PV CONTAINER FOR GREEN ENERGY PRODUCTION

Efstathios FIORENTIS[1], Irina VÎLCIU[2], Octavian Mihai GHIȚĂ[3], Laurentiu LIPAN[4], Bogdan-Adrian ENACHE[5]

Recently, more mobile energy storage models have been designed and used. Among them, the containerised ones, thanks to their standard dimensions, offer a variant that can be easily transported and installed where needed. This paper presents the design and optimisation of a containerised energy storage system prototype, with $LiFePO_4$ Li-ion batteries, with a capacity of 40[kWp], realised within the project, "green" mobile services for energy systems in the smart city - SMARTELTER". The projected plan is designed to ensure the necessary energy to charge the batteries using a system of 75 photovoltaic panels with manual deployment. Regarding the choice of the container, a standard six-meter container is used. Before making the final system, to study and optimise the behaviour of the design, a 1:10 scale prototype was created using 3D printing techniques, and to optimise the operation of the electrical installation, the entire energy conversion chain from the photovoltaic panel system up to the batteries system was simulated using the Matlab simulation environment and its extension, Simulink. After the tests, we can observe the efficiency of the designed method, maintaining the delivered parameters at optimal values for the entire conversion process and finally charging the batteries.

Keywords: energy storage system, lithium-ion batteries, containerised systems, retractable photovoltaic panel system, green energy, off-grid power

1. Introduction

Technological advancements have been pivotal in fostering economic and cultural development and enhancing global connectivity. A notable trend in this development is the increasing reliance on electricity, often lauded for its environmentally friendly characteristics, as it is perceived to be non-polluting and benign to the planet. However, this shift towards electrification presents a challenge, particularly equitable access to electricity. There remain areas globally

[1] Assistant, Department of Measurements, Electrical Devices and Static Converters, Faculty of Electrical Engineering, UNST POLITEHNICA Bucharest, Romania, e-mail: efiorentis@upb.ro
[2] Lecturer, Department of Measurements, Electrical Devices and Static Converters, Faculty of Electrical Engineering, UNST POLITEHNICA Bucharest, Romania
[3] Professor, Department of Measurements, Electrical Devices and Static Converters, Faculty of Electrical Engineering, UNST POLITEHNICA of Bucharest, Romania
[4] Associate Professor, Department of Electromagnetic Systems, Faculty of Power Systems Engineering, UNST POLITEHNICA of Bucharest, Romania
[5] Associate Professor, Department of Measurements, Electrical Devices and Static Converters, Faculty of Electrical Engineering, UNST POLITEHNICA of Bucharest, Romania

where electricity grid access is limited due to geomorphological, economic, or infrastructural issues, including power line defects and other exceptional circumstances [1].

Another pressing concern is environmental pollution and its impact, which has directed the focus of engineering efforts towards renewable energy sources, termed 'green sources', and the integration of energy storage systems. Predominantly, these efforts utilise lithium-ion battery cells [1]–[4]. In recent years, there has been an emphasis on developing mobile electricity generation and storage systems, primarily using solar, wind, or fuel cell technologies for power generation and lithium-ion cells for energy storage [2], [5]. The Earth's receipt of solar energy, which is a thousand times greater than our total consumption, underscores the potential and the challenge of harnessing this resource [6].

Several studies have proposed solutions in this realm. For instance, research suggests a cost-effective solar panel-based system for heating water up to 60°C in winter [7]. Another study introduces a mobile system, based on photovoltaic panels, for powering an irrigation system [8]. Further studies detail mobile units for powering air-conditioning systems in refugee camps using photovoltaic systems, highlighting their mobility through trailer mounting and incorporating energy storage accumulators and conversion systems [9], [10]. An additional study presents a mobile system designed to power a van equipped with various appliances, powered by a combination of wind, photovoltaic panels, fuel cells, and supported by significant battery and hydrogen storage capacities [11].

These applications' mobility is crucial in energy storage and generation systems [12]. A recent trend is the development and utilisation of containerised systems, valued for their transport flexibility due to standard container dimensions. One study illustrates a containerised system that, using photovoltaic panels, wind energy, and a battery system, can power off-grid applications [13]. Other studies explore container-type mobile storage systems for energy provision, utilising photovoltaic panels in various configurations [14]–[16]. The issue of effectively storing and deploying retractable photovoltaic panel assemblies is addressed in a study proposing a solution based on Miura origami techniques for safer and more accessible storage and deployment [17].

