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OPTIMAL BATTERY SIZING FOR A SOLAR HOME SYSTEM CONSIDERING BATTERY OPERATION AND CAPACITY LOSS

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ABSTRACT

In this study, we aim to find an optimally sized battery that can be installed to an existing grid-tied solar home system without a prior energy storage system, in order to maximize the user's financial benefits while maintaining reliable power supply to the home. To solve this optimization problem, we formulate the objective function as the net present value of the investment on the battery. Solution to the optimization problem returns the optimal battery size, power flows and battery age status during a 10-year evaluation period. In order to identify the most favorable solution to the user, we apply the proposed optimization algorithm to five typical photovoltaic (PV) generation and home load levels, and find that the optimal battery size is very sensitive to the level of PV power generation and the home load. In addition, it is more financially viable to have the battery when the daily PV power generation is less than the home load.

Keywords: Microgrid, energy modelling, energy optimization, battery life, solar home system.

1. INTRODUCTION

Battery energy storage systems (BESS) are widely used in renewable energy systems. There are a broad range of technical, financial and hybrid performance indicators for determining the size of a BESS [1]. The financial indicators refer to the net present value (NPV), levelised cost of electricity (LCOE), and cost benefit ratio, etc. The technical indicators include renewable curtailment, forecast errors, power quality, battery charge/discharge rate, battery degradation and state of health (SoH). These parameters can either be optimized individually or in combination. For instance, [2] presents an optimal sizing algorithm of grid-tied PV battery system for residential homes by minimising the user's annual electricity expenditure. Ref. [3] optimizes both the PV and battery sizes by optimizing the reliability of power supply and minimizing the LCOE. The financial indicators are carefully assessed in [4] and [5] with optimal sizing of the PV battery solar home system, and both the technical and financial indicators are optimized in [6].

The component (battery, PV panel, and wind turbine, etc.) sizing problem in various renewable energy systems is indeed an interactive process of size, operation, and maintenance optimizations. Size and capacity of the system components directly influence their operation patterns, while the operation patterns usually play an essential role on the life span of the components. Many existing studies considered sizing and operation in combination while other studies focus on the components' capacity losses over their lifetime. However, existing studies rarely consider the renewable energy system component sizing problem as an integration of sizing, operation, and maintenance optimization problem.

In this study, our primary goal is to decide the optimal battery size that can be installed in an existing grid-tied solar home system without a prior energy storage system, such that user's financial benefits can be maximised while maintaining reliable power supply to the home. An optimization problem is formulated with the main objective to maximize the net present value of the investment on batteries. Optimal solution to the optimization problem returns the optimal battery size, power flow and battery age status during a 10-year evaluation period. In order to identify the most favorable solution for the user, we apply the proposed optimization algorithm to five typical PV generation and home load levels, and find that the optimal battery size is very sensitive to the level of PV power generation and the home load. In addition, it is more financially viable to have batteries when the daily PV power generation is less than the daily home load.

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2. BACKGROUND AND DATA DESCRIPTION

Demand and solar PV generation data are recorded for 300 residential customers located in an Australian distribution network, the Ausgrid. These are half-hourly electricity and PV data for a three-year period between July 2010 and June 2013, which are publicly available [7]. Figure 1 shows the general diagram of grid-connected PV system. The existing system does not have a battery and this study focuses on the sizing and operation optimisation of the battery. For such systems the sizing of PV and battery depends on the load demand, load consumption pattern and the amount of power needed to be injected to the battery or grid. Electricity generated from PV can be used to supply the demand from loads, store in the battery or sell back to the grid. Electricity must be purchased from the electric grid if the PV generation and battery discharging cannot meet the demand. Due to variable electricity prices through the day in a time of use (TOU) tariff with peak, shoulder and off peak, electricity can also be purchased from the grid when the price is low, and be sold back to the grid when the price is high.

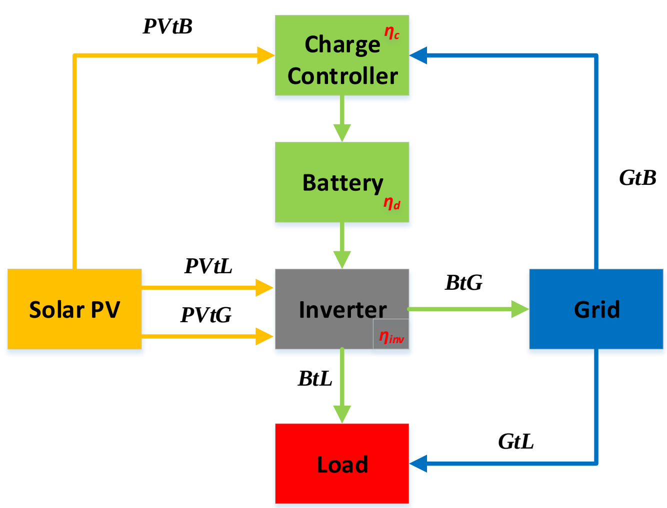

Figure 1: Configuration of the solar home system.

