Design and Analysis of a Proposed EPS for the PEDAGO-SAT Nanosatellite

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***Abstract*—In space, solar radiation offers a significant advantage for energy generation because it is more intense and constant than on Earth. Without atmospheric filtering, the full electromagnetic spectrum, including visible, ultraviolet, and infrared radiation, reaches solar panels. This unfiltered radiation allows space photovoltaic systems to operate with higher efficiency. Solar panels are therefore widely used as the main energy source for satellites in orbit. However, despite the abundance of solar energy in space, their performance can still be affected by several environmental factors. Temperature variations, the angle of solar incidence, and occasional shading caused by satellite structures or orbital dynamics may lead to fluctuations in power output.**

To mitigate these effects and ensure optimal energy extraction, a control technique known as Maximum Power Point Tracking (MPPT) is imbedded in order to continuously adjusts the operating power of the solar panels by regulating the current–voltage (I–V) characteristics to track the point where maximum power is produced, even under changing conditions. This function is essential for maintaining the stability and efficiency of the satellite Electrical Power Subsystem (EPS), responsible for power generation, storage, and distribution. The objective of this study is to design, develop, and evaluate a robust EPS with reconfigurable solutions for the educational nanosatellite platform (PEDAGO-SAT), designed to improve power management reliability and efficiency in academic satellite missions, supporting education and research in space technologies.

***Keywords*—EPS, power budjet, Solar Panel, MPPT, Li-Ion battery, load-switch, Educational Nanosatellite, PEDAGO-SAT.**

I. Introduction

As part of the effort to improve national capabilities in space engineering and align with strategic technological development goals, we have launched an educational initiative centered on the implementation of a nanosatellite development platform, named ”PEDAGOSAT” [1]. This platform is designed to promote applied research and technological innovation within the university, focusing on embedded systems, telemetry, and space-based applications. Its primary objective is to train highly skilled engineers and researchers in spacecraft systems, capable of contributing to the full lifecycle of satellite systems, from subsystem design : Attitude Determination and Control System (ADCS) , EPS, OnBoard Computer (OBC), Communication Subsystem (COM), to final integration and orbital qualification, including design, integration, and functional testing phases, see Fig.1.

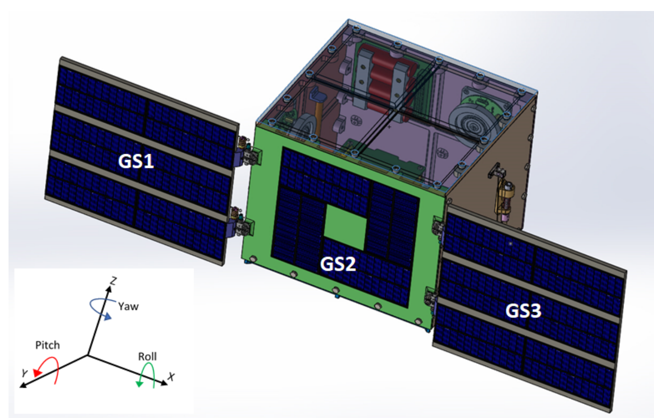

Fig. 1. A deployed view of PEDAGO-SAT.

In this work, special emphasis will be placed on the development, management, and optimization of the Electrical Power System (EPS), a critical subsystem that ensures satellite energy autonomy, on-orbit resilience, and operational stability of all embedded systems. In particular, dedicated tests will be conducted on the MPPT algorithms to evaluate their efficiency under varying illumination and load conditions, ensuring maximum energy harvesting from emulated solar arrays in the laboratory.

II. Sunlight intensity & Temperature effect in I-V characteristic

Understanding the influence of the satellite's orbit and attitude on the voltage, current, and temperature of the solar panels is crucial. As an illustrative case, consider the BIRD-4 nanosatellite, which was deployed into a 400km altitude orbit with an inclination of 51.6° and an orbital period of 92.6 minutes. In the absence of active attitude control, the satellite undergoes free rotation at approximately 3°/s on each axis. Consequently, the performance of the solar panels is affected by two main factors: the beta angle, which governs the alternation between eclipse and sunlight, and the attitude-induced rotational perturbations. As shown in the figure, at low beta angles, significant temperature fluctuations (˜48°C) occur during transitions between eclipse and sunlight, while smaller variations (˜4°C) result from the satellite's rotation on its axes.

