DYNAMIC PERFORMANCE EVALUATION OF A TRANSPORTABLE ENERGY STORAGE SYSTEM SUPPLYING OFF-GRID LOADS

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Abstract

This study analyzes the dynamic behavior of a power electronic converter, integrated into a Transportable Battery Energy Storage System (TBESS), operating in grid-forming mode to supply an isolated power system. Simulations were conducted using PSIM software. The evaluation focused on transient events, including grid energization, short-circuits, and sudden load changes. The converter demonstrated reliable and rapid control response: during startup, the 380 V/60 Hz grid connection was established, with voltage and current waveforms stabilizing in approximately 150 ms. The system exhibited adequate dynamic stability during disturbances, with stability often restored in approximately 100 ms. Specific findings include: Sudden resistive load connections caused RMS voltage to decrease by approximately 10%, but the controller restored the voltage to 95% of nominal in roughly 66 ms. When integrating Photovoltaic (PV) generation, load voltage rises of up to 11% above nominal were corrected within about 100 ms (with small phase unbalance fully corrected in 200 ms). The system maintains high power quality, achieving a Total Harmonic Distortion (THD) of 2%, which is well below the maximum limits established by PRODIST (10% for voltages up to 2.3 kV and 8% for 2.3 kV to 69 kV). These results confirm the TBESS's suitability for off-grid operation and its capability to effectively coordinate active and reactive power, highlighting its potential to support power outages and enhance supply continuity for critical loads in a distribution network

Keywords: TBESS, Distribution Network, Off-Grid, Transient events.

1. Introduction

Due to technological advancements and the progressive reduction in costs, photovoltaic (PV) energy has globally solidified its position as a highly efficient and accessible technology. Brazil reflects this trend, with PV leading the expansion of generation capacity for the fourth consecutive year and accounting for 9.4% of the total energy generated in 2024 (EPE, 2025). However, the inherent intermittency of renewable sources necessitates the adoption of storage systems to maintain the quality, security, and stability of the electrical grid in light of the high penetration of PV (Campos et al., 2019).

The use of Battery Energy Storage Systems (BESS) is accelerating, driven by characteristics such as their high-speed response to grid demands, the capability for continuous energy supply over long durations, and the flexibility of installation, with no geographic constraints or necessity for complex infrastructure (Jafari, 2020; Yang, 2018). These systems offer a wide spectrum of applications, including voltage control, frequency regulation in islanded systems, loss reduction, and electricity management (Sandia, 2010). Furthermore, projections indicate a significant downward trend in BESS costs in the coming years (BloombergNEF, 2021; Goldman Sachs, 2024). In this context, Transportable Battery Energy Storage Systems (TBESS), which consist of mobile BESS units installed on trucks, emerge as a flexible and agile solution for supplying energy at various

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locations according to demand (Abdeltawab, 2017).

The growth in BESS utilization highlights the necessity for more detailed studies regarding their integration into the electrical grid, encompassing both potential benefits and the possible adverse impacts stemming from their operation. Steady-state analyses, while important, are insufficient to ensure secure connection, given that severe transient events (such as short circuits, voltage sags, and abrupt variations in load or frequency) can compromise system stability, thereby making a more comprehensive assessment of these phenomena essential (Boloorchi et al., 2017).

Various studies address enhancements in the dynamic response of grids featuring high penetration of non-synchronous sources. Ioan Serban and Catalin Petrea Ion (2017) analyzed, via MATLAB/Simulink, the improvement of the dynamic response in off-grid networks through a grid-forming inverter operating as a Virtual Synchronous Generator, complemented by a Supercapacitor-based Energy Storage System, aiming to maximize the inverter's transient response capability and the overall dynamic stability of the grid. Focusing on the impact of loads, Asad Mujeeb, et al. (2021) analyzed how the impulsive effect of sudden-switching inductive loads affects isolated hybrid microgrids, proposing the use of a BESS to provide ancillary services such as voltage and frequency balancing. Finally, Josua, et al. (2020) modeled and evaluated the transient behavior of Distributed Generation under various faults in both grid-connected and islanded operation modes, utilizing PSCAD, emphasizing the role of BESS in stabilizing transients during transient effects within the microgrid.

Focusing on the TBESS functionality of feeding islanded grids caused by grid maintenance, this study aims to analyze, using the PSIM software, the impacts of the WEG-developed TBESS converter operating in grid-forming mode within an isolated system. The focus is on evaluating transient phenomena, such as short circuits, abrupt load variations, and the grid energization processes. The modeled network is composed of three real loads with PV generation and BESS integration.