3. PROBLEM FORMULATION

In this section, the battery sizing problem for a solar home system is formulated as a nonlinear optimization problem with constraints, which also considers the optimal power flow management and battery aging.

3.1 Battery capacity degradation model

In the literature, the most popular battery degradation model to evaluating the capacity loss of lithium-ion batteries was presented and experimentally validated in [8]. This model takes considerations of the cycling time, test temperature, depth-of-discharge (DoD), and charging and discharging current rates. The model is given in (1), which is widely adopted in practical applications [9].

$$Q_{loss} = Be^{-\frac{E_a}{RT}} A_h^{\rho}, \quad (1)$$

Q_{loss} is the percentage of battery capacity loss, B is the pre-exponential factor. E_a is the activation energy from Arrhenius law in J/mol. A_h is the Ah-throughput, T is the absolute temperature in Kelvin, and R=8.314 J/(mol$\cdot$K) is the gas constant. ρ=0.55 is the power law factor. The rest parameters of the capacity loss model were empirically obtained from a large set of testing data. The E_a is related to the charge current, and

$$E_a = 31500 - 370.3Crate, \quad (2)$$

where $Crate$ is the current rate. The Ampere-hour throughput A_h is calculated by $A_h = N \times DoD \times C$, in which N is the cycle number, DoD is the depth-of-discharge and C is the full capacity of the battery in Ah.

The model (1) was initially tested under four current rates, 1/2C, 2C, 6C and 10C, and was extended to general scenarios for current rates below 10C in [8], which resulted in

$$\ln B = ae^{-\lambda Crate} + d, \quad (3)$$

where *a*=1.226, λ =-0.2797, and *d*=9.263.

When evaluating the Ah throughput in [8], the battery current rate was uniform. However, in practical applications for a solar home system, the battery current rate is non-uniform due to unpredicted charging and discharging behaviors. In this case, we first obtain the daily charging and discharging current profile I_t, and *t* is the sampling instance over a typical day. For each current rate $|I_t|$ the life capacity (Ah) of the battery can be calculated by Eq. (1), with the life capacity defined as the amount of charge that a battery can provide at a specific current before its capacity loss reaches 20%. If we assume the battery charging and discharging profile is repeating on daily basis, then the daily battery capacity loss DQ_{loss} is

$$DQ_{loss} = \sum_{t=1}^{t_d} \frac{|I_t|\frac{\Delta t}{3600}}{LC(I_t)}, \quad (4)$$

where t_d is total number of time intervals per day, and $LC(I_t)$ is the life cycle capacity in Ah at each current rate $|I_t|$.

3.2 Battery sizing and power flow optimization considering battery aging

In this section, an optimization problem is formulated to identify the optimal size of the battery for a typical solar home system. Solutions to the optimization model also return the optimal power flows and battery aging status.

The objective function of the optimization problem is formulated as the NPV of the battery sizing project. The NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. The NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project. In this study, the cash inflow refers to the selling back electricity to the grid according to the given feed-in tariff (FIT), while the cash outflow refers to the expenditures on the battery procurement, and electricity cost over the evaluation period. Since we aim to decide both the battery size and power flow in an optimal manor, our design variables are the battery size B_s (in kWh), and the daily power flow profiles including 1) *PVtL(t)*, which is the PV power supplied to the load in kW; 2) *PVtB(t)*, which is the PV power supplied to charge the battery in kW; 3) *PVtG(t)*, which is the PV power sold back to the grid in kW; 4) *BtL(t)*, which is the battery power supplied to the load in kW; 5) *BtG(t)*, which is the battery power sold back to the grid in kW; 6) *GtL(t)*, which is the grid power supplied to the load in kW; and 7) *GtB(t)*, which is the grid power supplied to charge the battery in kW, where *t* refers to the time interval [*t*-1,*t*).

