



SIMULATION OF PHOTOVOLTAIC SYSTEM WITH BATTERY STORAGE FOR SUPPLY OF AUXILIARY SERVICES IN HIGH VOLTAGE SUBSTATION

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ABSTRACT

The integration of photovoltaic systems (PV) with battery energy storage systems (BESS) has emerged as an effective strategy to enhance reliability, autonomy, and flexibility in supplying critical loads. This paper presents the development and implementation, in Python language, of a computational model for simulating PV systems integrated with BESS, aimed at supplying auxiliary services in high-voltage transmission substations. The model enables hourly resolution of energy flows between photovoltaic generation, load, and battery, incorporating variables such as state of charge (SoC), depth of discharge (DoD), and battery state of health (SoH). The methodology involves comparing load and generation curves, followed by deriving the net energy balance curve for the system. Based on this balance, the model was coded using PyBaMM (Python Battery Mathematical Modelling), an open-source computational platform for battery simulation written in Python. PyBaMM is employed to simulate charge and discharge current profiles required to meet demand and charge the battery bank, considering BESS operational constraints. The model is applied to a case study with two months of simulated operation, allowing assessment of the system's dynamic behavior and validation of the implemented control logic. Results demonstrate the feasibility of the proposed approach and highlight its potential to support sizing and performance analysis of hybrid systems in real-world applications.

Keywords: Auxiliary Services; Battery Energy Storage System; Photovoltaic System; PyBaMM; Python.

1 INTRODUCTION

The growing demand for sustainable energy solutions and the expansion of renewable sources have driven the development of hybrid systems that integrate photovoltaic generation with energy storage. Among the key benefits of this integration are the mitigation of solar generation intermittency, increased energy autonomy, and the assurance of continuous supply to sensitive loads. Battery Energy Storage Systems (BESS), particularly those based on lithium iron phosphate (LFP) batteries, have demonstrated satisfactory thermal stability, longer lifespan compared to other lithium-ion (Li-ion) battery technologies, and adequate operational safety, making them suitable for both grid-connected and off-grid applications [1].

Modeling BESS is essential for evaluating performance, reliability, and lifespan in energy applications. Various approaches allow for the representation of phenomena such as variations in state of charge (SoC), dynamic voltage behavior, efficiency, thermal effects, and capacity degradation over time. Battery models are typically categorized into four main groups according to technical literature: electrical (or equivalent circuit), electrochemical, empirical, and semi-empirical [2]. Electrical or equivalent circuit models represent the battery using resistors, capacitors, and controlled sources, offering a good balance between simplicity and accuracy. Empirical models are based on experimental data and enable rapid simulations, though with limited generalization. Semi-empirical models combine experimental data with simplified physical relationships, balancing accuracy and low computational cost by considering variables such as depth of discharge (DoD), charge rate (C-rate), and temperature.



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Electrochemical models, such as the Doyle-Fuller-Newman (DFN) model, describe internal cell processes with high precision but require significant computational effort and specific physico-chemical parameters [3].

The degradation of Li-ion batteries is one of the main limiting factors for their adoption in mission-critical energy storage systems. This process results from a combination of physicochemical mechanisms, including loss of active material, growth of the solid electrolyte interface (SEI) layer, lithium-ion entrapment, and increased internal resistance [2]. Collectively, these phenomena lead to progressive capacity loss and reduced energy efficiency. Moreover, operational variables such as DoD, temperature, and usage profile directly influence the degradation rate, reinforcing the need for models capable of representing these effects. In this context, the development of computational methodologies aimed at estimating battery state of health (SoH) and remaining useful life (RUL) has become essential for applications requiring high reliability [4][5].

Modeling and simulation of energy storage and renewable generation systems play a strategic role in evaluating solutions for critical applications in the power sector. Among these applications, the supply of auxiliary services in high-voltage substations stands out as a key element for operational continuity and the safety of power systems. These services power essential loads such as protection systems, command and control units, supervision, telecommunications, emergency lighting, and panel climate control, whose unavailability may lead to unplanned outages and compromise grid integrity. Traditionally, energy supply for auxiliary services is provided by tertiary windings of transmission substation power transformers, distribution lines from the local utility, and backup systems composed of diesel generator sets. Additionally, every high-voltage transmission substation includes a stationary lead-acid battery bank that supplies a 125 V direct current bus for essential services. Although diesel generator sets are widely used due to their low initial cost and ease of implementation, these sources present limitations in autonomy and availability and rely on fuel supply and frequent maintenance. In this scenario, the integration of PV systems with BESS emerges as a promising technological alternative, capable of enhancing resilience, extending autonomy, and reducing dependence on external sources, ensuring continuous operation even during prolonged grid failures [6].