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

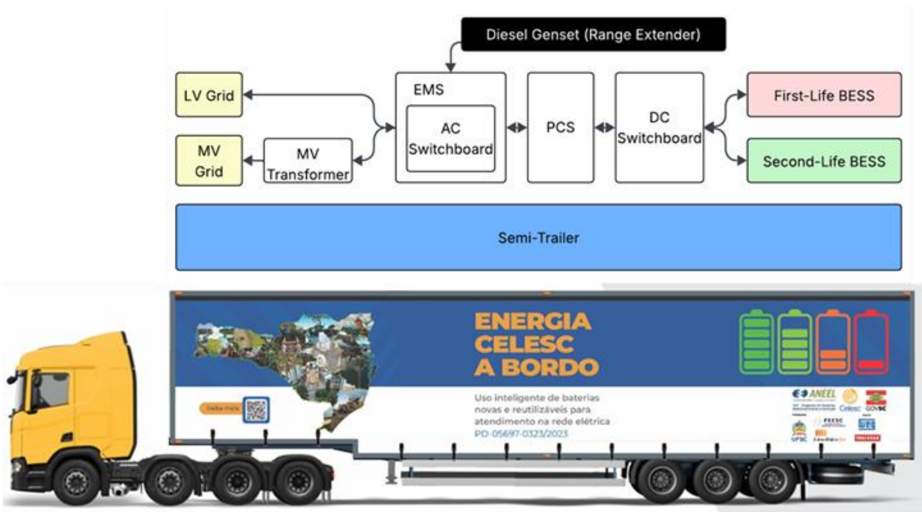

Fig. 1 – Illustrative image of the TBESS

2.1. Simulated System

The microgrid system model is composed of three constant impedance loads, totaling 40 kVA. This system was developed based on the loads of the Photovoltaics Laboratory at UFSC, which consists of three main buildings: A, B, and C. Buildings A and B account for a total load of 30 kVA, while Building C presents a 10 kVA load. Each building has PV systems installed, totaling 300 kW, and a 100 kW BESS, which were also considered in the simulations. Fig. 2 shows an aerial view of the Laboratory.

Fig. 2 – Buildings A, B and C of the Laboratory

The loads are supplied by a TBESS consisting of a 75 kVA converter capable of four-quadrant operation, with both grid-following (on-grid) and grid-forming (off-grid) capabilities. The energy storage system architecture consists of both first-life and second-life batteries connected to a power converter and an isolation transformer. Fig. 3 shows a schematic of the microgrid studied in this paper.

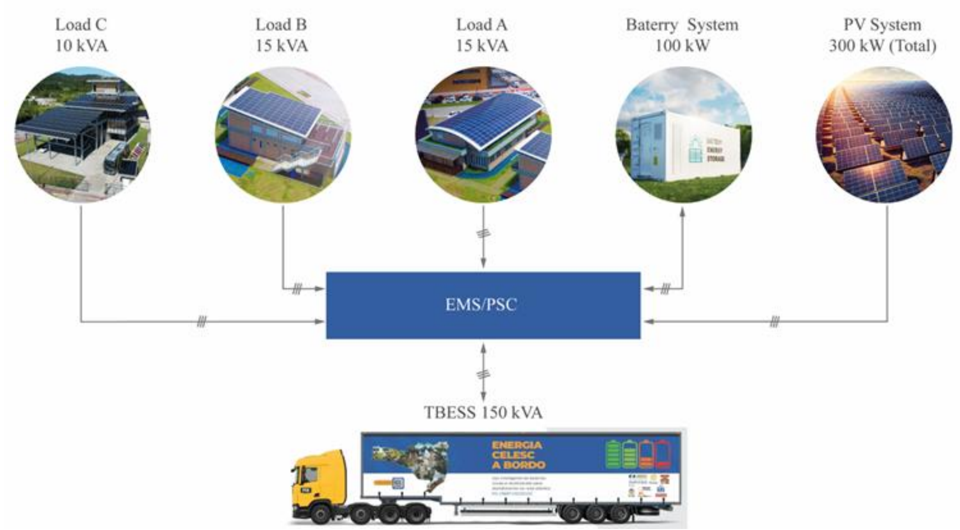

Fig. 3 – Microgrid schematic

The TBESS under study has, as its primary function, the supply of electrical energy during interruptions in the distribution system for maintenance purposes. This enables the isolation of maintenance zones and the continuous supply of downstream loads in locations where load transfer to another feeder is not possible, using the energy provided by the TBESS. As a secondary function, the TBESS is designed to supply power to critical consumers during grid contingencies.

Therefore, the performed simulations aim to verify whether the TBESS is capable of supplying energy in compliance with the power quality criteria established by PRODIST — the Procedures for the Distribution of Electric Energy in the National Electric System (ANEEL, 2021). This assessment is essential since consumers must not experience any degradation in service quality due to the change in the energy source feeding the system. For this assessment, the Total Harmonic Distortion (THD) must be calculated, utilizing Eq. (1):

$$THD\% = \sqrt{\frac{V_2^2 + V_3^2 + \cdots + V_n^2}{V_1}} \times 100 \quad (1)$$

In this context, the results were obtained through simulations carried out in the PSIM software. The simulated TBESS models were provided by WEG, the company responsible for the product design and development, in collaboration with CELESC and the Photovoltaic Laboratory of UFSC. To protect the project's intellectual property, specific details of the control strategies and power conversion structure are not disclosed. Instead, the system is represented by the block diagram shown in **Fig. 4**.

