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PV Solar Battery Sizing Autonomy for Residential Applications

Mr. Olatunde A, Adeoye, Prairie View A&M University

Olatunde A. Adeoye received his BSC from the University of Lagos, Nigeria in 2005 after which he worked as a pupil engineer with the Electric Gas Turbine of the Nigeria Electric Power Authority (NEPA) and Ogun State Water Board as an Electrical Engineer till 2010. He became a member of the Nigerian Society of Engineers (NSE) in 2009 and the Council for the Regulations of Engineering Services (COREN) in 2010. He received his MSEE from the University of Texas at El Paso in 2012 where he was a graduate research assistant. He later worked at Haliburton Energy Services and worked at the Houston Independent School district as an APcalculus, Precalculus, and College Prep. Math instructor till 2019. From 2020 to the present, he is a Ph. D student at Prairie View A&M University/Electrical and Computer Engineering Department where works as a research assistant at the Center for Advancing Innovation in Smart Microgrid. His main research interests are sustainable power and energy systems, microgrids, power electronics and motor drives, digital methods for measurements control systems, and digital signal processing.

Samir Abood, Prairie View A & M University/ Electrical and Computer Engineering Department

Samir I. Abood received his B.S. and M.S. from the University of Technology, Baghdad, Iraq, in 1996 and 2001; respectively, he got his Ph.D. in the Electrical and Computer Engineering Department at Prairie View A & M University. From 1997 to 2001, he worked as an engineer at the University of Technology. From 2001 to 2003, he was a professor at the University of Baghdad and Al-Nahrain University. From 2003 to 2016, Mr. Abood was a professor at Middle Technical University / Baghdad-Iraq. From 2018 to the present, he has worked at Prairie View A & M University/ Electrical and Computer Engineering Department. He is the author of 30 papers and ten books. His main research interests are sustainable power and energy systems, microgrids, power electronics and motor drives, digital PID Controllers, digital methods for electrical measurements, digital signal processing, and control systems.

Dr. Penrose Cofie, Prairie View A&M University, College of Engineering

Dr. Penrose Cofie is a professor in Electrical and Computer Engineering at Prairie View A and M University, College of Engineering, Texas. His research interests are in Power Systems, including Renewable Power Supplies, Power Electronics, Controls, and Motor Drives. He is currently working on Renewable Energy Generation, Micro Grid and Advanced Electric Vehicle Technology Systems.

Photovoltaic Solar Battery Sizing Autonomy for Residential Applications

Olatunde Adeoye, Penrose Cofie, Samir Abood

Electrical and Computer Engineering Department
Prairie View A&M University Texas

Abstract

Prolonged abnormal harsh weather conditions make it impossible for residential Photovoltaic (PV) solar systems to generate enough electric power to meet the residences' electricity demand. A Battery Energy Storage System (BESS) is employed to back up the power supply. Designing an adequate BESS to meet the load demand during unstable weather conditions has proved quite challenging since the weather is not perfectly predictable throughout the year. A cost-effective strategy for Lead Acid battery sizing with adequate battery autonomy for residential PV solar systems is proposed. An optimization scheme using Energy Management System Flow Chart (EMSFC) is employed in this strategy to estimate average daily load, battery capacity, battery charge and discharge power limit, maximum allowable depth of discharge, and the number of battery modules. The reliability of the method, considering the weather conditions, is verified using Monte Carlo simulation (MCS).

Introduction

The causes of significant power outages in the US are hurricanes and storms. The recent winter storm of 2021 that collapsed the Texas power grid and left millions of homes without electricity for almost two weeks sparked much attention on renewable power generation. Unfortunately, the available residential PV solar BESS is not designed to solve this prolonged outage problem. The battery is crucial in renewable energy systems for storing electric energy. Then, the battery must be reliable enough to deliver the required energy and power at all times to the end-users. The solar power system is one of the best renewable energy technologies [1], cost-effective and environment-friendly. Solar energy is one of the sustainable forms of energy available to meet all humanity's energy usage, provided it is harnessed and stored economically. A total of 173,000 TW of solar energy strikes the earth continuously [2]. The PV solar system collects sunlight and converts it into electricity only when the sun's rays are stronger for most of the day. However, PV solar systems cannot store the energy for later use. Thus, a battery bank saves electrical energy from the PV solar system. The battery backup is always the best way of supplying a continuous power supply that is adequate for a living during the worst weather conditions.