The approach adopted in this study is based on the development of a parameterizable electrochemical model in Python, implemented using the open-source PyBaMM library [7]. This platform enables the implementation of electrochemical and semi-empirical models, combining the flexibility of Python programming with the physical detail required to accurately represent battery performance under various operating conditions. The proposed application focuses on the reliable supply of essential loads in high-voltage substations, contributing to the autonomy and resilience of auxiliary services, even under adverse conditions or during extended interruptions of external power supply.

2 METHODOLOGY

The proposed methodology consists of implementing a computational model to simulate the behavior of a hybrid photovoltaic system (PV) integrated with a Battery Energy Storage System (BESS) in Python language, operating autonomously and off-grid. The model performs hourly representation of energy flows, applies control logic for battery charging and discharging, incorporates operational constraints, and enables degradation analysis over time under different generation and demand scenarios.

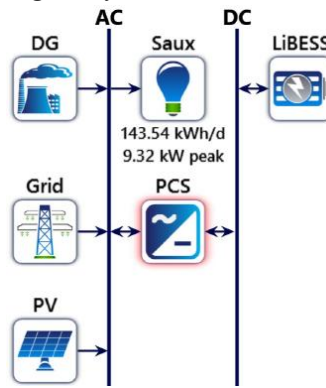


Figure 1 presents the diagram of the PV-BESS-Load arrangement. The PV system is coupled via a DC-AC converter, while the BESS is connected through a bidirectional inverter referred to as the Power Conversion System (PCS), which operates under active power control. The load represents the auxiliary services of the substation.

It is assumed as a premise that demand must be met as a priority whenever photovoltaic generation and/or stored energy is available. When the battery's state of charge (SoC) reaches its lower limit or when the demanded power exceeds the capacity of the inverter, the supply to auxiliary services is interrupted.

This paper is based on a field case study involving a PV system integrated with BESS, located at the Trindade Substation (SE Trindade) in the municipality of Trindade - GO. The system supplies the control house of the transmission line bay operating at 230 kV, which connects SE Trindade (500 kV/230 kV) to SE Firminópolis (230 kV), in the municipality of Firminópolis - GO.

Figure 1 – Diagram of the PV-BESS-Load arrangement



The characterization of load demand was obtained through field measurements using a Fluke 435-II power analyzer, resulting in the hourly time series $P_{load}(t)$ (Load). The set of auxiliary services includes protection systems, control, supervision, telecommunications, emergency lighting, and panel climate control.

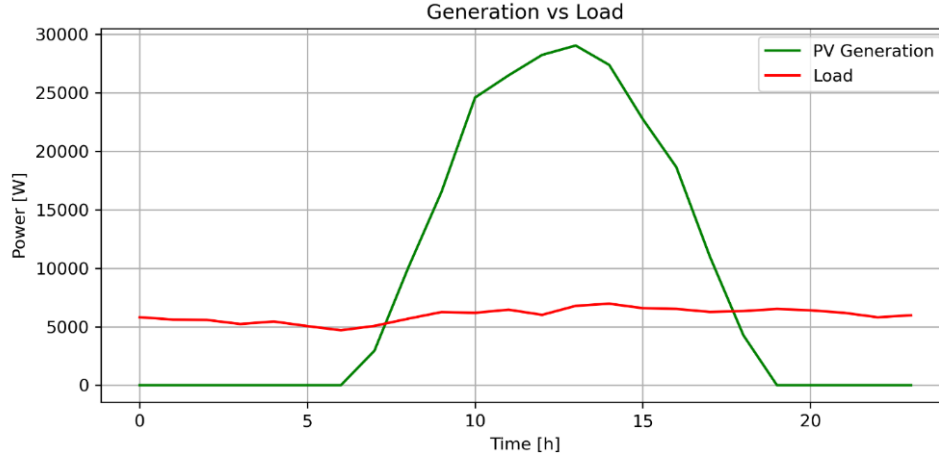
As a follow up to the analysis of the measured data, the average daily energy consumption was estimated at approximately 143.5 kWh/day (Figure 2). This value was adopted as the reference for the simulation of the load profile (in red).