In **Fig. 4(b)**, emphasis is placed on the inverter block, whose analysis is of great importance for assessing system performance in terms of power quality. The inverter is responsible for generating the voltage waveforms supplied to the loads and for controlling current, active power, and, when necessary, reactive power. As illustrated in the block diagram representing the control scheme for grid-forming operation, the inverter also includes a DC–DC converter, which adjusts the voltage levels from first- and second-life batteries to the required DC bus voltage. This DC bus serves as the input stage for the DC–AC converter.

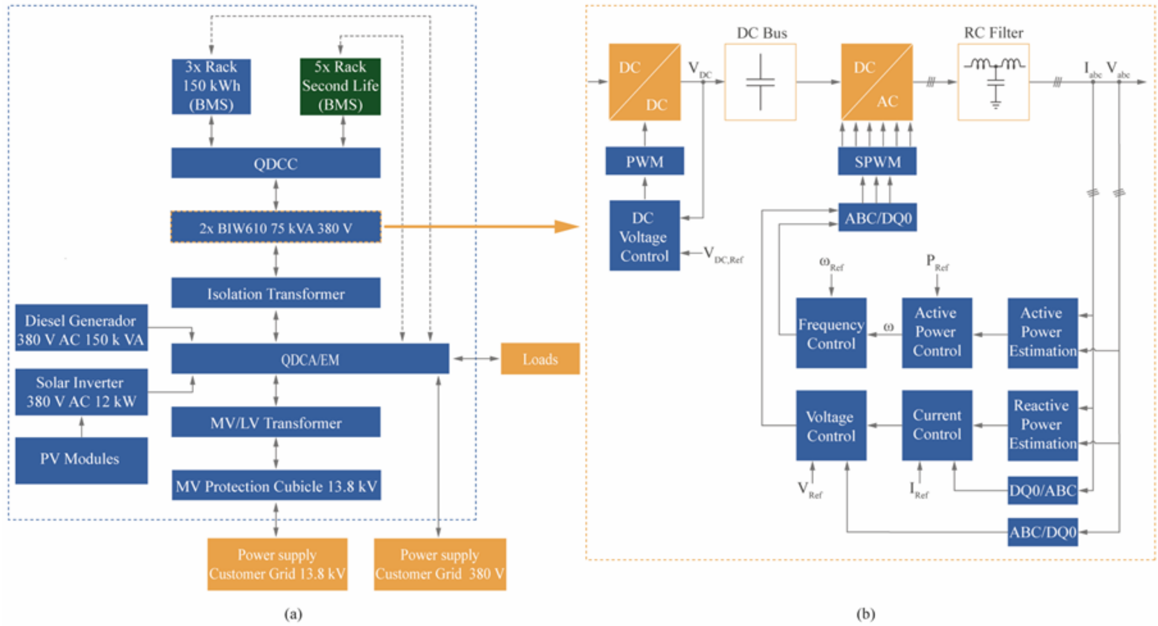

Fig. 4 – (a) TBESS block diagram. (b) Forming grid inverter generic block diagram control.

2.2. Simulations

The simulations performed in this paper focus on the dynamic behavior of the TBESS power electronic converter in grid-forming configuration in a microgrid. The study considers the system being subjected to different types of events, namely: grid energization, load variation, and a three-phase-to-ground short-circuit at the loads.

The grid energization simulation focuses on the converter's start-up transient. The analysis includes the frequency, the phase shift, the stabilization time and the RMS values of the line-to-line voltages on the loads.

The load variation simulations focus on the converter's behavior when there is a sudden change in the supplied load. Given that the modeled loads have PV systems installed, sudden changes in the PV generation cause sudden changes in the demand perceived by the TBESS. The intermittent nature of the solar resource and the rising number of PV systems installed within the distribution grid highlight the necessity of an adequate response by the TBESS to such variations in load. The simulations include sudden increase and decrease of resistive loads, sudden increases of inductive and capacitive loads, and the connection of PV and battery systems to the grid.

- To simulate a step in resistive load, the simulation starts with building B disconnected from the microgrid. The building is then connected momentarily, increasing the load to 40 kW, and subsequently disconnected;
- To simulate sudden increases in inductive and capacitive loads, an inductive load is connected to the microgrid, lowering the Power Factor (PF) to 0.95 lagging. Subsequently, the inductive load is disconnected, while a capacitive load is simultaneously connected to the microgrid, converting the PF to 0.95 leading;
- To simulate the connection of PV and battery systems to the microgrid, a block consisting of a PV system model and a controllable load (representing a BESS being charged) was connected to the microgrid. When the block is connected to the grid, the PV system is capable of supplying all the power required to charge the BESS and part of the demand of the loads, so the block acts as a generator. Eventually, the PV system's generation is reduced, and the block acts as a load due to the power demanded by the BESS.

