exhibit no direct relationship between the PV power output and storage capacities. So the resultant sizing combination between PV modules and energy storage batteries of PV systems is not optimal and the system does not have a good economy.

In this paper a design method based on the concept of reliability of the power supply to a specified load for a stand-alone PV system with VRB storage is proposed. The system reliability is usually quantified by the loss of power supply probability (LPSP) technique [13]. LPSP can indicate the system configuration to meet the load requirement for a certain period. And based on the proposed method a sizing simulation has been done for the PV system with VRB storage. The weather and power demand data adopted in this study are based on real world measurements of central region of China.

In addition, economy is an important issue in PV systems design. The paper also presents a detailed economic analysis based on the Unit Cost of Energy (UCE) concept. And a cost comparison is given for the proposed PV system as well as VRB storage and LAB storage. Furthermore, to minimize operation cost of the system, an optimization method is presented for meeting the desired LPSP with the lowest UCE.

Modeling of PV system with energy storage

The proposed PV system in Fig. 1 consists of PV modules, energy storage system, DC/DC converter, DC/AC inverter. And VRB was adopted as energy storage unit in this paper. Modeling of the system plays an important role in sizing calculation. The modeling of PV modules and energy storage unit are summarized in the following sections.

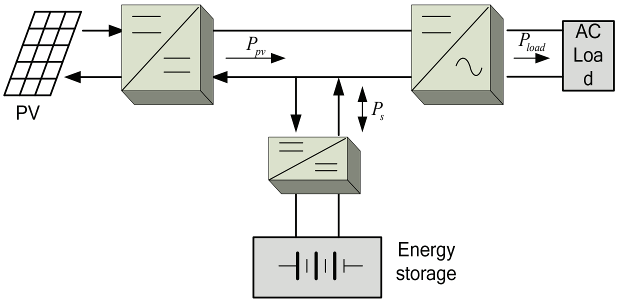

Fig. 1. Proposed PV system with energy storage

Modeling of PV modules. In order to estimate the output power of PV modules, the solar radiation available on the modules surface, the ambient temperature and the manufacturer's data for the PV modules are used as model inputs. The calculation method is given below.

The output power of the PV modules P_{PV} is given by

$$P_{PV}(t) = Ins(t) \cdot A \cdot \eta_{cell}\,, \tag{1}$$

where η_{cell} is the PV modules efficiency, A is the total area of the PV modules (m^2) and Ins represents the solar radiation (W/m^2). The efficiency of PV modules is determined by

$$\eta_{cell} = \eta_r \eta_{pc}(1 - \beta(T_c - T_{cref}))\,, \tag{2}$$

where η_r is the efficiency modules reference, η_{pc} is the power conditioning efficiency, β is the temperature coefficient of array efficiency, T_{cref} is the reference temperature for the cell efficiency and T_c is the monthly average cell temperature. According to (1) (2), the output power of PV modules can be expressed as

$$P_{PV}(t) = Ins(t) \cdot A \cdot \eta_r \cdot \eta_{pc}(1 - \beta(T_c - T_{cref}))\,. \tag{3}$$

Modeling of VRB. VRB is an electrochemical cell divided into two compartments, positive and negative tanks containing electrolyte and a pump, and piping for circulating the electrolyte from the tanks to the cell.

The power and voltage range of the VRB depends on the cell stack, while the energy capacity depends on the tank size. This independence between energy and power ratings provides high flexibility in terms of design. These characteristics make VRB suitable for energy applications. The output voltage of VRB is given by [14]

$$V_{cell} = V_{equ} + 2\frac{RT_i}{F}\ln(\frac{SOC}{1 - SOC})\,, \tag{4}$$

where T_i is the temperature impact on battery operation, R is the VRB internal resistance (in VRB cases the internal resistance is constant), F is the Faraday's number, and V_{equ} is the equivalent voltage of cell stack.