The photovoltaic system (PV) was represented by a 54.72 kWp array composed of monocrystalline silicon modules. The time series $P_{PV}(t)$ was obtained through hourly-resolution simulation based on average solar irradiance and ambient temperature data for the period of interest. A global system efficiency (Performance Ratio) of 75% was considered, accounting for module, inverter, and cabling losses. Figure 2 illustrates the adopted generation profile (PV Generation), represented by the green curve. The Battery Energy Storage System (BESS) considered in this study is based on lithium iron phosphate (LiFePO₄ or LFP) technology, which is the most widely used in stationary applications due to its satisfactory thermal stability, operational safety, and longer lifespan compared to other lithium-ion (Li-ion) technologies [2]. The computational model was designed to be parameterizable, allowing configuration of key operational variables such as nominal capacity, voltage, maximum depth of discharge (DoD), and permissible charge rate (C-rate). In addition to the electrochemical structure of the battery bank, the model incorporates the operation of the Battery Management System (BMS), which is responsible for continuous monitoring and



enforcement of operational constraints that ensure battery safety and longevity. Among its functions are limiting the maximum charge and discharge rates, preventing overcharging or deep discharge.

Figure 2 – Hourly load-curve of auxiliary services



The characteristic parameters for both the BESS and the BMS are presented in Table 1, summarizing the operational conditions adopted to represent the supply of auxiliary services in the substation.

Table 1 – Characteristics of the BESS

Parameter	Value
Rated Capacity	215 kWh / 358 Ah
Rated Voltage	768 V
Maximum C-rate	0.5C (1/2C)
Maximum DoD	0.8 (80%)
Initial SoC	1 (100%)

The net power P_{net} represents the instantaneous balance between load consumption and photovoltaic generation. When positive, it indicates the battery is discharging to meet the load demand; when negative, it reflects a surplus of energy available for charging the BESS. This calculation is performed at each simulation time step and serves as the foundation for the system's operational logic, as defined by (1):

$$P_{net} = P_{load} - P_{FV} \quad (1)$$

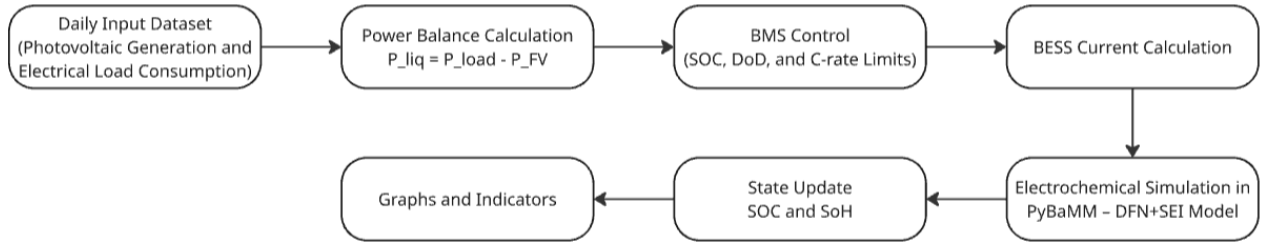
The operation of the modeled system follows a control logic aimed at maximizing reliability in load supply. Priority is given to directly meeting the demand, with the load being fully supplied whenever photovoltaic generation and/or stored energy are sufficient. In situations of generation surplus, P_{net} , exceeding energy is directed to battery charging, respecting its capacity limits and conversion efficiency. Conversely, when the load demand is lower than the available generation and the BESS is fully charged, the PV inverter operates off the maximum power point tracking (MPPT) mode and limits photovoltaic production to match the load demand. This operational logic reflects the typical constraints of off-grid systems and enables evaluation of system behavior under various consumption profiles, solar seasonality, and battery bank sizing strategies.



The Doyle-Fuller-Newman (DFN) model, a relevant reference in electrochemical battery modeling, is implemented within the PyBaMM environment through the numerical resolution of differential equation systems that describe ionic transport, electrode reactions, and potential variations. The library also allows for the inclusion of degradation mechanisms, such as the growth of the solid electrolyte interphase (SEI) layer, enabling simulation not only of the transient behavior of cells, but also of aging effects over time. As a result, the model supports detailed analysis of performance, efficiency, and lifespan of storage systems under realistic operating conditions [3][7].

Figure 3 presents the flowchart of the simulator implemented in Python/PyBaMM. In the beginning, input data are loaded, including the hourly photovoltaic generation curve and the load consumption profile. Next, the net energy balance is calculated to determine the need for charging or discharging the BESS. This power is then processed by the Battery Management System (BMS), which applies safety limits related to SoC, DoD, and C-rate. After adjustment, the corrected current is defined and applied to the electrochemical model developed in PyBaMM. Based on this simulation, the internal battery states (SoC, SoH, and available capacity) are updated, along with reliability indicators such as the number and duration of interruptions. In the end, the results are stored and displayed through performance metrics and graphical outputs.