In the project "Green Mobile Services for energy systems in the Smart City - SMARTELTER", the primary objective is to create a mobile power source for green energy generation, which can be effortlessly installed and accessed through mobile battery containers. This power source is designed to optimise the power-to-weight ratio while complying with transportation laws, utilising a standard 20-foot container to house all electrical components.

2. The Design Approach

The envisaged containerised system, in addition to housing a photovoltaic (PV) panel assembly, will incorporate a comprehensive conversion system. This system includes an inverter for transforming direct current (DC) into alternating current (AC), a rectifier to convert AC back to DC, and a mechanism to maintain optimal voltage for battery charging alongside necessary filters [18], [19]. These filters are imperative and must be strategically placed between each conversion stage.

To achieve the required power output and consider the spatial limitations of our container for panel storage (as detailed in Table 1), the system will utilise 75 PV panels. These panels will be organised into groups of five, forming independent strings. This arrangement facilitates swift transportation and installation at chosen sites, yielding an electrical power output of 2725 Wp per string.

The system's design includes three sets of strings. The first and second sets will each comprise six strings, while the third will contain three strings. Each set will be connected to its dedicated single-phase inverter-type conversion system. To optimise space utilisation and reduce costs, the system will employ three single-phase inverters instead of three-phase inverters. These inverters will be interconnected using a star connection with a shared neutral point, forming a three-phase voltage set. This set will then be channelled to the rectifier system. Subsequently, a boost-type conversion system will be employed to adjust the voltage level, ensuring it is appropriate for charging the batteries.

The Matlab/Simulink simulation environment will be utilised to analyses the designed system's behaviour.

Table 1

Solar panel characteristics

Characteristics	Value
Maxim power (P_{max})	545 [Wp]
Nominal voltage (V_{mp})	41,5 [V]
Nominal current (I_{mp})	13,14 [A]
Open circuit voltage (V_{OC})	49,4 [V]
Short circuit current (I_{SC})	13,95 [A]
Efficiency	21,3 [%]

The control system is a critical element in the proposed application, tasked with maintaining a precise 120° phase shift between the three inverters. This precise phase alignment is integral to forming an effective three-phase voltage set. The chosen strategy for this control system is vector control, which is specifically tailored to manage the output parameters – current and voltage – of each inverter.

In this system, the current and voltage from each inverter are first measured to create a comprehensive set of three-phase measurements. These estimated quantities are then transformed into the dq coordinate system; a method commonly used in vector control to handle AC quantities effectively. Within this coordinate system, the control operations are executed.

The control system employs Proportional-Integral (PI) type regulators, a choice driven by their proficiency in maintaining steady error values and quick response to changes. These regulators play a pivotal role in minimising the reactive component of the power while simultaneously maximising the active part of the voltage waveforms. This approach ensures that the voltage output remains stable and efficient, as illustrated in Fig. 1. Combining these elements – precise phase control, vector control strategy, and PI regulators – ensures the designed application's robust and efficient performance of the three-phase voltage set.

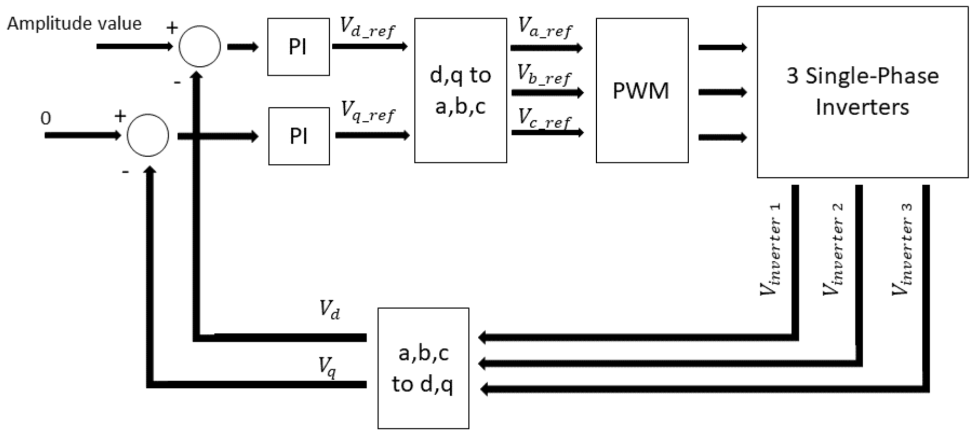

Fig. 1. Block diagram representation of the three single-phase inverters vector control

The control mechanism for the rectifier is designed to achieve a phase shift of 60° between each switch, and a 180° phase difference between switches located on the same arm. Through design calculations, a duty cycle of 0.38 has been determined as optimal for the boost conversion system within this setup.