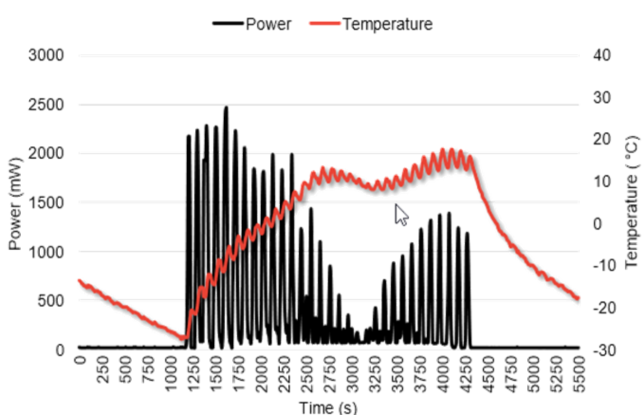

Fig. 2. Panel power and temperature fluctuation.

III. The EPS Subsystem Constitution

The basic EPS module [2], illustrated in Fig. 3, is composed of several functional submodules: the power generation submodule implemented on the backplane card [3], the power conversion and storage submodule (EPS0), the power regulation, distribution, and control submodule (EPS1).

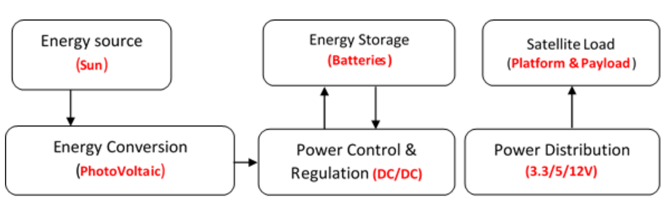

Fig. 3. Typical Diagram of EPS Nanosat [4].

The solar generator (SG) is an essential component of the EPS that ensures the electrical energy by photovoltaic conversion. In the space domain, two main strategies are generally adopted for the selection and sizing of solar panels onboard satellites, each adapted to the specific constraints of the mission. The first strategy involves oversizing the energy source from the design stage by installing solar panels capable of delivering more power than initially required, with the extra energy regulated by shunt modules that dissipate the unused power. This approach is particularly suitable for long-duration missions, such as geostationary satellites or deep space exploration missions, where the efficiency of photovoltaic cells degrades over time due to radiation and aging [3]. As performance decreases, the system can gradually reduce shunt usage to maintain a sufficient power level. This method has the advantage of anticipating panel degradation in the long term, ensuring stable energy production throughout the mission, and allowing for simpler energy management in the early phases. However, it comes with a higher initial mass and cost as a result of oversizing and intentional energy loss at the start of the mission, which lowers early efficiency. The second strategy focuses on precisely sizing the solar panels according to the mission's energy budget, without excess. It is particularly well-suited for short- or medium-term missions, such as low Earth orbit (LEO) satellites, CubeSats, or satellite constellations, where mission lifespan is shorter and mass and cost constraints are more demanding [4]. In this case, energy efficiency relies heavily on the integration of an MPPT (Maximum Power Point Tracking) system, a DC-DC converter combined with a tracking algorithm that continuously adjusts the operating point of the photovoltaic generator to extract the maximum available power despite variations in sunlight, temperature, or orbital conditions. This strategy offers continuous optimization of collected power, reduced size and weight, and lower costs, making it ideal for highly constrained platforms [5]. However, it provides less margin to cope with long-term panel degradation and introduces greater system complexity, relying heavily on MPPT efficiency. As a complementary solution to both approaches, incorporation of a solar panel orientation mechanism can significantly enhance performance by dynamically tracking the Sun's position to maximize incident irradiation in photovoltaic cells. Although this increases mechanical complexity and energy consumption, it helps optimize energy yield, particularly for missions requiring continuous and stable power production, such as observation satellites, telecommunications platforms, or scientific payloads in geostationary orbit [6].

In the PEDAGO-SAT EPS (Electrical Power Subsystem), we have recently finalized several key functionalities and defined the main stages of the power system architecture, as illustrated in Fig.4. The subsystem is implemented across two separate boards.