The short circuit simulations focus on the behavior of the converter during a short circuit event. A 30 ms three phase-to-ground short circuit was simulated, with the purpose of demonstrating the converters response to a short duration event, and how it behaves after the contingency is extinguished. The analyses include the active and reactive power supplied by the TBESS and demanded by the load, the RMS line-to-line voltages on the loads, and the RMS currents supplied by the converter.

3. Results

Initially, the voltage behavior across the loads and the current at the TBESS connection point were observed. These waveforms are presented in **Fig. 5**. On the left, the inverter startup can be analyzed, while on the right, the voltage waveform imposed by the inverter is shown in more detail. It can be observed that the line RMS voltage of the generated waveform is 380 V, the frequency is 60 Hz, and the phase shift between each phase voltage is 120°, making it compatible with the existing electrical grid. It can also be observed that after the inverter startup, the voltage takes approximately 150 ms to reach the appropriate values to establish the grid connection.

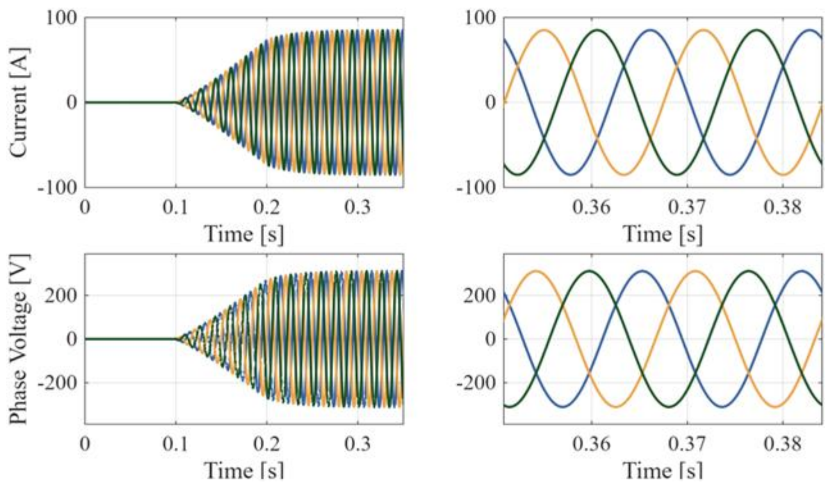

Fig. 5 – Current and voltage across the load.

In **Fig. 5**, the current waveform at the inverter output terminals is also presented. Similar to the voltage, the current does not reach its nominal value instantaneously, taking approximately 150 ms to do so. The steady-state current waveform is shown in more detail on the right side of the figure. From this waveform, it can be concluded that the current envelope behaves as expected, since the phases currents are displaced by 120° from each other and the frequency is 60 Hz.

To evaluate the inverter behavior during an abrupt load connection and disconnection, load B, initially disconnected from the system, is connected at t = 0.5 s, as shown in **Fig. 6**.