In addition, the system incorporates a lithium-ion battery configuration, modelled using predefined blocks in Simulink. This configuration consists of eight lithium iron phosphate (LiFePO4) batteries. Each battery module is characterised by a nominal voltage of 64[V] and a capacity of 76.5[Ah], ensuring adequate energy storage and efficiency for the system's requirements.

Regarding the physical housing of the system, a standard six-meter container has been selected. This choice is based on space efficiency and standardization considerations, facilitating easier transport and deployment.

As previously mentioned, the PV panels' deployment process will be manual. This approach involves storing the panel strings in the container and transporting them to the desired location using a trolley. Once at the site, the panels will be positioned at an optimal angle of 40°. This specific angle and orientation are chosen based on studies [20-23] and also the container's storage space limitations, which are facilitated by specially developed adjustable limiters. These limiters ensure the panels are set up at the correct angle to maximise solar energy capture, as depicted in Fig. 2.

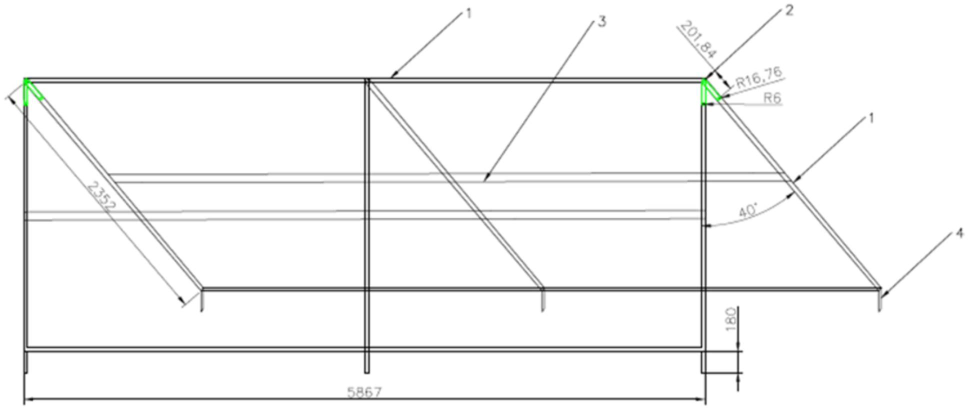

Fig. 2. Design model of on photovoltaic string, 1 - C type aluminium alloy profile, 2 - adjustable limiter in galvanised steel, 3 - C type aluminium alloy profile, 4 - aluminium alloy system for fastening in massive anchorages

To test the efficiency of the designed system after its modelling, the durations required to charge the batteries will be calculated, based on the results, for two cases:

- charging scenario 1 from 0% to 80% SoC
- charging scenario 2 from 0% to 100% SoC

3. Results and Discussions

Prior to the full-scale implementation of the deployable green energy supply container, a prototype at a 1:10 scale was constructed (as shown in Fig. 3). This prototype, crafted using 3D printing techniques, serves a critical role in the development process. It provides a tangible platform for analysing and refining the operational mode of the system.

The use of a scaled-down prototype is a strategic choice, allowing for a thorough examination of the design and functionality before committing to the construction of the full-size version. This approach enables the identification and rectification of potential issues in a controlled and cost-effective manner. The 3D printing technology employed in the creation of the prototype adds another layer of innovation, as it allows for rapid prototyping and easy modification of design elements.

This prototype serves as a crucial step in the development process, offering insights into the practical aspects of assembly, deployment, and operation of the containerised green energy supply system. The learnings derived from this smaller-scale model are invaluable in ensuring the success and efficiency of the final 1:1 scale construction.