The EPS_0 board is responsible for managing the power delivered by the solar panels, following the MPPT (Maximum Power Point Tracking) stage and a DC-DC buck converter located on the backplane [2]. This stage provides a regulated output voltage of 16.8 V, used to charge two 4S Li-Ion battery packs [7]. EPS_0 also integrates battery management functionalities (BMS), including over-discharge protection, battery charge regulation, and control of the onboard heaters.

The EPS_1 board handles DC/DC power conditioning to generate multiple voltage rails (12V, 5V, -5V, and 3.3V) and

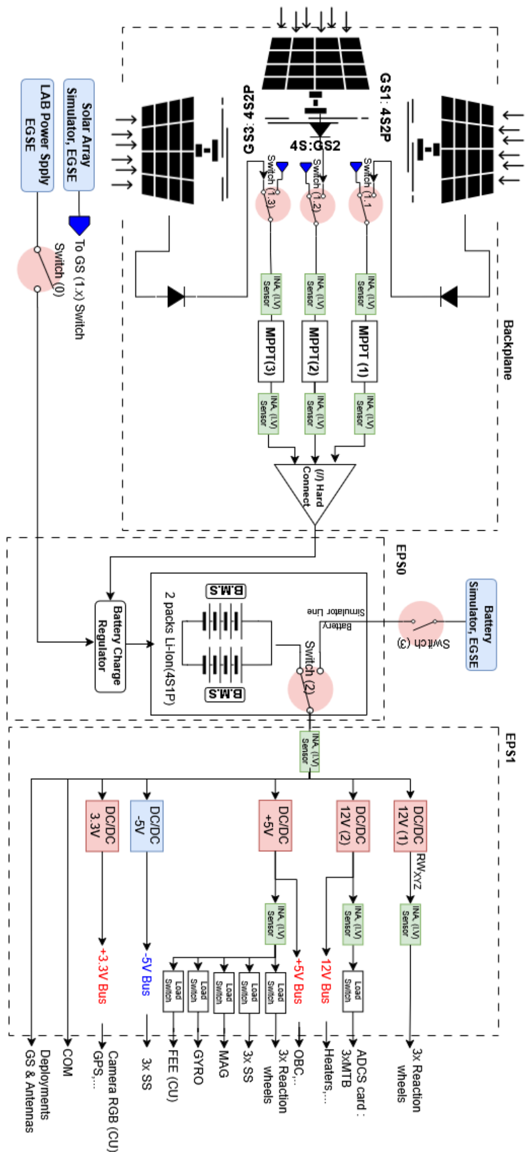

Fig. 4. The EPS adopted architecture.

manages power distribution to satellite subsystems. It includes ON/OFF switching control for five critical load channels. A dedicated high-power line is reserved for the deployment systems of the antennas and the left/right solar panels. INA components are used as voltage and current sensors at various points in the system, enabling the generation of current/voltage telemetry (TM) and derived power telemetry. Additionally, three switches are integrated to support multiple external power supply configurations during laboratory testing (solar panels, solar array simulator, AIT power supply, battery simulator).

IV. The Solar Generator (SG) in PEDAGOSAT

The architecture proposed in PEDAGOSAT is based on 3 solar panels installed in the +Y wall, each independently managed by its own MPPT module as illustrated in Fig.4. Our solar generator is designed to be folded during the storage and launch phases to minimize the volume occupied. Once the satellite reaches its operational orbit, a deployment mechanism is activated to align the solar panels into their functional configuration [8]. To emulate this phase in the laboratory, this mechanism is integrated into the two lateral panels (left and right), while the central panel remains fixed directly on one of the faces of the nanosatellite, as shown in Fig.1 [9].

For initial prototyping tests, we selected a monojunction polycrystalline silicon solar cell to be assembled and integrated into our panels [10]. This type of cell, with dimensions of 110 mm × 60 mm, is widely available on the local market and is particularly well-suited for small-scale academic projects like ours. It delivers a maximum power of 1 W, with an open-circuit voltage of 6 V. In direct sunlight, the cell provides a continuous voltage of 6 V and a current of approximately 167 mA at its maximum power point; see Fig.5. To fulfill the power requirements of our mission, multiple cells and panels are connected in series and/or in parallel, allowing adjustment of the output voltage and current according to the operational modes.

