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DYNAMIC PERFORMANCE ANALYSIS OF A DISTRIBUTION FEEDER WITH A TRANSPORTABLE STORAGE SYSTEM CONNECTED

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Abstract

The study analyzes the effects of integrating a Transportable Battery Energy Storage Systems (TBESS) into a distribution feeder under both steady-state and transient conditions, evaluating its performance in load supply, reactive power supply and power quality within a feeder. The performance analysis focuses on electrical quantities at nodes along a 13.8 kV feeder, calculated through EMT simulations that consider a detailed representation of both the electrical network and the TBESS. The study examines steady-state conditions and the occurrence of a three-phase short-circuit, both with and without the TBESS in operation. In addition to the benefits related to load supply, the TBESS is found to provide a slight improvement in voltage levels regardless of whether operated in voltage profile support mode or load supply. The results indicate that the steady-state and transient demands observed are compatible with the grid requirements, suggesting that the TBESS can be considered a viable solution to support the continuity and quality of power supply in various operational and emergency scenarios.

Keywords: TBESS, Distribution Network, On-Grid, EMT simulations.

1. Introduction

Battery Energy Storage Systems (BESS) have been gaining prominence due to their fast response capability when interfacing with the power grid, continuous energy supply, and high versatility (Yang, 2018). These characteristics make them particularly effective in applications such as voltage and frequency control, as well as energy management (Smith, 2010). The incorporation of new battery technologies has become a strategic priority for distribution utilities, driven by the ongoing cost reduction and the growing demand for systems with high responsiveness. Due to the intermittent nature of renewable sources, the use of storage systems is pointed out as a solution to guarantee the quality, security, and stability of the electrical grid under high generation intermittency (Campos et al., 2019).

The global installed capacity of battery storage reached 155 GW in 2024, with an exponential growth projection to 863 GW by 2030 (Greener, 2024). The continuous reduction in costs and the growing demand for high-response systems have consolidated the incorporation of new battery technologies as a strategic priority for distribution utilities. The work by Gabriel E. Mejia-Ruiz, et al. (2023) proposes the use of power injection from a BESS to offer voltage and frequency support in the transmission network. Furthermore, the research by Godfrey Macharia Njok, et al. (2025) analyzes the optimization of BESS location and sizing with a focus on improving frequency and voltage stability.

In this expansion scenario, Transportable Battery Energy Storage Systems (TBESS) emerge, representing a mobile and agile solution for supplying loads, thereby providing significant operational flexibility to the

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electrical system (Abdeltawab, 2017). The inherent mobility of these systems is one of their major advantages, as it enables utilities to attend to needs during periods of existing infrastructure expansion, assist with scheduled maintenance, and provide service in locations with emergency situations, in addition to the possibility of being easily transported to another location. The applicability of these storage systems extends to a vast range of uses in distribution systems throughout the country.

However, the implementation of these systems requires a thorough analysis of their integration into the grid, particularly regarding the impacts of transient events such as short circuits, which can compromise the stability of the power system (Boloorchi et al., 2017). In this context, studies focused on evaluating the potential benefits these systems can offer to grid operation become especially relevant. To explore the multiple functions that a TBESS can perform when connected to the distribution grid—such as meeting seasonal demand peaks (thus postponing or even avoiding investments in distribution network upgrades) and controlling reactive power (contributing to improved power quality and distribution system efficiency)—this study aims to model, using PSCAD™/EMTDC™ software, a real feeder from the utility CELESC, located in eastern Santa Catarina, Brazil, including its segments, loads, and transformers. Additionally, simulation results are presented using a TBESS model developed following the approach of Teodorescu et al. (2011), with the objective of analyzing the joint behavior of the TBESS and the elements of the electrical network. Due to its mobile nature, it is of interest to perform studies with different connection points in the system, aiming to find a Point of Connection (POC) where the system provides the best possible contribution. Subsequently, the behavior of the TBESS and the grid is analyzed under a three-phase short-circuit at the selected POC.

2. Methods

The TBESS model used in this work is based on the equipment designed in the ANEEL R&D project 05697-0323/2023, consisting of first and second-life batteries (150 kW and 400 kWh) and a diesel generator (150 kVA), which serves as a backup and "range extender" for the TBESS, to connect to low and medium voltage distribution grids (13.8 kV), aiming to support outages, meet seasonal demand peaks, and provide reactive power control in the distribution grid.

Figure 1 presents the base configuration of the TBESS developed in the R&D project.