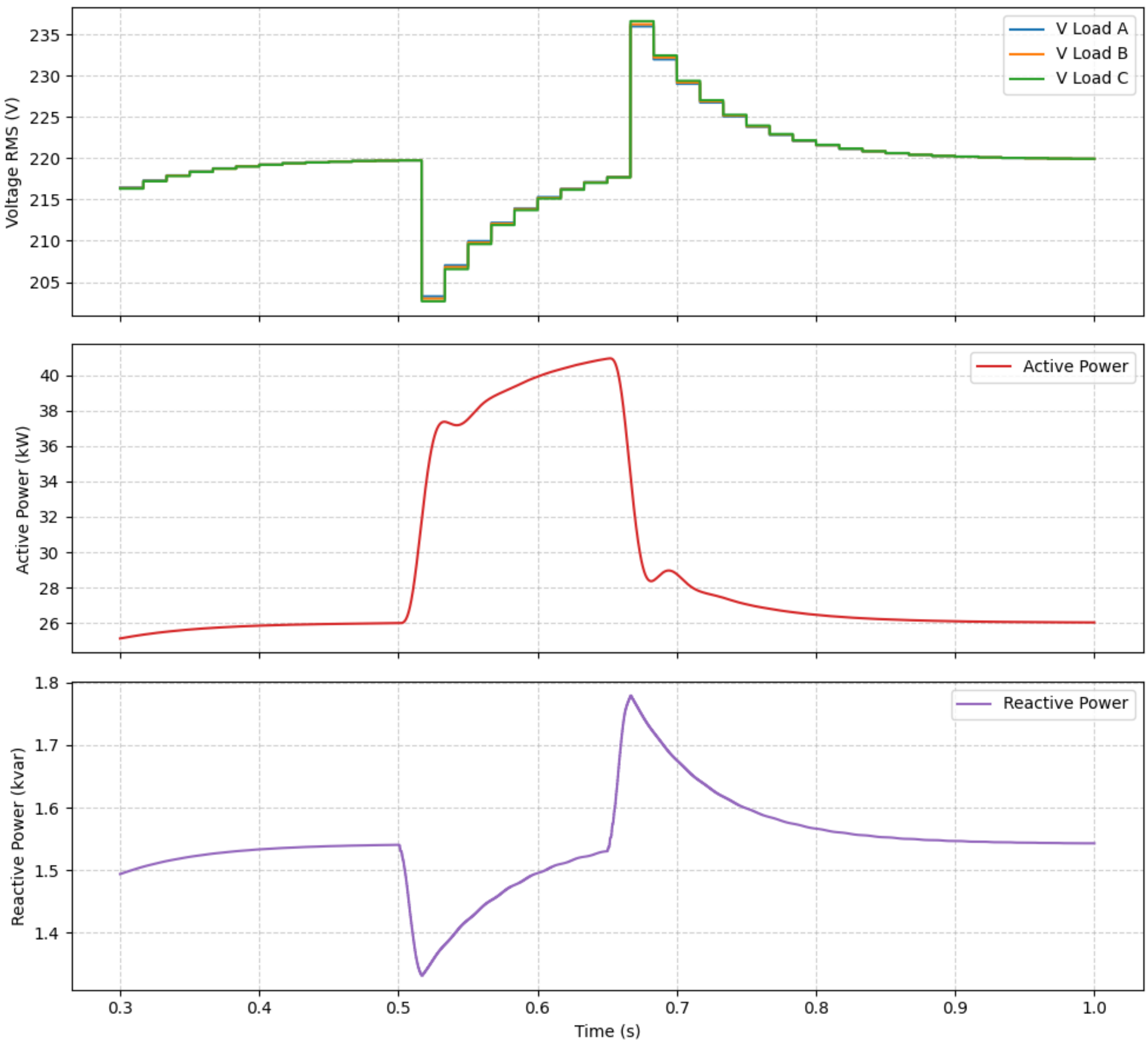

Fig. 6 – Resistive load step.

At the moment of connection, the RMS voltage across the loads decreases by approximately 10%. However, within approximately 66 ms, the controller action restores the load voltage to 95% of its nominal value, and after approximately 150 ms, the voltage reaches its nominal level. At t = 0.65 s, load B is disconnected, causing the voltage across the remaining loads to rise by around 7% above its nominal value. The inverter responds by injecting reactive power into the system, bringing the voltage back to its nominal value in approximately 150 ms. The active power increases proportionally to the load added to the system, and once this load is removed, the inverter correspondingly reduces the active power injection.

The RMS voltage, active power, and reactive power values for the connection between the inverter and a 40 kVA load with unity power factor, as well as for operating conditions at 0.95 capacitive and 0.95 inductive power factors, are presented in **Fig. 7**. Initially, only a resistive load of 41 kW was connected to the system. At t = 0.6 s, an inductive load was added, resulting in an overall power factor of 0.95 lagging. This connection caused an increase of approximately 5% in the RMS voltage at the point of common coupling. The voltage controller acted to restore the nominal value within approximately 80 ms, demonstrating an adequate dynamic response. Subsequently, at t = 0.9 s, a capacitive load was connected, adjusting the system power factor to 0.95 leading. At that moment, the RMS voltage supplied to the loads decreased by approximately 4%; however, the controller compensated for this deviation within approximately 85 ms. Under this condition, the inverter started operating by absorbing reactive power from the system, maintaining voltage stability.