It is important to note that a large number of cells were characterized to select the appropriate number of cells to build our solar panels [10]. Fig.6 presents typical I(V) and P(V) data of selected cells. The cell selection methodology was based on three key electrical parameters. First, priority was given to cells that deliver maximum power (Pmax) between 0.8 and 1 W to ensure adequate energy generation capacity. Second, the short-circuit current (Isc) was verified to lie within the range of 0.15 A to 0.20 A to guarantee current uniformity for series integration. Finally, the open-circuit voltage (Voc) was checked to be between 6.34 V and 7.32 V to ensure compatibility with the required voltage level of the power subsystem.

V. Maximum power tracking mechanism (MPPT)

The power characteristic curve of a photovoltaic generator (PVG) represents the relationship between output power and voltage under specific irradiance and temperature conditions, see Fig.5. This curve typically shows that the power initially increases with voltage, reaches a peak known as the Maximum Power Point (MPP) and then decreases as voltage continues to rise. The MPP corresponds to a unique operating point defined by the voltage V_{MPP} and current I_{MPP}. Due to environmental changes such as sunlight intensity and temperature, the posi-

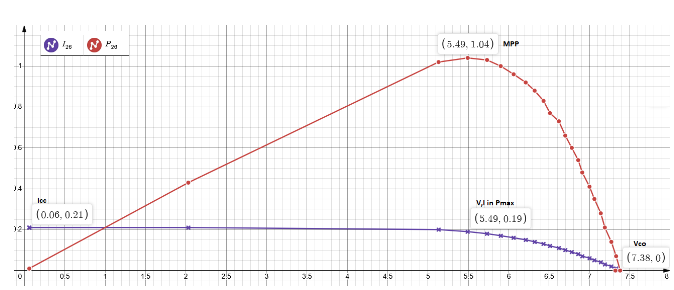

Fig. 5. Characterization test to select solar cells.

V_{26}	I_{Cmd}	I_{26}	P_{26}	V_{26}	I_{Cmd}	I_{26}	P_{26}
7.32	0	0	0	6.51	0.13	0.12	0.77
7.38	0.01	0	0	6.43	0.14	0.13	0.83
7.33	0.02	0.01	0.07	6.32	0.15	0.14	0.88
7.27	0.03	0.02	0.14	6.21	0.16	0.15	0.92
7.19	0.04	0.03	0.21	6.06	0.17	0.16	0.96
7.14	0.05	0.04	0.28	5.9	0.18	0.17	1
7.06	0.06	0.05	0.35	5.73	0.19	0.18	1.03
7	0.07	0.06	0.41	5.49	0.2	0.19	1.04
6.91	0.08	0.07	0.48	5.13	0.21	0.2	1.02
6.86	0.09	0.08	0.54	2.03	0.22	0.21	0.43
6.78	0.1	0.09	0.6	0.06	0.23	0.21	0.01
6.7	0.11	0.1	0.66	0.06	0.24	0.21	0.01
6.62	0.12	0.11	0.73	0.06	0.25	0.21	0.01

Fig. 6. Typical I(V) solar cell data collected from test.

tion of the MPP shifts over time. To continuously extract the maximum available power from the PVG, a DC-DC converter with a Maximum Power Point Tracking (MPPT) algorithm is required. This system dynamically adjusts the voltage and current to track the MPP in real time, ensuring optimal energy harvesting from the solar panels.

VI. The Final Configuration of the PEADAGO-SAT Solar Panels

The three built solar panels are configured, as illustrated in Fig.7, as follows: each of the two lateral panels consists of a panel of cells in a 4S2P configuration (four cells in series, duplicated in parallel) that produces 8W, and they are connected in parallel with the central panel, which is configured as 4S (four cells in series) that deliver 4W. This setup results in a final solar generator configuration of 4S5P. This architecture allows for a maximum power output of 19.9W with a current of 0.9A.

Fig. 7. Final assembly of the solar panels.