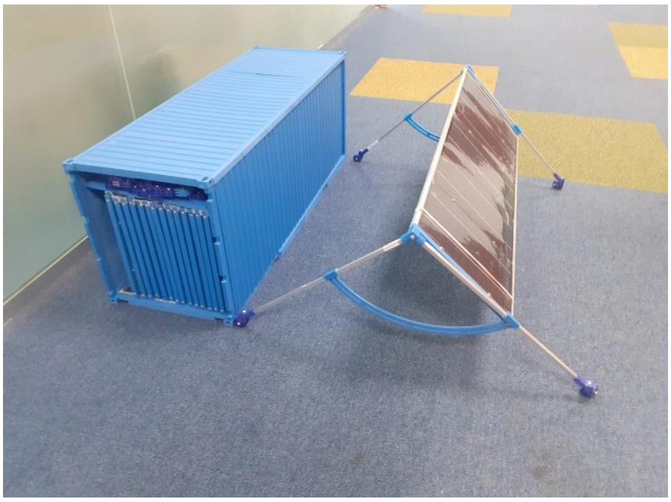

Fig. 3. Container model, scale 1:10.

The project's electrical system was meticulously designed using the Simulink environment, a choice that facilitated detailed and accurate modelling. Within this environment, predefined blocks were employed to represent various critical system components. These components include the three sets of PV panels, the single-phase inverters, the rectifier, the boost converter, and the pack of $LiFePO_4$ batteries. Figs. 4 and 5, as well as 9, visually represent these components within the Simulink environment.

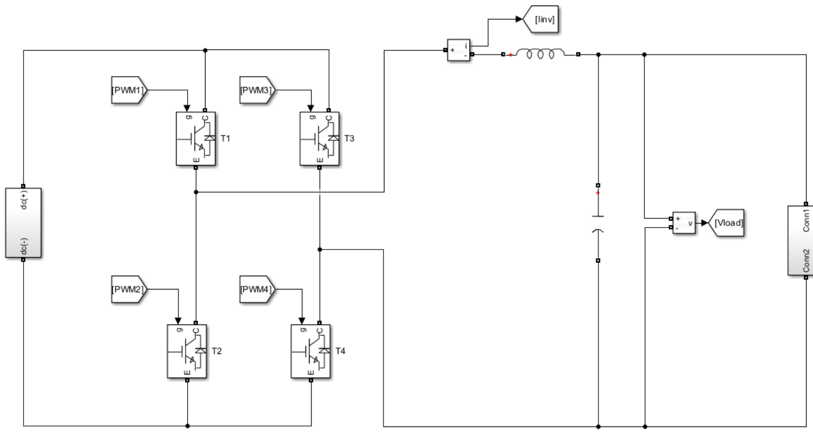

Fig. 4. Block diagram in Simulink for modelling a single-phase inverter

For the inverter system (Fig. 4), IGBT (Insulated-gate bipolar transistor) transistors were used as semiconductor elements. For the rectifier, thyristors were used, and for the boost-type conversion system, a diode and a MOSFET-type transistor were used (Fig. 4 and 5). [24]- [26]

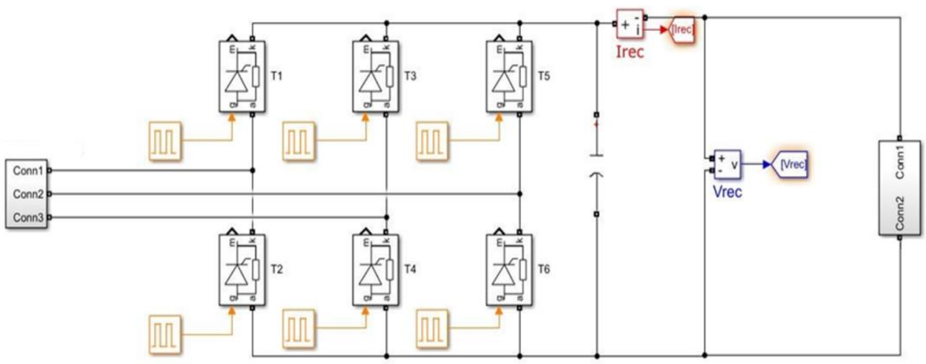

Fig. 5. Block diagram in Simulink for modelling the three-phase rectifier

Following the modelling of the primary components within the system, the inclusion of necessary filters was undertaken to optimise operational efficiency. These filters are essential in ensuring the smooth functioning of the electrical system, particularly in managing fluctuations and maintaining stability in the power output.