The objective function J_{NPV} in terms of NPV is formulated as:

$$\max \ J_{NPV} = -B_s C_{bat}\left[1 + \mathrm{floor}\left(\frac{Q_{loss}}{20\%}\right)\right] + \sum_{k=1}^{K} \frac{S(1+i)^k}{(1+r)^k}, \tag{5}$$

where B_s and C_{bat} are the battery size (in kWh) and battery cost (in \$/kWh). Q_{loss} is the loss of battery capacity due to aging over the evaluation period. S is the annual income in \$, i and r are the interest rate and discount rate per annum, k is the index of year, and K is the total number of years involved in the evaluation period. The annual income *S* is the net benefit by comparing electricity expenditure in the baseline case y_{cost}(in \$) (solar home system without battery energy storage) and the post-retrofit case By_{cost} (in \$) (solar home system with battery energy storage), and

$$S = Y_{cost} - BY_{cost},$$

where

$$Y_{cost} = 365 \times \left(\sum_{t=1}^{t_d} GtL(t)\Delta t ToU(t) - PVtG(t)\eta_{inv}\Delta t FIT(t)\right),$$

$$BY_{cost} = 365 \times \left(\sum_{t=1}^{t_d} (GtB(t) + GtL(t))\Delta t ToU(t) - (BtG(t) + PVtG(t)\eta_{inv})\Delta t FIT(t)\right),$$

where $ToU(t)$ and $FIT(t)$ are the time of use tariff from the grid, and the feed in tariff, respectively, Δt is the sampling interval.

The objective function is subject to the following equality and inequality constraints. The equality constraints are

$$PVtL(t) + PVtB(t) + PVtG(t) = GG(t), \tag{6}$$

$$PVtL(t)\eta_{inv} + BtL(t) + GtL(t) = P_L(t), \tag{7}$$

$$E_B(t) = E_B(t-1)(1-\sigma) + [GtB(t) + PVtB(t)]\Delta t \eta_c - [BtG(t) + BtL(t)]\Delta t/(\eta_{inv}\eta_d), \tag{8}$$

$$[GtB(t) + PVtB(t)][BtG(t) + BtL(t)] = 0, \tag{9}$$

$$E_B(1) = E_B(t_d + 1), \tag{10}$$

where $GG(t)$ is the total power generation from the solar panel. $P_L(t)$ is the total load demand of the residential home. σ is the self-discharging rate per hour; η_c and η_d are the charging and discharging efficiency of the batter, respectively; and η_{inv} is the efficiency of the inverter. Constraint (6) indicates that the total power produced by the solar panels during time *t* can be used to supply the load, charge the battery, or feed back to the grid. Constraint (7) shows that the load demand can be supplied by the battery, solar panel, and the grid. Constraint (8) formulates the battery energy balance. Constraint (9) restricts that the battery cannot be charged and discharged simultaneously, and Constraint (10) ensures the initial battery energy on each day is the same.

The inequality constraints are

$$(1 - \mathrm{DoD})\mathrm{B_s} \leq \mathrm{E_B}(t) \leq \mathrm{B_s}, \quad (11)$$

$$0 \leq \mathrm{BtG}(t) + \mathrm{BtL}(t) \leq \mathrm{P_d^{max}} \eta_{\mathrm{inv}}, \quad (12)$$

$$0 \leq \mathrm{GtB}(t) + \mathrm{PVtB}(t) \leq \mathrm{P_c^{max}}, \quad (13)$$

where *DoD* is the depth of discharge of the battery, and $\mathrm{P_d^{max}}$ and $\mathrm{P_c^{max}}$ are the charging and discharging ramp rate limit of the battery during the time period [*t*-1,*t*). Constraint (11) is the capacity limits of the battery. Constraint (12) indicates the battery can supply power to the load and grid at the same time but the discharging is limited by $\mathrm{P_d^{max}}$ and Constraint (13) indicates that the battery can be charged by both the grid power and PV generated power at the same time, but the charging capacity is limited by $\mathrm{P_c^{max}}$.

The optimization model formulated in Eqs. (5)-(13) is a nonlinear constrained optimization problem, which can be solved by the "fmincon" toolbox in Matlab.

4. CASE STUDY

In this study, we apply the proposed battery sizing optimization approach to identify the most cost-effective solution for battery sizing, power flow management, and battery aging status, in order to demonstrate the effectiveness of the proposed model described in Section 3. Target of the optimization is to solve the optimal battery size, power flows between battery, PV, load and grid, and the aging status of the battery. In order to solve the optimization, following initial parameters are required.