Figure 3 – Simulation flowchart



The depth of discharge (DoD) of the battery is determined by (2):

$$DoD = \frac{\int_0^t i_D(t) dt}{Q_C} \quad (2)$$

Where:

Q_C : Battery charge capacity in coulombs or As

$i_D(t)$: Battery discharge current in amperes at time t

t : Time instant during discharge operation in s

The state of charge (SoC) of the battery is determined by (3):

$$SoC = \frac{Q_0 - \int_0^t i_D(t) dt}{Q_C} = SoC_0 - DoD \quad (3)$$

Where:

Q_0 : Initial battery charge at time $t = 0$ s, expressed in coulombs or As

SoC_0 : Initial state of charge at time $t = 0$ s (unitary dimensionless value)

3 RESULTS AND DISCUSSION

The representation by the computational model enabled hourly resolution representation of the electro-energetic behavior of the system composed of photovoltaic generation (PV) and a battery energy storage system (BESS), operating in off-grid mode to



supply the auxiliary system of the substation. The simulation considered hourly operational data over two consecutive months, using actual power demand profiles from the auxiliary systems of the control house in the transmission line bay connecting Trindade to Firminópolis, along with a solar time series derived from the historical average irradiance in Trindade [8]. This approach allowed for integrated analysis of power flows among system components, battery state of charge (SoC) dynamics, and the progression of degradation represented by the state of health (SoH) over time. The battery's state of health (SoH) is determined by (4):

$$SoH = \frac{Q_{CA}}{Q_{C0}} \quad (4)$$

Where:

Q_{C0} : The charge capacity of the battery at the beginning of its life (new battery), expressed in coulombs or As

Q_{CA} : The charge capacity of the battery as computed by the electrochemical model, expressed in coulombs or As

Figure 4 represents a typical snapshot of the daily operation of the system, highlighting the power curves for photovoltaic generation (P_{FV}), effectively utilized photovoltaic power (P_{FV_util}), load power (P_{load}), and BESS power (P_{BESS}). During nighttime hours, the load is fully supplied by the battery bank, yielding positive values for P_{BESS} . As solar generation begins, a transition in operation is observed as the energy generated initially reduces battery discharge and subsequently reverses the flow, starting to charge the battery. This process is evidenced by negative values of P_{BESS} .

Charging continues until the state of charge (SoC) reaches its upper limit (100%), at this point the PV generation is no longer to charge battery, as P_{FV} and P_{FV_util} have the same values. After the solar peak, the system resumes using stored energy to supply the auxiliary services as adjusted by the power flow control. The SoC curve during the daily operation cycle confirms the role of the BESS in compensating for solar source intermittency, assuring stability to supply critical loads.

Figure 5 illustrates the evolution of the state of health (SoH) of the battery over the simulated cycles, revealing an accumulated degradation of 1.16%, indicating a final value for SoH of 98.84% at the end of the analyzed period. The cause of the degradation is mainly associated with the activation of the solid electrolyte interphase (SEI) growth model implemented in PyBaMM.