Autonomy is the length of time that a PV solar system can provide energy to the load without power from the solar module. The electrical load description of the power system, within the autonomy period, is needed for the sizing of the battery [3]. Nowadays, the battery sources usually employed to overcome this challenge are not optimally sized to achieve the desired autonomy. An EMSFC is required to maintain stability between electric power generation and energy demand during downtime periods.

Thus, a cost-effective way of storing this energy is to use a Lead-Acid battery, an energy storage device with residential PV solar systems capable of supplying backup power during the downtime periods that often last up to weeks. However, an optimal battery sizing strategy is essential to ensure efficient battery autonomy, prevent under-sizing and oversizing of the battery during harsh weather conditions, and prevent extended outage occurrences from meeting demand peaks [4]. It is estimated that 80% of the residential PV solar systems are used in standalone implementation, and the State of Health (SOH) defines the battery's life and useable charge [5].

Several research studies on PV solar battery sizing strategies are reported daily. Andreas et al. [6] investigated the increase in cost efficiency of adding a battery energy storage system to an existing residential PV solar system. The results of their work showed that BESS profits considering future price consumption. Borowy et al. [7] reported an optimal sizing combination of a battery bank and a PV array in a wind/PV hybrid system. Their results indicated that an optimum design choice depends on the relative costs of the PV modules and the battery. Jenkins et al. [8] presented lifetime prediction and sizing of Lead-Acid batteries for microgeneration storage applications. Their statistical methods result showed that battery life increases with battery size. Chee et al. [9] reported a stochastic process for battery sizing with uninterruptible power and demand shift capabilities in PV systems. Their results pointed out that customers could base their sizing decisions on the historical data, local risk of outage statistics, and the success rate of meeting the demand shift required. Singh et al. [10] reported using reliability criteria such as Loss of Load Probability (LOLP) to calculate the optimum number of batteries. Their results demonstrated that the system reliability degrades with an increase in peak demand due to the size of the storage capacity. Zhao et al. [11] reported an optimized PV solar system and BESS for microgrids and residential homes to maximize the life of the BESS. Their results revealed considerable progress in improving solar panel sizing analysis accuracy by introducing an additional battery-life loss penalty. All previous research studies that reported PV solar system battery sizing strategy for residential applications did not address downtime issues due to incessant adverse weather conditions that often continue for days and sometimes weeks. The main objective of this paper's research study is to develop a cost-effective strategy for battery sizing with adequate autonomy for residential PV solar systems. This strategy requires applying an optimization scheme using EMSFC, and the reliability of the result is verified using MCS.

Methodology

This paper reports on a study to design a battery storage capacity adequate for the prolonged weeks of overcast sunless weather in residential PV solar systems. The proposed strategy, EMSFC, uses uniform random numbers (between 0 and 1) to optimize battery sizing autonomy; as shown in Fig. 1, the SOH defines the battery's lifetime, indicating the battery's ability to discharge and charge energy and power. The input information is the customer load power profile, the PV power profile, the Depth of Discharge (DOD) describes the proportion of battery discharge about the overall battery capacity and the design factor. The Energy Management System (EMS) uses input information and the present battery State of Charge (SOC) to control the entire system flow chart and battery lifetime. The SOC indicates the amount of the available capacity (Ah) expressed as the percentage of the rated capacity (Ah) [12]. This process can be simply briefed as below.

1) The proposed EMSFC reads all input information, defines the battery size, and estimates SOH.
2) If the SOH initial value equals 1, proceed to EMS and battery autonomy model. Otherwise, return to estimate SOH.
3) If SOH is greater than 0, return to the battery autonomy model. Otherwise, estimate battery size.
4) Return to estimate SOH if optimum battery size is not attained. Otherwise, evaluate optimum point, record the optimization results as the outcomes, and end the process. The EMS and the battery model perform this process repetitively as long as the battery can still hold its charge.