1) home daily load profile and PV generation profile: in this study, the daily load profile and PV generation profiles of 300 households are recorded at half hourly interval from July 2010 to June 2011 in Australia. Without loss of generality, we randomly selected one household from the dataset for detailed investigation. Out of the annual data records, we selected five typical scenarios, namely a) the opportunistic scenario: maximum PV generation and minimum load demand over the year; b) average summer profiles; c) annual average profiles; d) average winter profiles; and e) the worst case: minimum PV generation and maximum load demand over the year. The five load profiles are presented in Figure 2.
2) Technical specifications of the solar PV and batteries, which are given in Table 1.

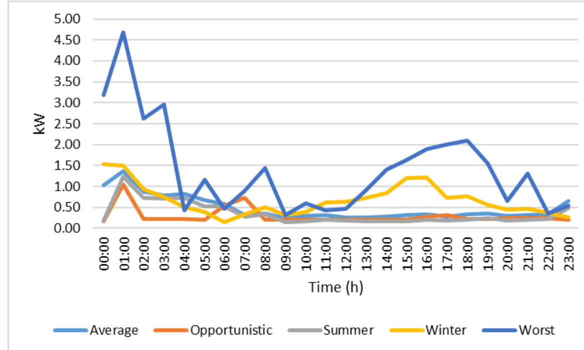

Figure 2: Load profile for a typical household

Table 1. Input values

Category	Value/parameter	Unit
PV properties		
Capacity	3.78	kWp
Battery properties		
Size	s	kWh
DoD	90%	
End of life	80% of capacity	
Inverter efficiency	95%	
Nominal C Rate	0.3	
Charge/discharge efficiency	98%	
Discount rate	1%	
Interest rate	4%	
Project cycle	10	Year
Battery cost	500	$/kWh
Initial SoC	50% of capacity	

3) The tariffs include solar electricity buy-back price and electricity supply price. Solar electricity buy-back price is a constant value, 6c/kWh. The electricity supply price has different values during the peak, shoulder and off peak time of use periods. Time details of electricity supply price are shown in Figure 3. The price details are 51.128c/kWh for peak demand, 19.657c/kWh for shoulder demand, and 10.758c/kWh for off peak.

With these initial values, computations to solve the optimisation problem are carried out by the "*fmincon*" code of the Matlab Optimisation Toolbox, where the "*sqp*" is chosen as the optimisation algorithm. The optimisation outputs are presented in Figures 4-5, and Tables 2-3. Due to space limit, this article only reports the optimal power flows of the winter case. The home load profile and PV generation profiles are shown in the top subplot in Figure 3. High demand is observed after the midnight as the geysers are controlled to heat up water in evening period to save electricity cost.

