Daily and Weekly Operation of Battery Energy Storage Systems in Networks with High Photovoltaic Generation Penetration: A Comprehensive Analysis

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ABSTRACT

This study provides a comparative analysis of the operation of Battery Energy Storage System (BESS) in distribution networks experiencing high levels of photovoltaic generation. The analysis considers daily and weekly operations on an hourly basis. A multi-period modelling approach is used, which includes temporal coupling of BESS charging and discharging. The model, implemented in AMPL and solved using the Knitro solver, has been validated in a recent paper. The convergence process occurs quickly, completing in less than one second, although the problem has been split into 168 hours for analysis. During the analysis period, all network and BESS constraints have been considered. The findings indicate that weekly BESS operation proves more effective than daily operation, achieving up to a 30.06% reduction in comparison to a network without BESSs, and 8.17% reduction when compared to daily operations, for the analyzed case.

Keywords: Battery Energy Storage Systems, Distribution Networks, Multi-Period Modeling, Photovoltaic Generation.

1 Introduction

In recent years, the growing demand for electricity, driven by an increasingly digitized and industrialized economy and society, has presented significant challenges in the efficient and sustainable management of electricity. Fluctuating power generation from intermittent Renewable Energy Sources (RES) and variability in demand create a complex scenario that calls for innovative solutions to ensure the stability, reliability and operational efficiency of these networks. In this context, the integration of Battery Energy Storage System (BESS) is emerging as a promising approach to addressing these challenges in an intelligent and effective way. One of the primary challenges confronting energy utilities is peak demand, otherwise known as peak hours. During these times of increased demand, the grid can struggle to provide a reliable and efficient power supply. The implementation of BESS provides the chance to alleviate demand peaks, as surplus energy can be stored during low-demand periods and subsequently discharged during peak times [1]. Some studies have been conducted on transmission [2] and distribution networks [3], with a particular emphasis on BESSs. This research has primarily focused on distribution systems. In [4], is used an approximated method for finding the optimal allocation of BESSs in 18 and 33 bus-systems to minimize both cost of purchase energy and active losses considering a 24-hour period. The study demonstrated a significant reduction in peak loads during high demand periods. A Mathematical Programming (MP) framework to model the coordination between BESSs and RES within a 24-hour time horizon. Simulations were conducted on two distribution networks, resulting in power loss reductions of 58.4% and 77% for the 33- and 141-bus networks, respectively. However, the weekly operation analysis is not considered [1]. The penetration of Photovoltaic (PV) generation into electrical grids for daily and weekly operations has resulted in the proposition of different methods [5]. Heuristics and meta-heuristics [6], [7] offer rapid but approximate solutions; however, MP models guarantee precision, although they may face difficulties with intricate network limitations.

From this brief overview, it is clear that the optimization of network operation of networks is particularly important when faced with a high penetration of PV. Taking into account the research works consulted in the literature review, the necessity and applicability of the proposed approach in network

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planning becomes clear, since this approach includes a multi-period study and a weekly operation of the battery energy storage system. Therefore, a knowledge gap is identified:There are no studies here that consider the weekly operation of BESS in networks with high PV generation. Therefore, the proposed model leads to the following research question: "Is it possible to optimize BESS operation while taking into account PV generation and weekly operation?"

2 Proposed Method

The proposed method aims to minimize energy losses and improve voltage profiles on buses by adhering to the constraints of a non-linear, non-convex, large-scale problem with high PV penetration. It can be represented using the objective function (1). The objective function (1) is subject to the following constraints: power flow constraint, Equation (2); voltage magnitude constraints, Equation (3); charging and discharging of BESSs, Equation (4); and the capacity of the BESSs, Equation (5). Details of equations (1), (2), (3), (4), and (5), as well as variable names, can be found in [1].

$$\min P_{Loss} \qquad f(x) = \sum_{t=1}^{T} \sum_{i=1}^{N_L} R_i (I_i^t)^2 \tag{1}$$