The battery that exhibits the best optimal size, out of all the prospective battery sizes, is the candidate for sizing autonomy. The MCS investigates the reliability of the EMSFC using statistical analysis. The simulation input information comprises the consumer's load profiles, DOD, and design factors from references [13] [14]. However, the possible optimal efficiency of the solar array system depends solely on factors such as total daily energy (Wh), the average sun hour per day, and the DC voltage of the system (VDC) [15].

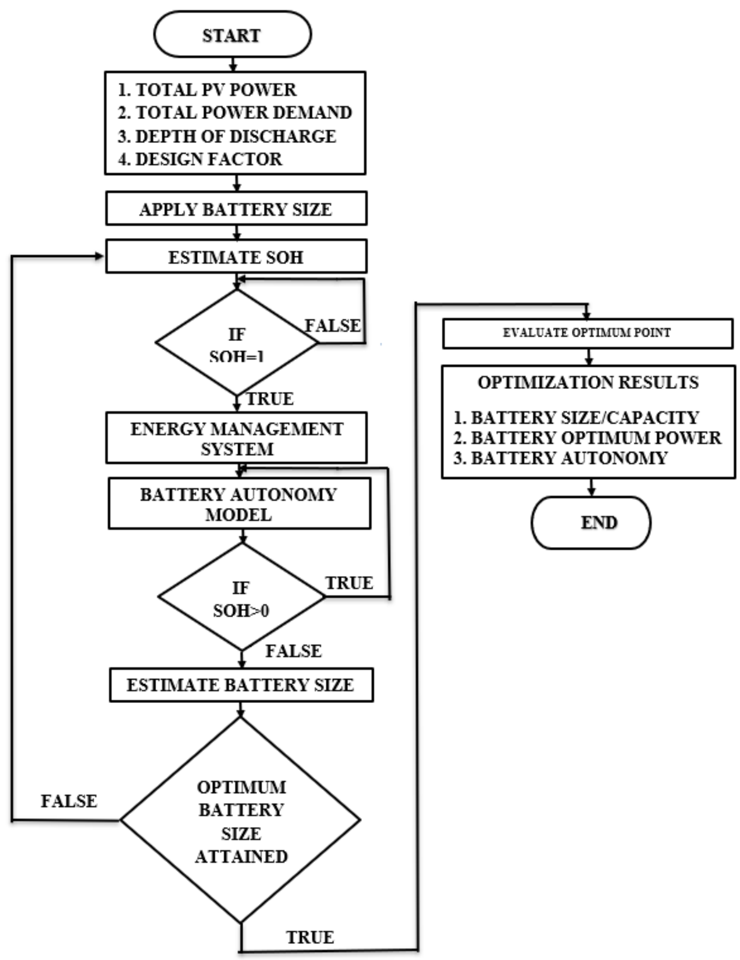


Fig. 1. Flow Chart of the Proposed Battery Sizing Autonomy

Elements of Energy Management Strategy

Temperature Consideration

The available capacity of the Lead-Acid battery is affected by its operating temperature [12, 15, 16]. The input information includes the consumer's load profile, the PV load profile, DOD, and the design factors. The load profiles data used in this simulation only cover two weeks of downtime due to incessant adverse weather conditions because the Lead-Acid battery's temperature plays a significant role in the battery sizing system. The Lead-Acid battery capacity decreases in cold temperatures, and its lifetime diminishes in high temperatures. Battery capacity modification is necessary for cold temperature applications but hardly for warm temperature purposes. Therefore, a design factor is required, which functions the battery's average temperature during the coldest time of the year [15].

Table 1. Recommended design factors [12]

Lowest Battery Temperature Averaged over 24 Hours		Design Factor
Degrees C	Degrees F	
25 or above	77 or above	1.25
20 to 24	68 to 76	1.39
10 to 19	50 to 67	1.43
0 to 9	32 to 49	1.60
-10 to -1	14 to 31	1.84
-20 to -11	-4 to 13	2.23
-30 to -21	-22 to -5	2.84
-40 to -31	-40 to -23	4.17

Days of Autonomy

The recommended design factor at various temperatures is shown in Table 2. Due to severe weather conditions, these downtime periods diminish the daily insolation (KWatts/meter^2). A storage factor is the number of days of autonomy required for the PV solar battery system to operate reliably throughout these off-time periods. Limiting the battery's average daily DOD is crucial to maintain the battery at its best lifetime.