Usually, the loss of VRB, consisted of fixed loss P_{fixed} and Tank loss, can be calculated by

$$P_{para} = P_{fixed} + k^{'}(\frac{I_{stack}}{SOC})\,, \tag{5}$$

where I_{stack} is current of electrode, $k^{'}$ is coefficient of loss. According to (4)-(5), the output power of VRB can be expressed as follows.

$$P_{VRB} = P_{vrbout} - P_{para} = V_{cell} \cdot I_{cell} - P_{fixed} + k^{'}(\frac{I_{stack}}{SOC})\,. \tag{6}$$

Sizing match method of PV system

Usually, when the energy demand of the load is greater than the available energy generated by the PV system, the energy storage devices will be used to help supply the load. The amount of energy at the time t $E_{store}(t)$ is

$$E_{store}(t) = E_{store}(t-1) - (P_{load}(t)/\eta_{dc/ac} - P_{gen}(t))/\eta_{dc/dc}\Delta t\,. \tag{7}$$

When the energy demand of the load is lower than the available energy generated by the PV system, the surplus energy will be stored in the energy storage batteries. The amount of energy at the time t $E_{store}(t)$ is

$$E_{store}(t) = E_{store}(t-1) + (P_{gen}(t) - P_{load}(t)/\eta_{dc/ac})\eta_{dc/dc}\Delta t\,, \tag{8}$$

where $\eta_{dc/ac}$ is the efficiency of DC/AC inverter, $\eta_{dc/dc}$ is the efficiency of bi-directional DC/DC converter, $P_{load}(t)$ is the power of load, and $P_{gen}(t)$ is the output power of PV system.

When the sum of the energy generated from the PV system and the energy available from storage is insufficient to supply the load, the loss of power supply (LPS) will be:

$$LPS(t) = \begin{cases} P_{load}(t) - (P_{gen}(t) + P_{store}(t)\eta_{dc/dc})\eta_{dc/ac} (LPS(t) > 0)\,, \\ 0\;, (LPS(t) < 0)\,. \end{cases} \tag{9}$$

The LPSP over a given time period T can then be calculated as follows

$$LPSP = \frac{\sum_{t=1}^{n} LPS(t)}{\sum_{t=1}^{n} P_{load}(t)} = 1 - \frac{\sum_{t=1}^{n} (P_{gen}(t) + P_{store}(t)\eta_{dc/dc})\eta_{dc/ac}}{\sum_{t=1}^{n} P_{load}(t)}\,. \tag{10}$$

LPSP is normally a very small number corresponding to the number of day supply over a given time period. It is an input parameter to estimate the system reliability. LPSP is defined of the probability that an insufficient power supply when the system is unable to satisfy the load demand.

A LPSP of 0 means the load will always be satisfied; and a LPSP of 1 means that the load will never be satisfied. LPSP is a statistical parameter; its calculation is not only focused on the abundant or bad resource period.

Cost of energy storage

UCE has been used to decide economic feasibility of the system. The system with lowest UCE is always preferred. For UCE analysis combined costs of initial capital investment, present value of operation & maintenance (O&M) cost, cost of energy storage due to their replacement over the system lifetime should be taken into account. The battery lifetime is mainly governed by the daily depth of discharge and also the energy available to charge the battery, which can be determined by the solar radiation. And UCE can be defined as

$$LCE = C_m \cdot CRF / E_{gen} , \tag{11}$$

where C_m is the initial capital cost of each component, E_{gen} is the total generation power, and CRF is the capital recovery factor. CRF is given by

$$CRF = \frac{r(1+r)^{L_T}}{(1+r)^{L_T} - 1} , \tag{12}$$

where r is capital depreciation rate, L_T is the battery lifetime. And the system total cost is made up of

$$C_m = C_{init} + C_{maintance} + C_{replace} , \tag{13}$$

where C_{init} is installation cost, $C_{maintance}$ is maintenance cost, and $C_{replace}$ is replacement cost.

Usually, capital cost of energy storage batteries can be defined as a function of two main parts. One is related to the storable energy; the other depends on the peak power that the storage device can deliver and it is controlled by the charge/discharge control system according to the demand requirements.

Electrodes and electrolyte of LAB are made as a whole, excluding control system, the cost is fixed. And it should be replaced only one time over the service life.

The cost of VRB funded mainly by the electrode, electrolyte, circulating pump, control system, etc. In its service life, only electrolyte replacement and pumps should be replaced. The initial cost of VRB is given by [15]

$$C_{capital} = C_P P_{\max} + C_w W_{\max} , \tag{14}$$

where $P_{\max}$ (kW) and $W_{\max}$ (kWh) are energy storage system power and energy capacities and their specific costs C_P ($/kW) and C_w ($/kWh). For LAB, C_P is equal to 0. So its initial cost is