In the context of the PV panels, key environmental parameters were factored into the simulation to mirror realistic operating conditions. Specifically, a standard sun irradiance value of 1000 W/m^2 and an ambient temperature of 25 ^{o}C were assumed. These parameters are critical as they closely represent typical conditions under which the PV panels would operate, thereby ensuring that the simulation results are as realistic and applicable as possible.

Considering the high mobility of the solution, some deployment rules were established based on PV installation recommendations and simulations performed to determine the optimal placement. In this context, the efficiency of a single panel with a load of 4 Ω for different irradiance values was investigated in Fig 6.

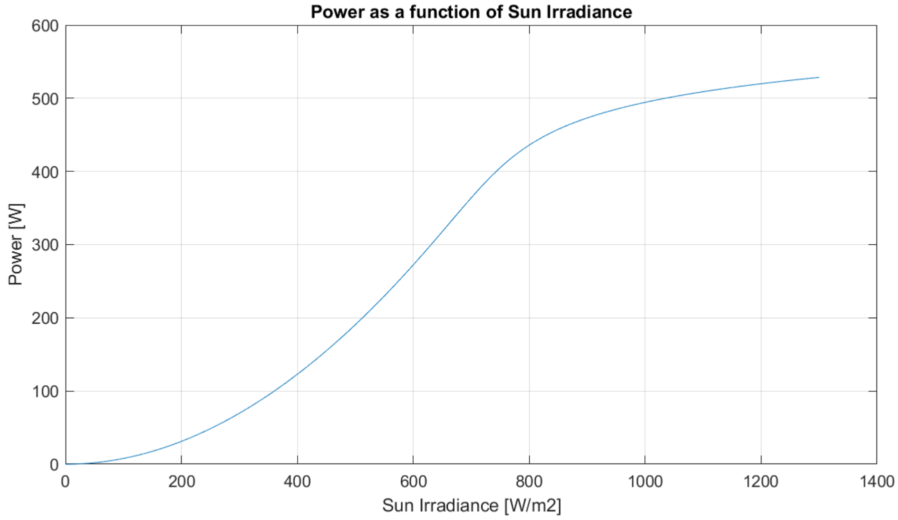

Fig. 6. Characteristic of the dependence of the power generated by a single PV panel with a load of 4 Ω as a function for different irradiance values

As can be observed, at lower irradiance, the output power of a single panel is highly reduced, threatening to underpower the battery bank if this condition persists for an extended period. So, to have a broader view of the whole system, two extra cases were considered and studied for standard submultiples of the irradiation 750 W/m^2, 500 W/m^2 with characteristics presented in Fig. 7 and 8.

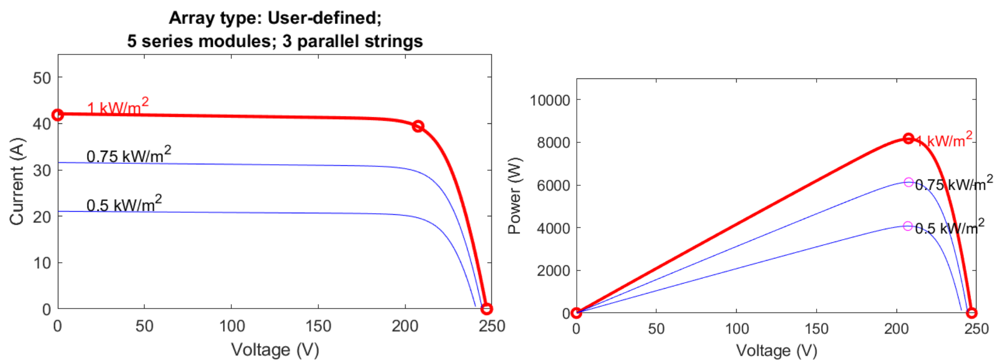

Fig. 7. Characteristic of the dependence of the current as a function of the voltage and of the generated power as a function of the voltage for set connected to the third inverter