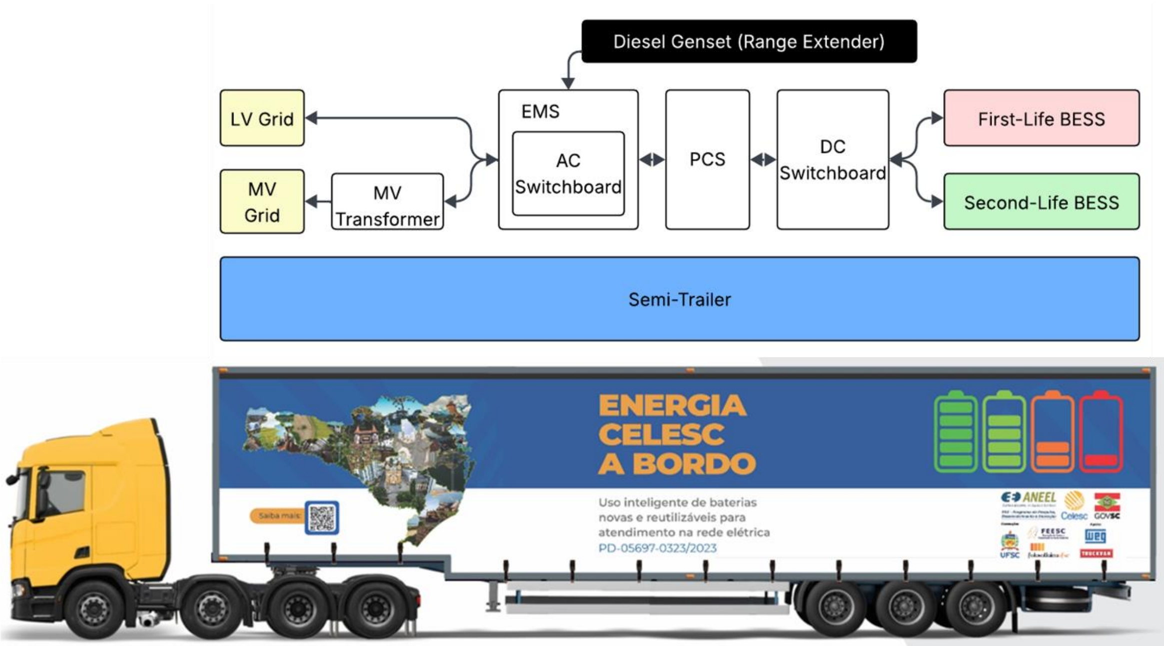

Figure 1 - TBESS developed in the R&D project.

Due to the research nature of the project, second-life systems and a diesel generator were used to study the utilization of second-life battery systems in the Electric Power System. Since the objective of this study is to evaluate the dynamic performance of a TBESS, the power considered is about 8 times greater than originally conceived in the project, due to the exclusive use of first-life batteries, making it possible to use a system of this size because of the removal of the second-life systems and the diesel generator.

The distribution feeder was modeled in PSCAD/EMTDC based on data provided by the utility. It features a radial configuration, with a voltage level of 13.8 kV at the distribution level and 380 V at the loads, which are modeled using the constant power load model and are connected to the system through distribution transformers. The model includes the parameters of the distribution lines utilizing a π model, distribution transformers, and the substation transformer. The grid model does not use line capacitance data because the utility company informed that it does not consider such data in its own model. An equivalent representation of the transmission system was also incorporated. The network model was validated using short-circuit and power flow simulations, which were compared against reference values supplied by the utility. Since the study aims to evaluate the dynamic behavior of the TBESS and the grid, the grid protection systems were not modeled.

Figure 2 illustrates the modeled electrical diagram of the feeder utilized in the study.

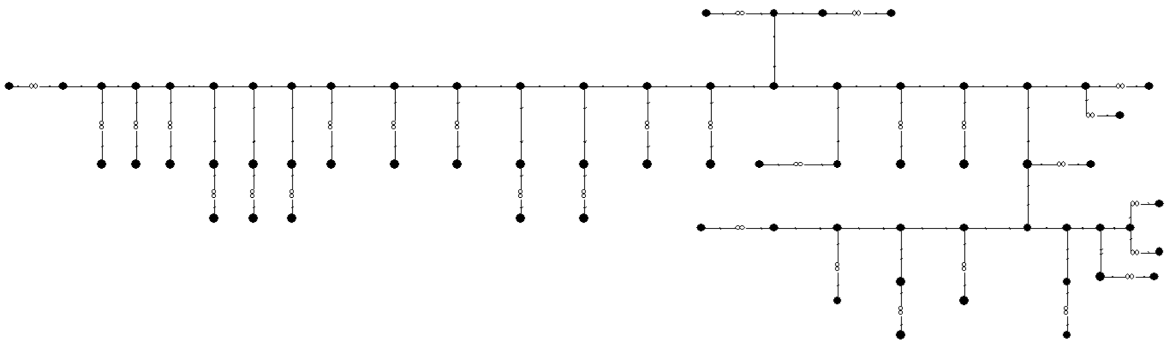

Figure 2 - Modeled electrical diagram of the feeder.