$$C_{capital} = C_w W_{\max} . \tag{15}$$

Sizing analysis of the proposed PV system

Due to the structure difference of LAB and VRB, there are great distinctions in their applications in PV systems. And the differences are mainly depth of discharge, self-discharge rate, efficiency, which used in comparing these two kinds of energy storage in sizing configuration .To embody the difference formulae (7) (8) can be amended as follows:

$$E_{store}(t) = \begin{cases} E_{store}(t-1)(1-\delta) - (P_{load}(t)/\eta_{dc/ac} - P_{gen}(t))\Delta t / \eta_{md} , \\ E_{store}(t-1)(1-\delta) + (P_{gen}(t) - P_{load}(t)/\eta_{dc/ac})\eta_{mc}\Delta t , \end{cases} \tag{16}$$

where $E_{store}(t)$ should be constrained

$$DOD \square E_{store}(t) \le E_{store}(t) \le SOC_{\max} \square E_{store}(t) , \tag{17}$$

δ is self-discharge of VRB or LAB, η_{md} is the product of the efficiency of DC/DC and discharge rate, η_{mc} is the product of the efficiency of DC/DC and charge rate, and SOCmax is the maximum state of charge.

Table 1 shows the parameter of VRB and LAB mentioned above [12].

Table1. Parameters of VRB and LAB

Parameter	VRB	LAB
Efficiency	75%	45%
Self-discharge	0	5%
DOD	75%	30%
SOCmax	100%	80%

In the sizing algorithm all data about the PV system are adopted from the PV station installed in Huazhong University of Science and Technology located at central region of China. Fig. 2 shows the location (east longitude 114°, north latitude 30°) yearly irradiance distribution. Fig. 3 is a typical daily load curve of a school building. And to simplify the analysis, the annual load curve was assumed to remain unchanged every day. And monthly average temperature is shown in Fig. 4.

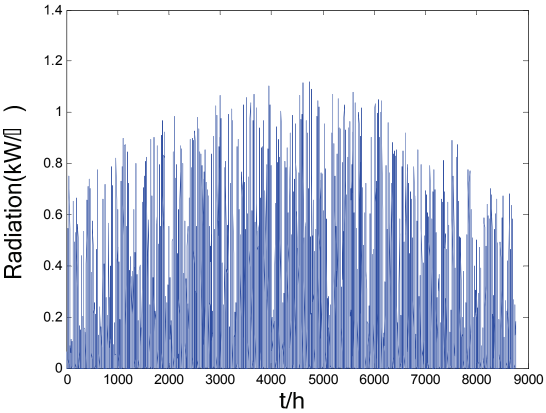

Fig. 2. Hourly average radiation

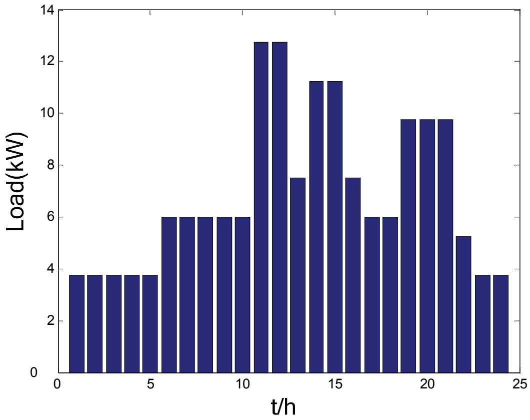

Fig. 3. Daily average load profile of a typical residence

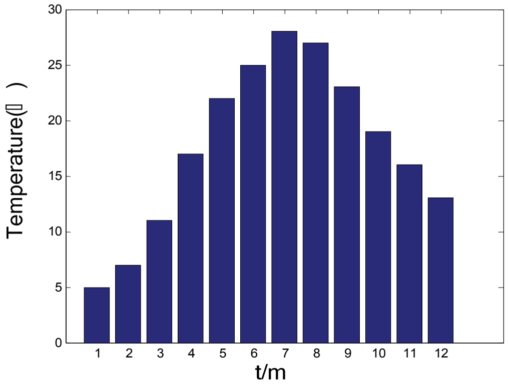

Fig. 4. Monthly average temperature

For estimating the PV output, the solar radiation, the ambient temperature, and the manufacturer's data for the PV modules are used as model inputs. The parameters of PV modules that have been used in this study are η_r =15%, η_{pc} =98%, T_{cref} =20C^{o}.

We take a year (8760 Hours) as a period to study the relationship between LPSP and different sizing configurations. The different combination of PV modules and VRB capacity can be calculated through the proposed method.