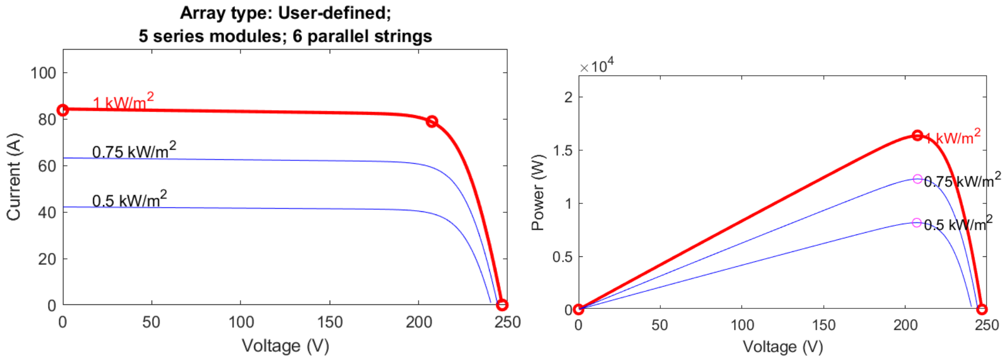

Fig. 8. Characteristic of the dependence of the current as a function of the voltage and of the generated power as a function of the voltage for sets connected to the first and second inverter

Based on the provided data, obtaining a minimal charge current of 40 A necessary for assuring an optimal charge of the battery pack in lower irradiance; a string of 5 modules connected in series and 6 strings connected in parallel are required. Also, all the panels should be placed facing South for this minimum connection to function correctly.

By incorporating these specific environmental and operational conditions into the simulation, the model achieves higher accuracy in predicting the system's performance in real-world scenarios. This thorough approach in modelling, inclusive of environmental factors and initial operating conditions, is vital for validating the design and ensuring its feasibility and reliability in practical applications. The final implementation of the simulation is depicted in Fig. 9.

For the battery component of the system, an initial State of Charge (SoC) of 10% was considered. This initial SoC is a crucial parameter in the simulation as it influences the charging and discharging cycles of the batteries and consequently affects the overall performance and efficiency of the energy storage system.

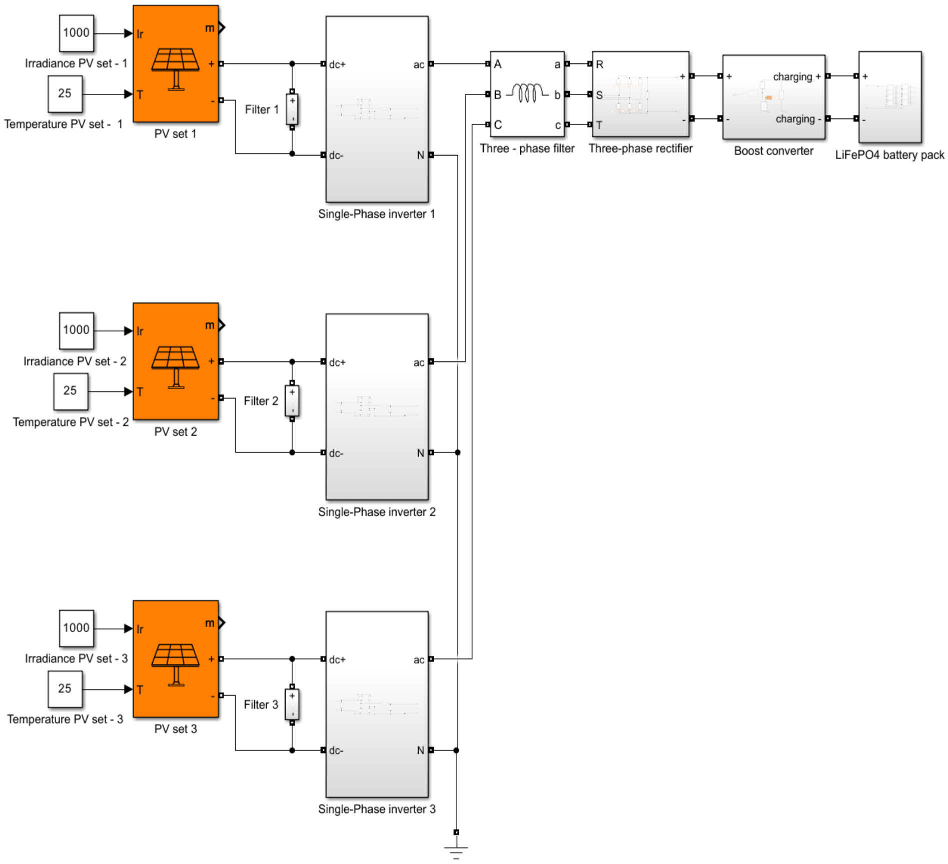

Fig. 9. Block diagram in Simulink of the final model for simulating the charging of the Li-Ion battery system using photovoltaic panels