Figure 4 – Snapshot of the Operation of a Typical Day

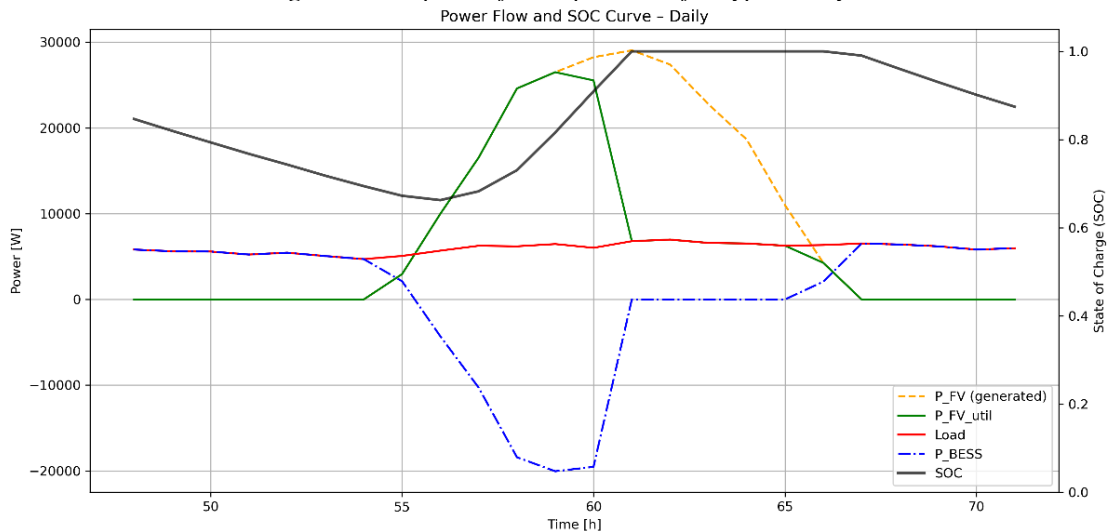
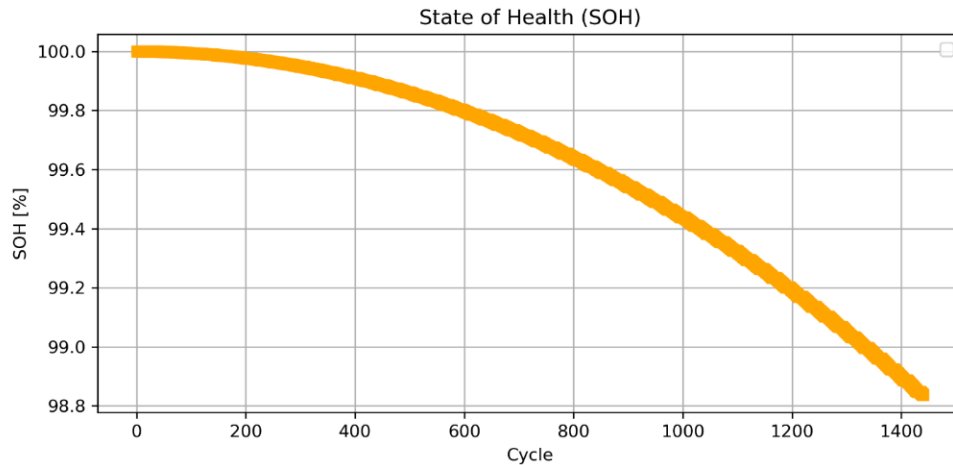




Figure 5 – Battery Life Degradation (SoH)



In addition to the SoH analysis, the number of equivalent full cycles (EFC) was calculated. EFC is a metric that estimates battery aging based on the total energy throughput relative to its nominal capacity, despite the operation under partial cycles [9][10]. The accumulated total of 20.25 equivalent cycles over the simulation period resulted in an average capacity degradation rate of approximately 0.057% per cycle. Although reference values in the literature indicate cumulative losses below 20% after 6000 cycles, leading to a corresponding average degradation rate of less than 0.0033% per cycle under idealized operating conditions of DoD and controlled temperature [5]. Whilst, in the present study, the implemented electrochemical model was applied to a realistic hourly operation scenario with dynamic load and generation profiles, where the DoD and current regime are directly derived from the power demand curve and available solar power. Therefore, the observed degradation reflects the specific characteristics of the application according to the model representation of the cumulative effects of partial cycles under operational conditions that closely resemble a realistic scenario.

4 CONCLUSIONS

This study presented the development and application of a computational model for hourly simulation of a photovoltaic system (PV) integrated with a Battery Energy Storage System (BESS), designed to supply auxiliary services to the control house of the Trindade–Firminópolis transmission line at the Trindade Substation, located in Trindade - GO. The implementation was carried out in Python using the PyBaMM platform, incorporating an integrated approach that combines energy control with the physicochemical mechanisms of battery aging.

The simulation of a two-month operational scenario indicates the model can represent phenomena associated with charge and discharge dynamics, the evolution of SoC, and the degradation of battery capacity (SoH). The adoption of the EFC concept enabled quantification of accumulated degradation in the context of partial cycles, providing an objective metric to assess the residual battery life. The application of high fidelity electrochemical DFN model allows for detailed representation of internal cell phenomena but requires robust computational effort, which limits the feasibility of long-term simulations, such as annual operational profiles.



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As a perspective for future, investigation can enhance scalability and robustness of the simulations, considering both computational aspects and model calibration using field data collected during the operation of the PV-BESS system. Hence, the adoption of high-performance computing strategies, such as code parallelization, model reduction techniques, or hybrid modeling approaches seem promising. Furthermore, the validation of physicochemical parameters used in the model based on specific experimental data is highlighted as essential to ensure representativeness and reliability in aging analysis, performance evaluation, and lifespan estimation of BESS systems under realistic operating conditions.

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