Fig.5 and Fig. 6 show the LPSP of the PV system which adopted VRB as energy storage unit.

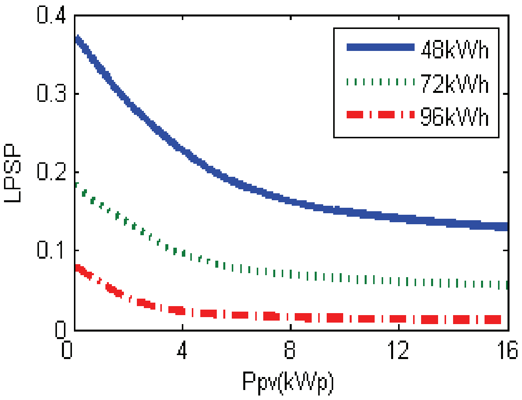

Fig. 5. LPSP of PV system with VRB storage

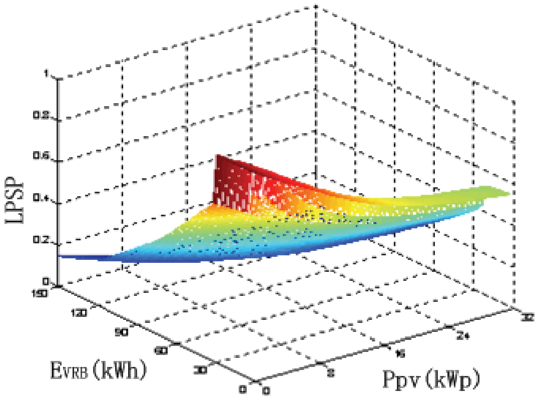

Fig. 6. Sizing combination of PV system with VRB storage

As seen from Fig. 5 to Fig. 6, a remarkable LPSP reduction can be achieved by increasing the capacity of PV modules and storage batteries. For a given PV modules output, higher storage capacity will cause a lower LPSP. And LPSP of the PV system with VRB storage is lower than the system with LAB storage, which has the same capacity. In this study, the combination with a given PV modules output of 12 kW and 72 kWh VRB capacity can get a LPSP of 0.1. Increasing VRB storage capacity to 96 kWh may result in a drop of LPSP to 0.025.

We also can see from these two figures above, to improve the system reliability, increasing the capacity of storage batteries is more effective than increasing PV modules capacity.

Economic analysis of the proposed PV system

The related cost of VRB and LAB has been analyzed in section 4. Table 2 indicates these two batteries' market price[15]. Within the working life of LAB, the replacement cost is equal to zero. As for VRB, the replacement cost which is caused by pump loss in its working life should be considered. Combining the parameters in Table 1 and Table 2, a simulation was carried out which adopted the method proposed in section 3. In this study, the UCE of the PV system, which adopted these two storage technologies, has been estimated. Fig. 7 shows the relation between UCE and total energy production of the PV system. We can see that the PV system with LAB storage achieves a higher annualized cost than the system with VRB storage. And configuring the larger storage capacity, the system cost is lower.

Table 2. Cost of VRB and LAB

Parameter	LAB	VRB
Cp[$/kW]	0	426
Cw[$/kWh]	100	150
Maintain Cost[$/kWh]	0.02	0.008
Replacement Cost[$/kWh]	0	$32
Life[Year]	5	15

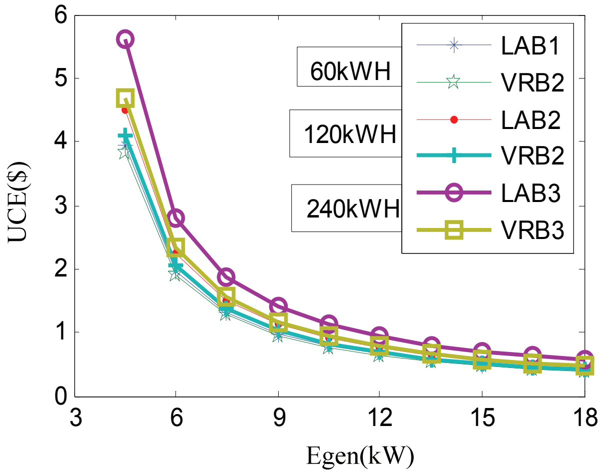

Fig. 7. UCE of the proposed PV system

As an example, Table 3 presents the UCE of different configuration for a fixed capacity of PV output (12 kW), where annual interest rate r is equal to 0.05.