The objective function is subject to:

$$\begin{cases} P_k^t + {P_{PV}}_k^t + {P_B}_k^t - {P_L}_k^t = V_k^t \sum_{m \in \Omega_\kappa} V_m^t (G_{km} \cos \theta_{km}^t - B_{km} \sin \theta_{km}^t) \\ Q_k^t - {Q_L}_k^t = V_k^t \sum_{m \in \Omega_\kappa} V_m^t (G_{km} \sin \theta_{km}^t - B_{km} \cos \theta_{km}^t) \end{cases} \tag{2}$$

$$V^{min} \leq V_k \leq V^{max} \tag{3}$$

$${B_S}_k^{t+1} = \begin{cases} {B_S}_k^t + n_c {P_B}_k^t \ \ \Delta t \ \ \forall \ \ {P_B}_k^t \geq 0 \\ {B_S}_k^t - \frac{1}{n_d} {P_B}_k^t \ \ \Delta t \ \ \forall \ \ {P_B}_k^t < 0 \end{cases} \tag{4}$$

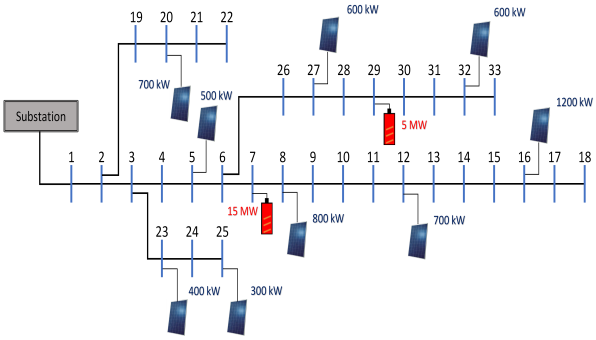
$$B_{Sk}^{t\,min} \leq B_{Sk}^t \leq B_{Sk}^{t\,max} \tag{5}$$

3 Tests and Results

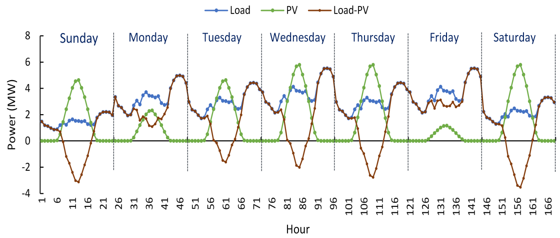
This section presents the results of the proposed approach considering the 33-bus distribution [8] with modifications and considerations of load and generation, as shown in the Figure 1. All simulations were performed on an Intel® Core™ i7 CPU @ 1.8 GHz computer with 8 GB of RAM and Windows 11 Home 64 bits.

Figure 1a illustrates the 33-bus distribution system. The system operates at a voltage of 12.66 kV. Voltage limits ranging from 0.90 to 1.05 p.u. are taken into account for all buses. The network was modified with the addition of two BESSs and nine PVs. The locations of the PVs and BESSs with their maximum capacities are shown in the Figure 1. The BESSs located at buses 7 and 29 have charging and discharging capacities of 2.5 MWh and 1 MWh, respectively. As with the previous test system, the size and location of these units have been were chosen empirically.

The illustration in Figure 1b displays a forecast of the sum of PV generation and load profiles over a discretized week on an hourly basis. The forecasts for load and generation fluctuate during the week. As PV generation is highly penetrated, some periods experience a situation where generation exceeds load, resulting in a reverse power flow at the substation. When analysing the operation of the network without the use of BESSs under the conditions presented, a total of 21.613 MWh of energy losses are observed over one week.



(a) The 33-bus test system modified.

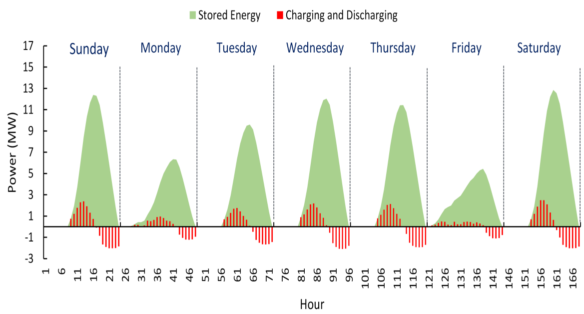


(b) Load and PV generation profile for a discretized hour-by-hour week.

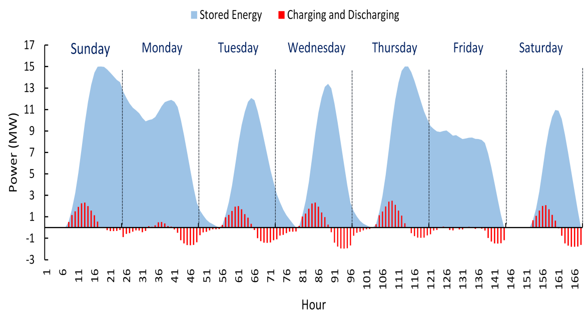
Figure 1: The 33-bus test system modified with load and PV generation profile for a week.