Table 2. Recommended day of autonomy storage [12]

kW/m^2/day	Days of Storage
4.5+	5
3.5 to 4.5	6
2.7 to 3.5	7
2.0 to 2.7	8
<2.0	Up to 14*
*Special Considerations Required	

Table 2 shows the recommended days of autonomy storage used in the paper's study. The DOD is a function of the minimum and maximum limit of the Lead-Acid battery SOC. The Lead-Acid battery size is determined by the charge and discharge power limit and its capacity. The SOC for a fully charged battery is 100% and for a dead battery is 0% [3]. The SOC is always observed because the efficiency of the charge and discharge cycles rely solely on it, and a 20% SOC means the battery is blocked from further discharging, while that of 100% means that the battery is fully charged and is blocked from further charging.

Battery Sizing Analysis

The amount of initial energy storage required equals the multiplication of the total power demand and the number of autonomy days for the PV solar battery storage autonomy [12, 13, 17].

$$E_{initial} = Total\ Power\ Demand\ (WH)\ x\ Days\ of\ Autonomy \qquad (1)$$

Considering the safety of the system,

$$E_{safe} = \frac{Initial\ Energy\ Storage\ Required}{Maximum\ Depth\ of\ Discharge} = \frac{E_{initial}}{MDOD\%} \qquad (2)$$

The battery bank's capacity (C_b) for battery sizing autonomy is estimated by dividing the safe energy storage required by the rated voltage (V_b) of one of the batteries selected.

$$C_b = \frac{E_{safe}}{V_b} \qquad (3)$$

Based on the number obtained for the battery bank's capacity (C_b), the capacity of each battery of the battery bank is denoted by (C_e). The battery bank is composed of several batteries, and the total number of batteries is obtained by dividing the battery bank capacity (C_b) in ampere-hours by the capacity of one of the selected batteries (C_e) in ampere-hours.

$$N_{battries} = \frac{C_b}{C_e} \qquad (4)$$

The number of batteries in series is estimated by dividing the DC voltage of the system (V_{DC}) by one of the selected batteries rated voltage (V_b).

$$N_s = \frac{V_{DC}}{V_b} \qquad (5)$$

Then the number of parallel paths (Np) is approximated by dividing the total number of batteries by the number of batteries that are connected in series (N_s).

$$N_p = \frac{N_{battries}}{N_s} \qquad (6)$$

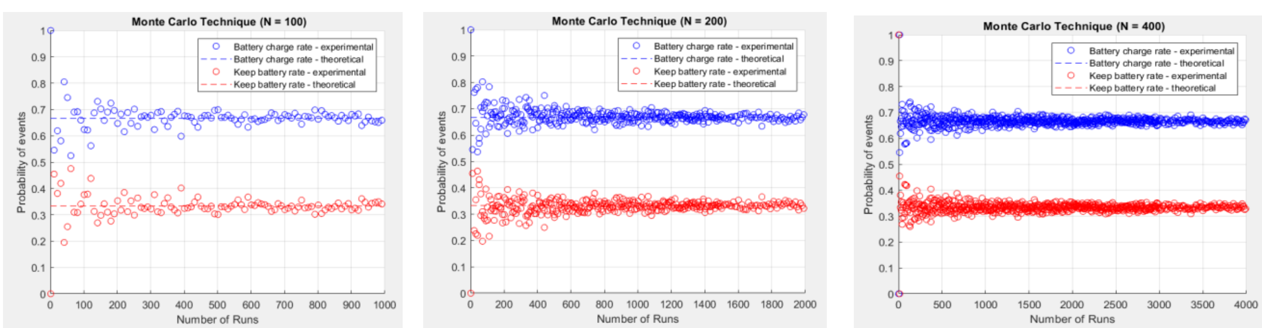
Equation (6) above completes the PV solar battery sizing autonomy for residential home.