The TBESS model implemented in PSCAD consists of three main stages: a DC-DC boost converter that operates as a step-up converter during battery discharge and as a step-down converter during charging; a three-phase inverter responsible for controlling active and reactive power at the grid interface; and an LCL filter that smooths the output waveform. The TBESS converter's control system is designed to inject constant active and reactive power depending on the setpoint defined by the operator. The converter also features a droop control implemented to aid in grid voltage.

This work evaluates the impacts of the TBESS regarding its use to support reactive power supply. The analysis consisted of verifying the performance of the TBESS by connecting it at different nodes along the feeder to analyze the voltage profile improvement across the entire grid. In this analysis, the TBESS is operating in reactive power control mode, where it supplies constant reactive power to the system in order to mitigate the voltage drop along the feeder. For this evaluation, four nodes were chosen to be assessed: the node that represents the system's substation (Node 1), the node with the largest load in the system (Node 2), the second node with the lowest voltage in the system (Node 3), and the point with the lowest voltage in the system (Node 4). The objective of this analysis is to identify the best Point of Connection (POC) so that the TBESS can contribute to the system as efficiently as possible.

Figure 3 illustrates the analyzed nodes throughout the modeled feeder.

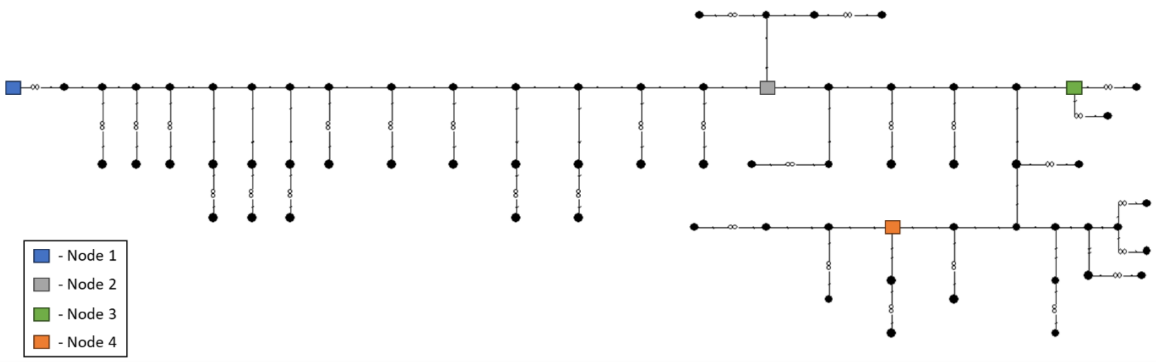

Figure 3 - Analyzed nodes throughout the modeled feeder.

Subsequently, with the TBESS connected at the optimized POC, a three-phase-to-ground short-circuit study is performed with the purpose of analyzing the behavior of a TBESS under such event. Two cases were considered for this event: one where the TBESS actively contributes to load shedding injecting active and reactive power into the system and another supplying constant reactive power, where the TBESS's sole purpose is the mitigation of the voltage drop on the feeder. In this short-circuit study, four other nodes were analyzed: at the substation outlet (Node 1); the second node with the lowest voltage in the system (Node 2); at the TBESS connection node (Node 3); and at a bus electrically close to the TBESS connection node (Node 4).

Comparative analyses are conducted between results obtained for each scenario with and without the insertion of the TBESS, focusing on two main cases: (i) improvement in voltage levels in the network; and (ii) a three-phase short circuit lasting 50 ms on the low-voltage side a bus electrically close to the TBESS connection node (Node 4).

3. Results

The Tab. 1 shows the average RMS voltage values at the four analyzed nodes, both with and without the TBESS supporting the feeder reactive power supply. The analysis considers a load condition of 6100 kW and 1600 kvar at the feeder inlet with a 900 kVA TBESS operating at 720 kvar.