A. *Daily and Weekly Operations of the BESSs*

The operation of the BESS at bus 7 for daily and weekly operations is depicted in Figure 2. Note that using the BESS weekly is more efficient than using it on a daily basis, as energy can be stored on one day and used on another. In addition, the BESS capacity is better utilized during weekly operation, as seen from the charge level in Figure 2a compared to Figure 2b. The operation of the BESS at bus 29 during daily operation Figure 3a and weekly operation Figure 3b is shown in Figure 3. The operation of the BESS on bus 29 is different from that on bus 7. This mainly occurs because it is in a different location in the network and also due to the equipment's capacity. As can be seen, the capacity of the equipment is underutilized during daily operation.



(a) Daily operation.



(b) Weekly operation.

Figure 2: Daily and weekly operation of the BESS allocated at bus 7.

B. *Active power losses and supplied by the substation for daily and weekly operations*

Figure 4 shows the active power losses and active power supplied by the substation in MW for each hour of the period, considering both daily and weekly operations. As can be seen in Figure 4a, the weekly operation is more efficient than the daily operation. Over the course of a week, the daily operation experienced losses of 16.460 MW, while losses for weekly operations were 15.116 MW. This resulted in a reduction of 1.344 MW or 8.17%. When considering weekly operations with and without the BESSs, the reduction amounts to 30.06%. Analysis of the power supplied by the substation, shown in Figure 4b, which is the network's balancing node, revealed that the energy flow was lower during several instances of weekly operation. On Saturday, the operation followed the same procedure as the BESSs, as it was the final day of the period. On Sunday, the substation experienced a significant reverse power flow, especially during daily operation. The total amount was 315.222 MWh for daily operation and 302.155 MWh for weekly operation.

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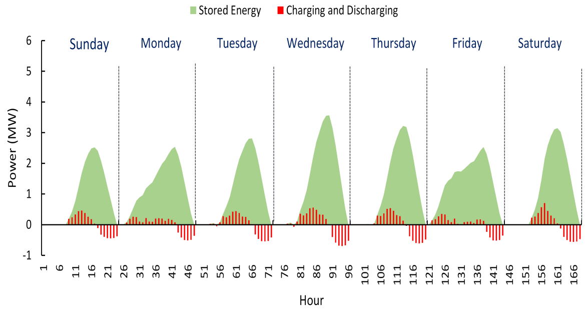
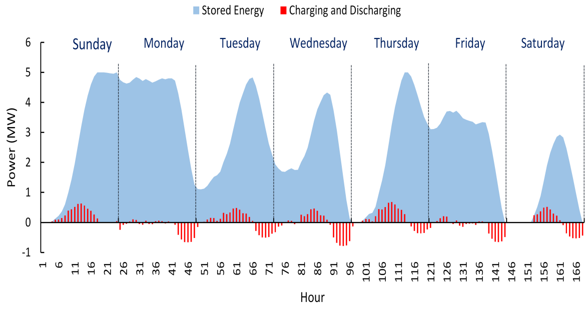
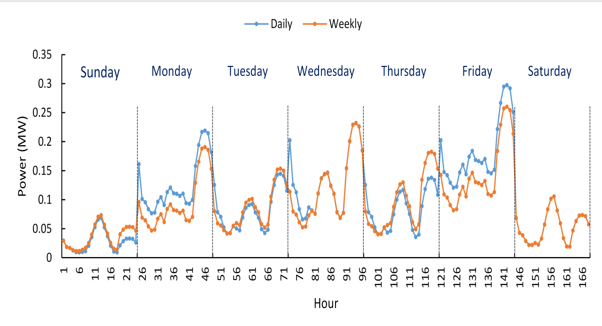


(a) Daily operation.

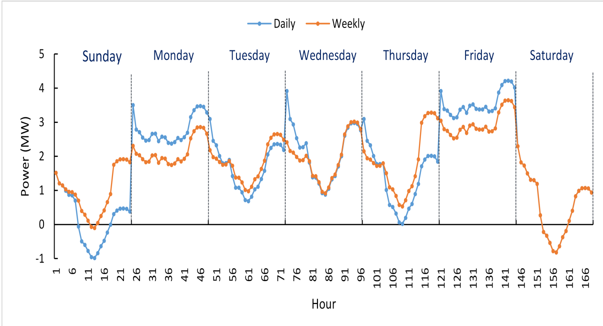


(b) Weekly operation.