Monte Carlo Technique

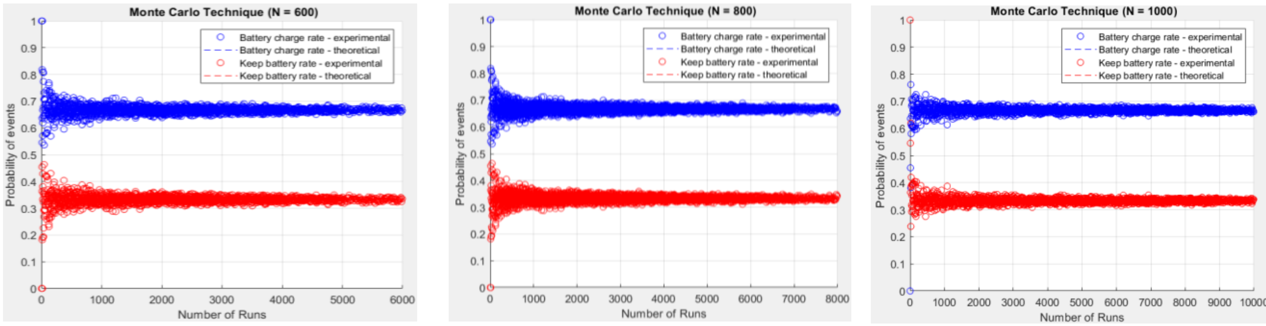
The Monte Carlo technique usually works with random numbers to solve uncertainty analysis, optimization, reliability-based design problems, and so on [18]. MCS was used to verify the reliability of this paper's proposed battery sizing autonomy strategy. The MCS applies random numbers for its iteration [19]. The stochastic optimization of this study considers uncertainty based on two weeks of downtime of the PV solar system due to harsh weather conditions. The Monte Carlo technique is generally known for risk analysis [19-20]. The battery sizing autonomy strategy is successfully executed, provided the battery capacity adopted in this paper's study can meet the power demand of the consumer during the two-week downtime period due to adverse weather conditions. The simulation of this stochastic event uses a set of uniform random variables to verify the reliability of the EMSFC.

Results and Discussion

The reliability of this paper's optimization scheme using EMSFC is verified using the MCS technique of generating an artificial history data vector of a single component modeled in a two-state Markov chain model. In addition, since there are no convergence criteria and error bound reduces as the number of runs increases, it is recommended to run the simulation many times with large number of samples and the same reliability data of the component (at least from 100 up to 1000 samples are recommended for reliable convergence). In Fig. 2 (a-f), the number of stages considered in the simulations is divided into the theoretical and experimental SOC of the battery and as well maintain this SOC of the battery. Fig. 2 (a-f) also show that as the number of runs increases, the simulation computation time increases, and high convergence simulation results are achieved, unlike at the low number of runs when the simulation results are scattered. This generates an exponentially distributed two-state Markov chain model between these two investigated cases considering the number of runs and the probability of events. The MCS results show the reliability of the battery sizing autonomy.



(a) **(b)** **(c)**



(d) **(e)** **(f)**

Fig. 2. Monte Carlo Chronological Simulations Results: (a) simulation total runs, N = 100 at run time, t = 2.5 secs. (b) simulation total runs, N = 200 at run time, t = 3.15 secs. (c) simulation total runs, N = 400 at run time, t = 6.42 secs. (d) simulation total runs, N = 600 at run time, t = 11.66 secs.
(e) simulation total runs, N = 800 at run time, t = 19.18 secs. (f) simulation total runs, N = 1000 at run time, t = 29.15 secs.

Conclusions

This study selected the Lead-Acid battery because of its various significances, such as matured technology, lowest cost per unit, high availability, and best value for power and energy per KWH, to mention a few [16]. The total PV power, total power demand, DOD, and design factors were used as input to the EMSFC. The Lead-Acid battery SOC was critical in determining the battery status. The values used for the SOC varies between 20% to 80% to protect the Lead-Acid battery from deep discharges and enhance the long life of the battery [21]. The MCS high convergence results using large number of samples, show that the MCS can efficiently verify the reliability of the EMSFC. The EMSFC analysis and MCS results also indicate that PV solar battery sizing autonomy is effective and adequate to meet the electricity demand of residential homes up to two weeks of sunless weather conditions.

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