The simulation of the operational behavior of the modeled system has demonstrated notable efficiency, as evident from the data presented in Figures 10 and 11. In the scenario characterized by solar irradiance of 1000 W/m², the currents and voltages of the three clusters PV panels remained consistently stable at 240 V and reached a maximum of 80 A. Conversely, for the instances of lower irradiance, specifically 750 W/m² and 500 W/m², a slight and negligible reduction in current was observed, while the voltage remained steadfast at 235 V with a peak current of 60 A, and 230 V with a maximum current of 40 A, respectively. Furthermore, the three-phase voltage and current waveforms consistently maintained a sinusoidal shape, with amplitude values attaining 26 A and 330 V in the first irradiance scenario. Meanwhile, in the second and third irradiance scenarios, the amplitude values reached 20 A and 195 V, and 13 A and 190 V, respectively.

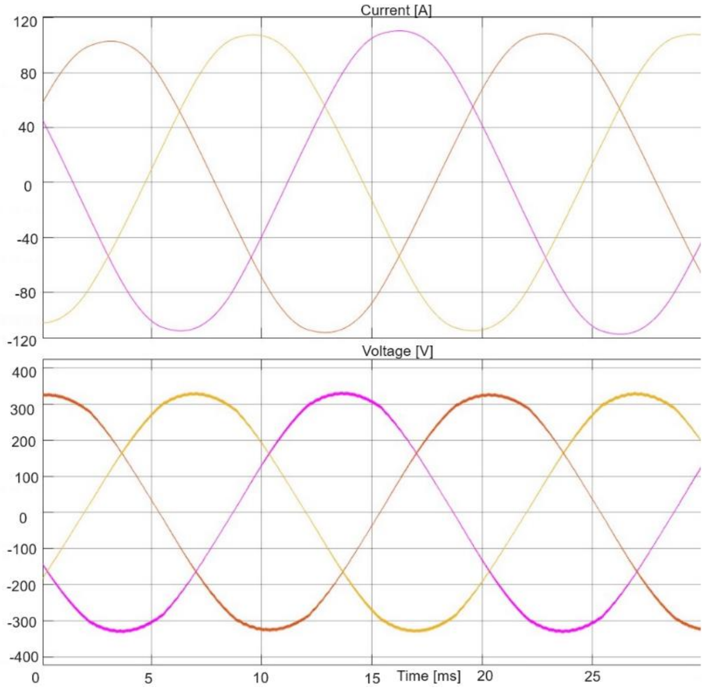

Fig. 10. Inverter’s output, a,b,c current and voltage forms for a sun irradiance value of 1000 W/m^2