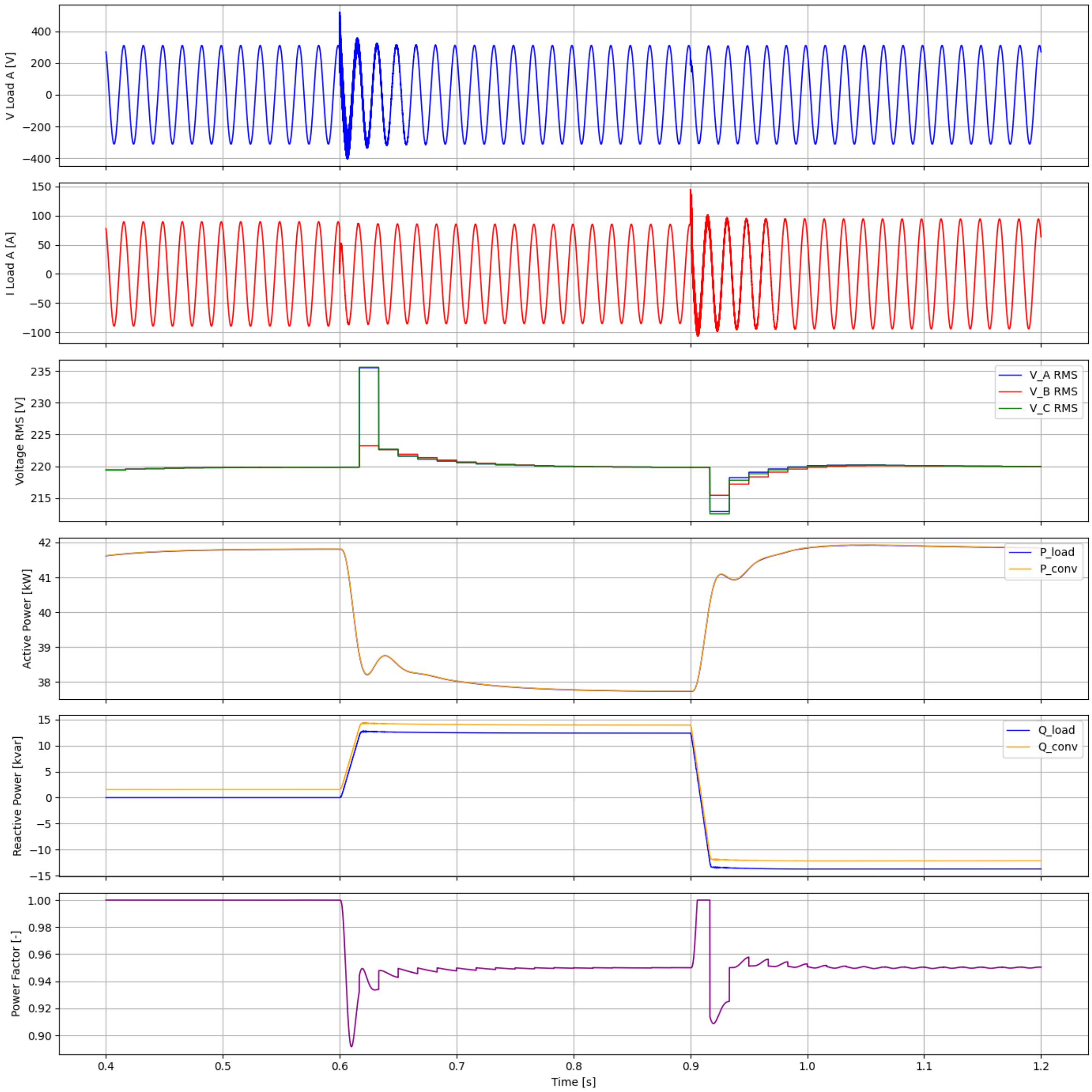

Fig. 7 – Resistive, Inductive and capacitive load steps.

The two first graphs of **Fig. 7** show the voltage and current waveforms for one of the phases. It can be observed that no significant distortion occurs in either quantity, confirming the maintenance of power quality delivered to the loads.

Fig. 8 shows the inverter operation under a single-phase short-circuit applied to phase B. As expected, the inverter shuts down immediately at the onset of the fault, at t = 0.5 s, and remains offline until the short-circuit is cleared. Once the fault is removed, the inverter initiates its restart sequence and gradually restores the nominal voltage and current values at the load.