Tab. 1: Voltage measurements at Nodes 1 to 4.

Parameters	Node 1	Node 2	Node 3	Node 4
Voltage [pu] (TBESS on Node 2)	0.9953	0.9730	0.9709	0.9700
Voltage [pu] (TBESS on Node 3)	0.9953	0.9731	0.9717	0.9709
Voltage [pu] (TBESS on Node 4)	0.9953	0.9731	0.9718	0.9713
Voltage [pu] (Grid without TBESS)	0.9920	0.9645	0.9623	0.9614

Figure 4 present the voltage profile at nodes 1 to 4, both with and without the TBESS supporting the feeder reactive power supply.

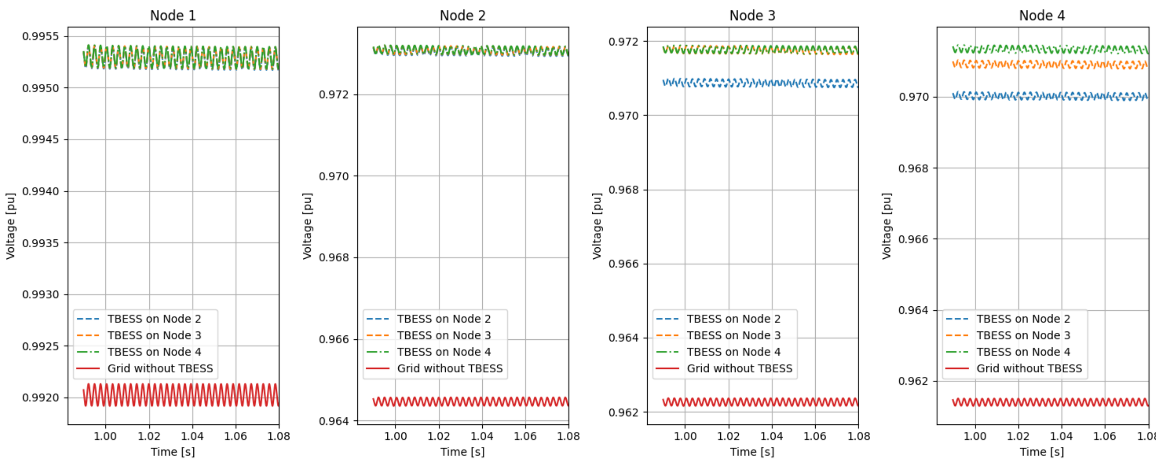

Figure 4 - Voltage profile at nodes 1 to 4.

The results indicate that connecting the TBESS to the network helps support the feeder reactive power needs and improves voltage levels at the monitored nodes. Of all the analyzed nodes, Node 4 demonstrated the best performance for grid voltage support, which raised the voltage at the respective nodes by 0.33%, 0.86%, 0.95%, and 0.99%. It is important to highlight that these results were obtained with the TBESS operating in reactive power control mode under steady-state conditions.

Due to the system having demonstrated greater efficiency when connected at the point of lowest voltage, the short-circuit (SC) simulations were performed with the TBESS connected at this location for a different set of nodes. For the first scenario, the TBESS is configured to assist in supplying power to the grid loads, where it provides 720 kW and 180 kvar (P/Q mode). For the second, the TBESS is contributing 720 kvar (Q mode) with the purpose of assisting in the grid's voltage profile and the last scenario, where the grid is subjected to a short-circuit without the TBESS connection.

Figure 5 illustrates the analyzed nodes throughout the modeled feeder during the SC event.

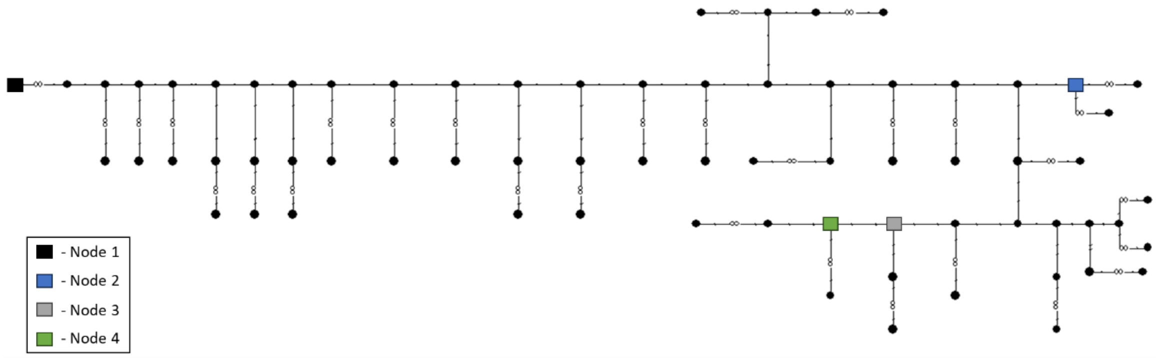

Figure 5 - analyzed nodes throughout the modeled feeder during the SC event.