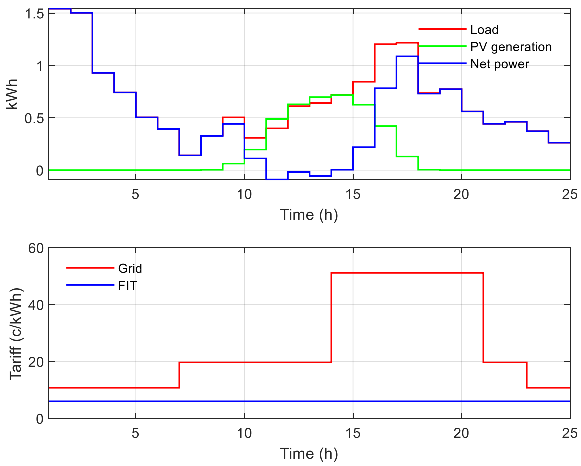

Figure 3: Power demand, PV generation (in Winter) and electricity tariffs

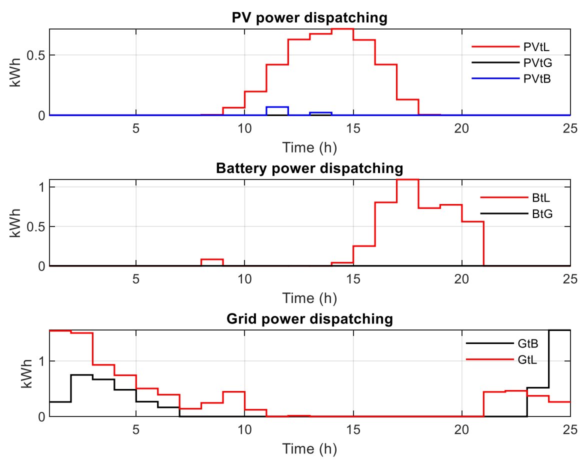

Figure 4: Power dispatching from PV, battery and the grid

Figure 4 shows the detailed power dispatching from the PV, battery and load. The top subplot shows majority of the PV generations are delivered to the load with a very small amount of power goes to charge the battery during at midday. The middle subplot shows that battery discharges to the load during the peak demand period. It shows in the bottom subplots that the grid power mainly supplies the load demand and charge the battery when the grid tariff is low. It is also observed that no battery and PV power is sold back to the grid in winter-time as the feed-in-tariff is very low as shown in the bottom subplot of Figure 3. Figure 5 shows the battery state of charge and the charging and discharging behaviours. The charging and discharging profile are reasonable as the battery is charged during low grid tariff period and discharge to the load at high grid tariff period.

In Tables 2, the optimal battery size, NPV, battery capacity loss, and daily load and PV generation energy during the evaluation period are presented.

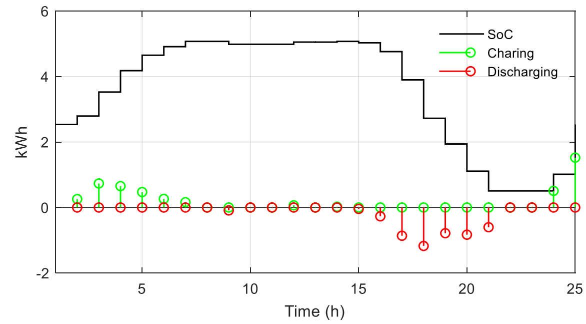

Figure 5: Battery status and charging/discharging profile

It shows that when the load is less than daily PV generation, the optimisation suggests smaller battery sizes and negative NPV values. The power flow optimisation shows that majority of the PV power generation should be sold back to the grid, because the load is also small. When the PV generation is less than the daily power demand, the optimisation suggests larger size of battery should be installed such that the PV generation can supply the demand in the daytime and battery to supply the demand in the peak demand period. It also shows that in the worst case, the battery is more stressed in terms of charging and discharging while the battery capacity loss is over 20%, which should be replaced at least once over the evaluation period.

Table 3 compares the daily grid supply and user's daily electricity cost before and after installation of the battery. It is observed that the grid supply does not change much on daily basis but the users save 32% of the electricity cost on annual average and save over 50% in winter and worst cases. This indicates the batteries are acting as energy storage to enable the load shifting function.

5. CONCLUSION, DISCUSSIONS AND FUTURE WORK

This study uses optimisation to investigate the battery sizing, power flow management and capacity loss characteristics in solar home systems. Some preliminary results have been identified. The proposed algorithm can also be generalised to study the feasibility of install solar home systems, with various PV generation capacity, load demand, and electricity tariffs and FITs. Potential future search activities will be conducted in following aspects:

1) Identify optimal solutions to an off grid solar home system;
2) Further investigations on other users in the Ausgrid dataset;
3) Identify optimal solutions when look at multiple technical and financial indicators;

Table 2. Optimal results

Scenario	Battery size (kWh)	NPV ($)	Battery capacity loss	Daily demand (kWh)	Daily PV generation (kWh)
Opportunistic	0.4019	-198.66	1.30%	6.975	25.954
Summer	0.5173	-10.532	1.81%	8.3741	9.1217
Average	1.2069	425.19	4.41%	11.7046	6.6653
Winter	5.0726	2622	10.48%	16.1328	3.9719
Worst case*	12.4115	7460	27.13%	33.977	3.944
Worst case	12.4115	1992	27.00%	33.977	3.944

*worst case without considering battery capacity loss.

Table 3. Optimal results (continued)

Scenario	Daily grid supply without battery (kWh)	Daily grid supply with battery (kWh)	Daily electricity cost without battery ($)	Daily electricity cost with battery ($)	Daily cost saving (%)
Opportunistic	4.20	3.90	$ (0.76)	$ (0.77)	2%
Summer	6.05	5.67	$ 0.40	$ 0.30	24%
Annual average	8.77	7.87	$ 1.09	$ 0.74	32%
Winter	12.32	12.77	$ 3.16	$ 1.54	51%
Worst case	30.89	31.26	$ 7.86	$ 3.71	53%
Worst case	30.89	31.29	$ 7.86	$ 3.71	53%

*worst case without considering battery capacity loss.

4) Sizing optimisation in a day ahead electricity market.

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