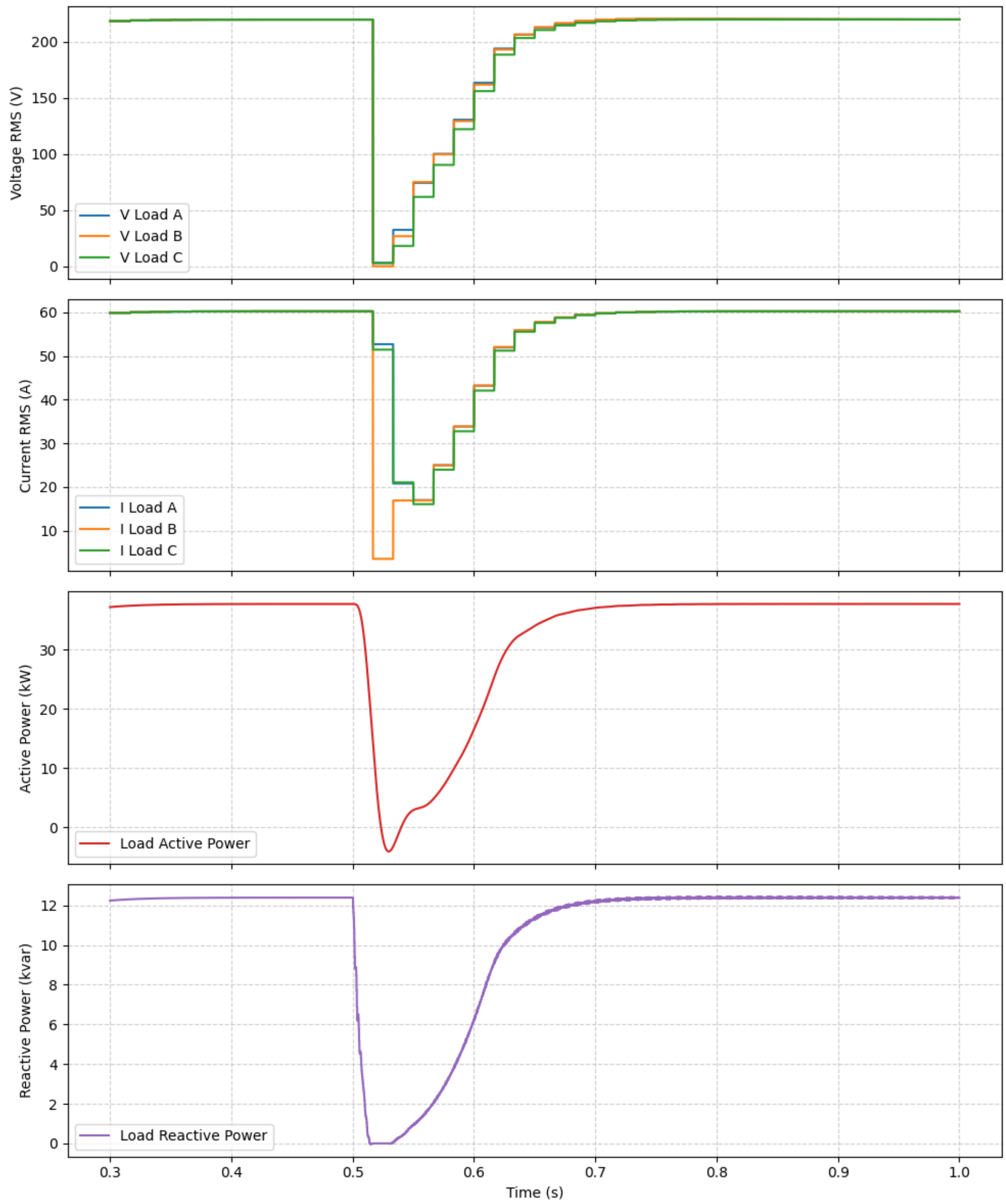

Fig. 8 – Inverter response to a short-circuit event.

Finally, the converter response when connected to a photovoltaic system was analyzed. Initially, the photovoltaic system does not generate enough energy to support the charging of the connected batteries; therefore, the inverter supplies not only the energy required to feed the loads but also the energy needed to charge the batteries.

At t = 0.5 s, the photovoltaic generation assumes the battery charging and part of the load supply. At this moment, the load voltage rises by approximately 11% above its nominal value. The converter begins to supply reactive power, restoring the voltage within about 100 ms. A small voltage unbalance between phases is observed, which is fully corrected within approximately 200 ms.

At t = 1 s, the photovoltaic generation is disconnected, causing the converter voltage to drop by approximately 10%. The converter then operates by absorbing reactive power and adjusts the voltage at the point of connection within approximately 100 ms.

The lower part of Fig. 9 shows the power supplied to or absorbed from the photovoltaic system connected to the batteries, while Fig. 10 shows the inverter operation considering PV and BESS integration.

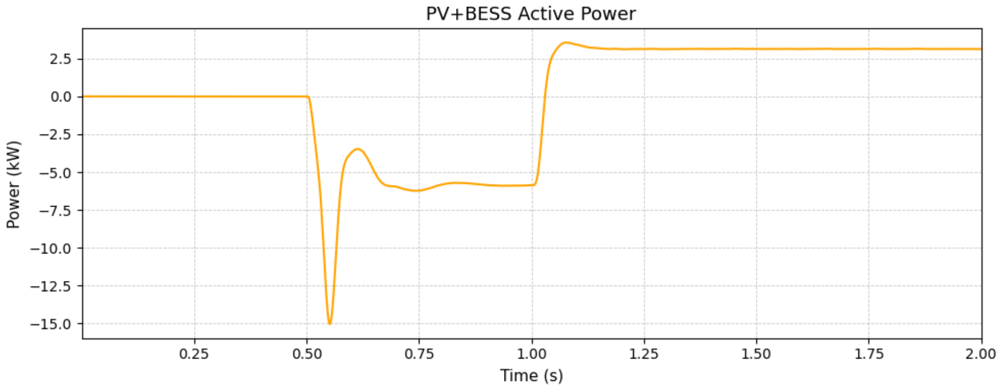

Fig. 9 – Power supplied or demanded by the PV+BESS block.