Figure 3: Daily and weekly operation of the BESS allocated at bus 29.



(a) Active power losses.

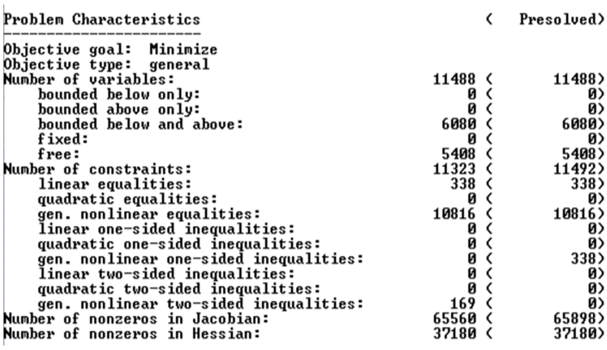


(b) Active power in the substation.

Figure 4: Active power losses and active power supply at the substation.

C. Computational Aspect

The Figure 5 illustrates the computational aspects related to the conducted analysis. The number of constraints and variables can be observed in Figure 5a. These numbers correspond to the 169 hours of operation, during which all network constraints need to be satisfied for each hour. Figure 5b presents the convergence process, wherein Knitro was set to select the solution algorithm. The specified error of 10E-7 p.u. was achieved in 15 iterations with a CPU time of 0.609 s.



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Problem Characteristics                               (    Presolved)
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Objective goal:  Minimize
Objective type:  general
Number of variables:                           11488 (        11488)
    bounded below only:                            0 (            0)
    bounded above only:                            0 (            0)
    bounded below and above:                    6080 (         6080)
    fixed:                                         0 (            0)
    free:                                       5408 (         5408)
Number of constraints:                         11323 (        11492)
    linear equalities:                           338 (          338)
    quadratic equalities:                          0 (            0)
    gen. nonlinear equalities:                 10816 (        10816)
    linear one-sided inequalities:                 0 (            0)
    quadratic one-sided inequalities:              0 (            0)
    gen. nonlinear one-sided inequalities:         0 (          338)
    linear two-sided inequalities:                 0 (            0)
    quadratic two-sided inequalities:              0 (            0)
    gen. nonlinear two-sided inequalities:       169 (            0)
Number of nonzeros in Jacobian:                65560 (        65898)
Number of nonzeros in Hessian:                 37180 (        37180)
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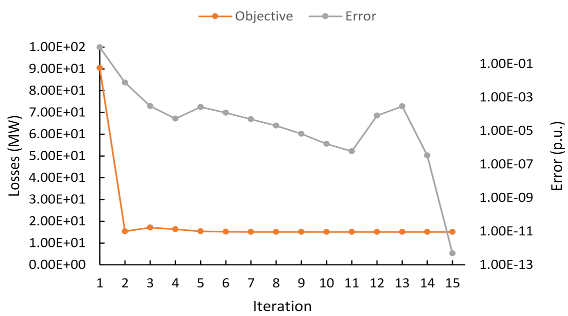
(a) Problem characteristic



(b) Convergence process

Figure 5: Computational aspects for weekly operation.

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4 Conclusions

This study provides a comparison of the operation of a network distribution with significant PV generation and the presence of two BESSs. Both daily and weekly hypotheses operating scenarios were included in the analysis. For daily operation, BESSs were discharged at the end of each day to prepare for the following days operation, even the operation being weekly. The issue of temporal coupling presents challenges for finding a solution. However, in the tested case, the methodology was suitable. A comparative analysis revealed an 8.11% decrease in weekly operation compared to daily operation. Analyzing the network without BESSs, the reduction was 30.06%. Although the methodology is appropriate, it requires accurate load and generation forecasts. However, the loads behaviour is cyclical and the environmental forecasts, especially for PV generation, have improved significantly in recent years.

The dependence on a correct prediction of PV generation and load curve is the main limitation of the proposed model. To further increase the integration of PV with BESS in modern electricity grids, it is recommended that new strategies be adopted to properly size and site renewable resources, paying particular attention to infrastructure and associated costs such as CAPEX and OPEX. For future work, the injection of reactive power from storage can be considered in the modeling of the problem.

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