Table 3. System UCE with a desired PV capacity of 12 kW

Storage capacity [kWh]	UCE with VRB storage [$/kWh]	UCE with LAB storage [$/kWh]	Price difference [$/kWh]
60	0.9534	0.9855	0.03215
120	1.0256	1.1242	0.0982
240	1.1702	1.4016	0.2314

As seen from Table 3, under certain load (Fig.3), total cost of the PV system with VRB storage is lower than the corresponding capacity system with LAB storage. And with the increase of storage capacity, the differential of system UCE is clearly. However, due to the separation design of power part and storage tanks in VRB and power part occupies certain of fixed cost, low volume sizing with VRB does not always demonstrate certain advantage. Fig. 8 shows the cost of different configurations of these two different storage batteries. According to actual analysis, sizing combination with lower storage capacity can not meet the requirement of power supply reliability under some certain load condition.

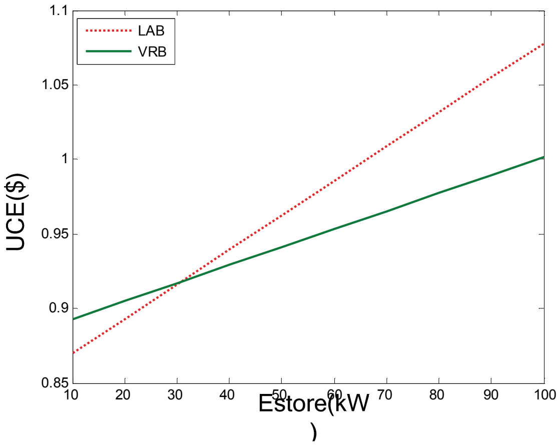

Fig. 8. UCE comparison of these two storage batteries

Conclusions

In this paper a new energy storage technology of VRB was applied in a stand-alone PV system. Sizing match method of PV modules and energy storage and an economical evaluation of the proposed PV system are presented. The method applied in the case study is based on weather conditions of central region of China under the given load. Through a comparative analysis the results show that the system adopted Vanadium redox battery storage has better reliability and economy than that of Lead-acid battery.

Further research work will be considered to extend this kind of analysis to the field of large-scale PV generation system.

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Guozhen Hu, Shanxu Duan, Tao Cai, Changsong Chen. Sizing Analysis of PV System with VRB Storage // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 2(118). – P. 43–48.

A new energy storage technology of Vanadium redox battery has been focused in the application of PV power system. This paper presents a discussion on sizing relation between PV modules and Vanadium redox battery capacity in a stand-alone PV system compared to the system with traditional Lead-acid battery storage. The method adopted is based on the Loss of Power Supply Probability (LPSP) concepts. And in this study the hourly average solar radiation, ambient temperature of central region of China are used to estimate performance of the proposed system and hence for the designing. Meanwhile economy is also an important index in PV system design. A detailed economic analysis has been done by using the concept of Unit Cost of Energy (UCE). A mathematical simulation is carried out and the results indicate that the system adopted Vanadium redox battery storage has better Power Supply Probability and economy, which are prior to that of Lead-acid battery. Ill. 8, bibl. 15, tabl. 3 (in English; abstracts in English and Lithuanian).

Guozhen Hu, Shanxu Duan, Tao Cai, Changsong Chen. Saulės elementų sistemos su VRB kaupikliu analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 2(118). – P. 43–48.

Tiriama nauja vanadžio oksidacijos-redukcijos baterijos energijos kaupimo technologija, taikoma saulės elementų energijos sistemoje. Nagrinėjamas saulės elementų modulio ir vanadžio oksidacijos-redukcijos baterijos talpos tarpusavio sąryšis, lyginant su sistema, kurioje naudojami tradiciniai rūgštiniai švino akumuliatoriai. Pritaikytas metodas pagrįstas energijos šaltinio nuostolių tikimybės koncepcija. Siekiant įvertinti siūlomos sistemos našumą, panaudoti duomenys apie vidutinį Saulės spinduliavimą ir aplinkos temperatūrą centriniame Kinijos regione. Atlikta detali ekonominė analizė naudojant energijos vieneto kainos koncepciją. Matematinis modeliavimas parodė, kad vanadžio oksidacijos-redukcijos baterija gali būti geresnis energijos šaltinis ir yra ekonomiškesnė, palyginti su rūgštine švino baterija. Il. 8, bibl. 15, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).