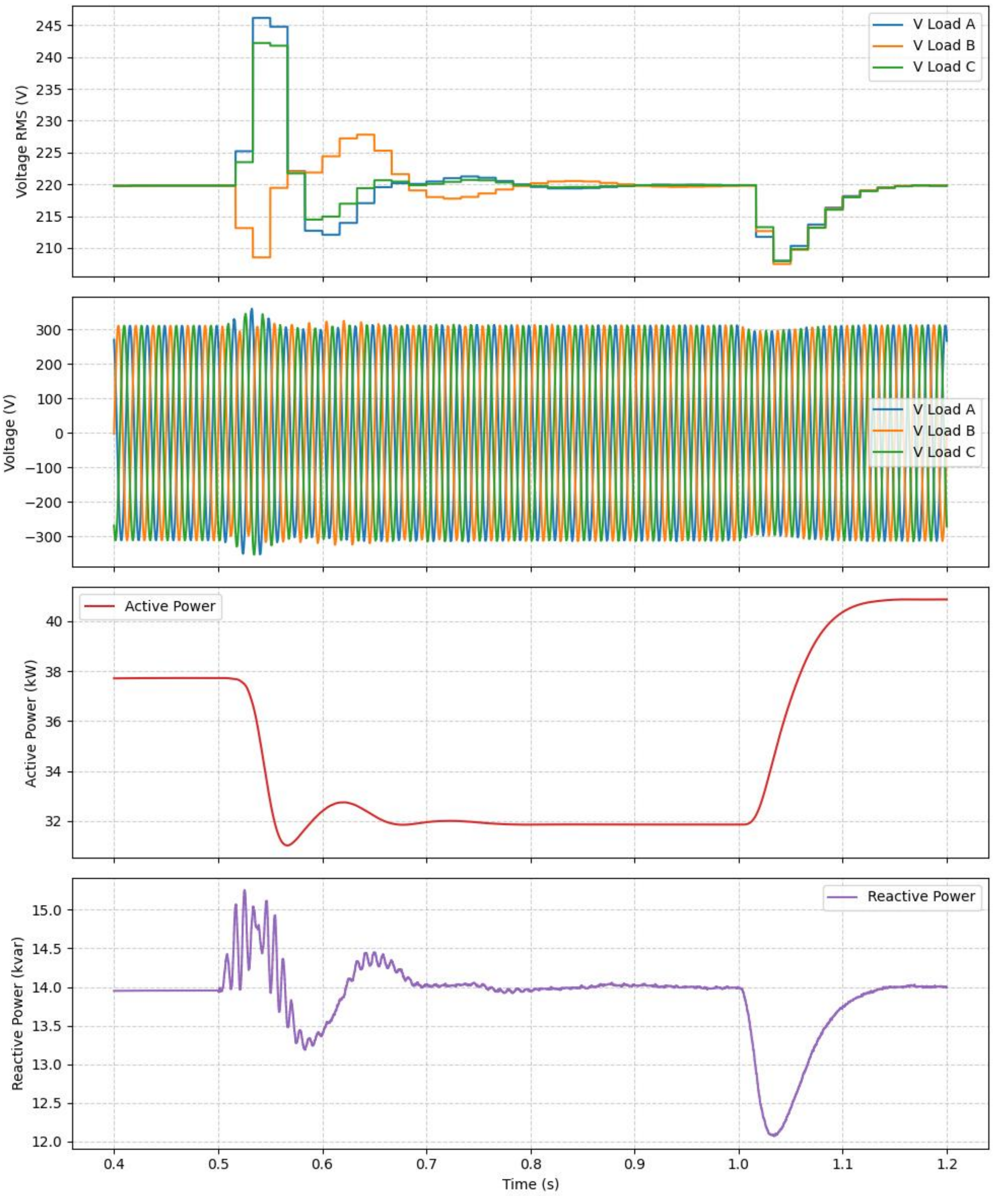

Fig. 10 – Inverter operation during photovoltaic generation integration.

Analyzing the harmonic spectrum and according to (1), the THD of the converter is 2%. Therefore, it can be stated that the converter complies with the maximum THD% limits established by PRODIST, which specifies the allowable THD% based on the fundamental voltage: 10% for voltages up to 2.3 kV and 8% for voltages between 2.3 kV and 69 kV.

4. Conclusions

This study evaluated the performance of the TBESS inverter under various operating conditions, including grid connection, load variations, short-circuit events, and integration with PV system and BESS. The results demonstrate that the inverter reliably maintains voltage and current within nominal limits, even under abrupt load changes and faults, restoring stability around 100 ms. The system also complies with power quality standards, as evidenced by the total harmonic distortion (THD) of 2%, well below the limits established by PRODIST.

Furthermore, the inverter effectively coordinates active and reactive power, ensuring stable operation during transitions between battery supply and photovoltaic generation. Voltage unbalances observed during transient events are quickly corrected, confirming the TBESS's capability to supply energy to critical loads while maintaining power quality.

Overall, the simulations indicate that the TBESS is suitable for providing reliable electrical energy, supporting critical consumers during grid contingencies, and integrating renewable energy sources, meeting both operational and regulatory requirements.

Due to the nature of the software, however, it proved inadequate to simulate extensive and intricate 3-phase systems such as a distribution network. As such, the analysis was limited to an isolated microgrid. The analysis of the TBESS's integration in a distribution network requires the use of specialized software such as PSCAD, and is the object of further studies within the scope of the project.

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