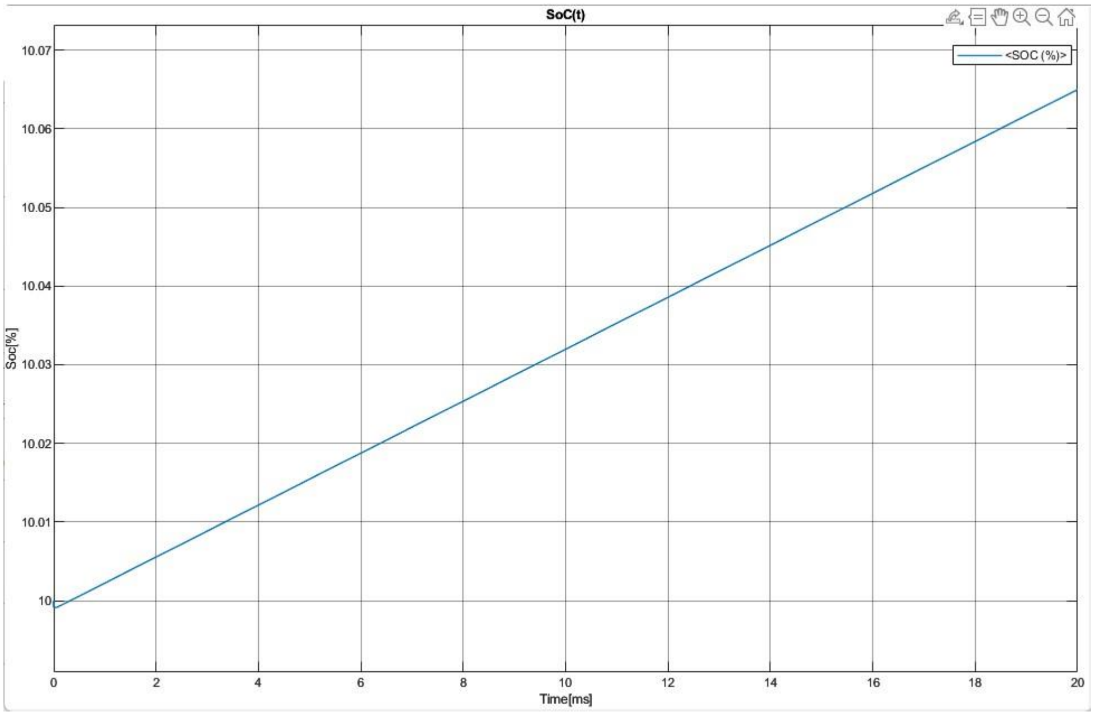

Fig. 11. Graphical representation of the evolution of batteries' SoC value

In terms of the rectifier's performance, the output voltage and current were recorded at 330 V and 24 A, respectively. The boost-type converter, tasked with adjusting the voltage for battery charging, successfully increased the voltage to 530 V, with a current of 10 A passing through each of the eight batteries. Crucially, these batteries' State of Charge (SoC) exhibited an increasing trend, with minor variations allowing the analysis to be done for only one battery and then extending it to all eight of them. Further research was conducted to calculate the durations required to charge the batteries under two different scenarios based on the data obtained from the simulations. As illustrated in the results in Fig. 11, a simulation over 20 seconds demonstrated an approximate increase in the SoC value of 0.065%. This increase is a basis for estimating the charging durations for the two outlined scenarios.

- For scenario 1 $t_{0\text{-}80\%} = 20s \cdot 80[\%]/0.065[\%] \approx 24.615s \approx 6h$ *and 50min*
- For scenario 2 $t_{0\text{-}100\%} = 20s \cdot 100[\%]/0.065[\%] \approx 30.770s \approx 8h$*and 30min*

4. Conclusions

This paper delineates the design of a containerised electrical energy storage system capable of providing energy derived from a retractable photovoltaic (PV) panel system. This system is developed as part of the "Green Mobile Services for Energy Systems in the Smart City - SMARTELTER" project.

The PV system is engineered to yield an electrical power of 40kWp. This output is achieved by maximising the number of PV panels that can be accommodated within a standard six-meter container, amounting to 75 panels. These panels are arranged into independent strings to facilitate ease of transport and rapid installation at various locations. The strings are categorised into three groups, with the first and second groups comprising six strings each, and the third group containing three strings. To enhance space efficiency within the container and reduce overall costs, the design substitutes three three-phase inverters with three single-phase inverters. These inverters are managed using a vector control strategy, maintaining a 120° phase shift between them. Additionally, a three-phase rectifier and a boost-type converter are incorporated to adjust the voltage appropriately for battery charging.

Before constructing the full-scale system, a 1:10 scale prototype was created, employing components fabricated through 3D printing techniques. This prototype was instrumental in testing and refining the system's design and functionality.

Subsequent simulations demonstrated that the system operates efficiently, sustaining optimal parameter levels throughout the conversion process and effectively charging the batteries. The durations required to charge the battery pack under two distinct scenarios were calculated using the data gleaned from these simulations. The first scenario, charging from an initial State of Charge (SoC) of 0% to 80%, was estimated to take approximately 6.8 hours ($t_{0\text{-}80\%} \approx 6.8h$). The second scenario, charging from an initial SoC of 0% to 100%, was projected to take around 8.5 hours ($t_{0\text{-}100\%} \approx 8.5h$).

Acknowledgment

This work was supported within the frame of the project Green mobile services for systems energy from the smart city SMARTELTER - 444/390120/13.03.2023, Cod SMIS: 156223

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