Figure 6 presents the voltage variations at the four analyzed nodes during the short-circuit event with and without the TBESS.

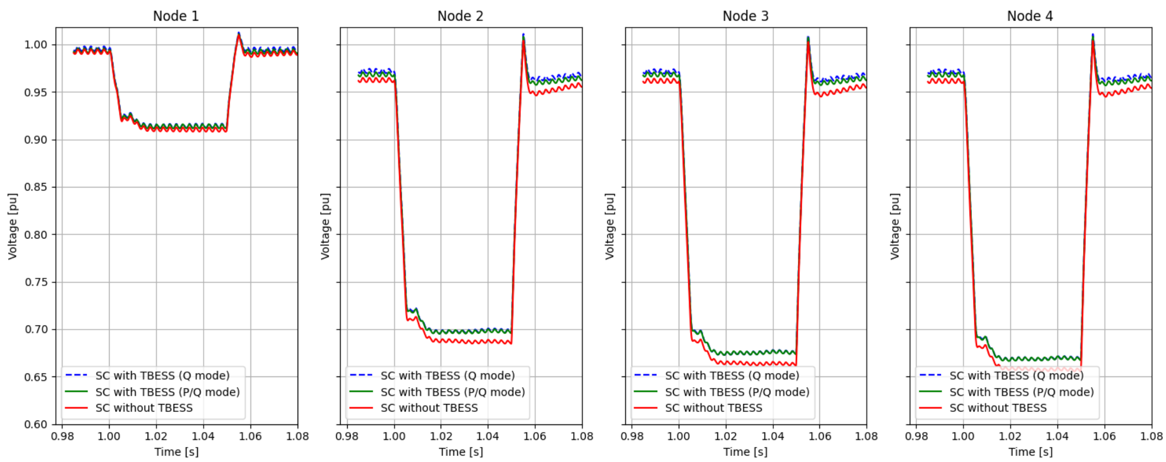

Figure 6 - Comparative analysis of the voltage profile during a short-circuit event.

The results indicate that the connection of the TBESS led to slightly higher voltage levels during the short-circuit event, particularly at Nodes 2, 3, and 4, compared to the scenario without the TBESS. This indicates that there is no evidence of voltage profile degradation; on the contrary, an improvement is observed. In the voltage recovery following the short-circuit, a difference in voltage magnitude is noticeable. An overshoot of voltage occurs in all scenarios; however, in the scenario without the TBESS connected, a slight voltage drop occurs immediately after this overshoot before stabilization into the steady-state, which is not evidenced in the scenarios where the TBESS is connected. The results also demonstrate that, regardless of the TBESS operating mode chosen, there is no degradation of power quality, indicating that a transportable system meets grid requirements and can satisfactorily support the grid load even in a short-circuit event scenario.

4. Conclusions

This study presents an analysis of the performance and integration impacts of a TBESS on the distribution grid under both steady-state and transient conditions. The initial analysis demonstrated that connecting the TBESS strategically, specifically at the optimal POC—identified as Node 4 (the lowest voltage point)—yields tangible benefits in system efficiency. In the steady-state reactive power control mode, the TBESS effectively supported the feeder's reactive power needs, resulting in a notable voltage rise at the monitored nodes, with improvements reaching up to 0.99%.

Furthermore, the simulation results under a three-phase short-circuit event indicated that the TBESS enhances grid resilience. The presence of the TBESS, regardless of whether it operated in P/Q mode (load supply) or Q mode (voltage profile support), led to slightly higher voltage levels during the fault and a stabilization slightly faster compared to the the scenario without the TBESS.

The study indicates that the transportable battery system meets critical grid requirements, demonstrating voltage support capabilities and power quality preservation, even during transient events. This demonstrates the TBESS as an effective and flexible solution for distribution utilities, capable of providing satisfactory load support and stability enhancement in various operational and emergency scenarios. It is important to emphasize that as the capacity of these systems increases, it becomes more necessary to perform transient stability studies for the integration of such systems into the distribution grid, avoiding any degradation of power quality.

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