VII. MPPT methods & Algorithm

In the context of nanosatellites, where available power is very limited (typically some ten watts), the choice of the MPPT (Maximum Power Point Tracking) method must optimize both energy efficiency, implementation simplicity, and low computational resource consumption. Among the various techniques, the Perturb and observe method (P&O) is often preferred. It offers a good compromise between performance, robustness, and ease of integration in embedded microcontrollers, even though it generates slight oscillations around the maximum power point. It may be less efficient in the case of rapid variations in the operating point, but this remains acceptable in space, where sunlight transitions are generally more predictable. In this case, it is recommended to adjust the perturbation frequency and the variation step to limit energy losses and the load on the embedded processor.

For platforms with more computational resources, the Incremental Conductance (InCond) method provides a more accurate alternative in dynamic environments, at the cost of higher algorithmic complexity.

In ultra-simplified or non-critical configurations, the Fractional Open Circuit Voltage (FOCV) method or the Fractional Short-Circuit Current (FSCC) method may be considered. Both consume very few resources but require periodic interruptions to measure either the open-circuit voltage or the short-circuit current, limiting their accuracy.

Finally, more complex approaches such as fuzzy logic or neural networks should be avoided in nanosatellites, as they are unsuitable for very low energy budgets and embedded computation constraints.

VIII. Synchronous Buck Converter

DC converters are static electrical devices used to modify voltage, current, or frequency in a power system. In our application, the DC converter will be directly connected to the photovoltaic generator (one of each solar panels). It will act as a dynamic electrical load that continuously regulates voltage and current to maintain operation at the photovoltaic system's maximum power point, thereby ensuring efficient and optimal energy use. For the EPS (Electrical Power Subsystem), several types of buck converters can be considered: the asynchronous buck, which is simple and low-cost but less efficient due to diode losses [11]; the synchronous, offering high efficiency and better thermal performance but requiring more complex control circuitry [12]; the multiphase buck, ideal for high-current or distributed systems due to its reduced ripple and improved thermal distribution, though it increases design complexity and component count; and the digital buck converter, which uses a programmable digital controller to offer adaptive, flexible regulation , at the cost of added software and design complexity. The choice among these depends on the mission requirements, power constraints, and the balance between efficiency, complexity, and reliability.

To optimize our MPPT module, we selected a synchronous buck converter, an improved version of the traditional buck converter. Unlike the basic asynchronous design that uses a single switch and a diode, the synchronous version ,see Fig.9, incorporates two MOSFETs (Q1:High-side and Q2:Low-side) controlled in a complementary way with dead time, significantly reducing switching losses and improving overall efficiency, an essential factor in space systems where power is limited and thermal constraints are critical.

IX. Power Distribution unit (PDU)

The Power Distribution unite (PDU) is responsible for conditioning, distributing, and managing electrical power within

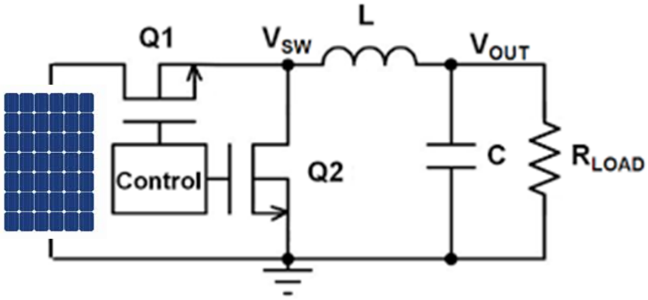

Fig. 8. Synchronous Buck Converter topology [11].

the overall system. It is located in the EPS1 card, as illustrated in Fig.3. The PDM incorporates multiple DC/DC converters to generate the required voltage levels, including +12 V provided by two independent buck converters, as well as +5 V and +3.3 V outputs. Load switch modules are employed to enable or disable power delivery to specific subsystems. Current, voltage, and temperature sensors are integrated to ensure safe and efficient real-time monitoring of power distribution for each input and output levels. Two microcontroller units (MCUs) are used to manage PDM operations, acquire measurement data, and handle external communication with the onboard computer (OBC) via the I²C bus [12].

X. The Electrical storage unit (battery)

The battery pack selected for this mission is based on Lithium-Ion technology using 18650-format cells arranged in a two string of 4S1P configuration [7]. The pack is charged through the battery charge regulator and provides a nominal output voltage of 16.8 V to meet the subsystem power requirements, with a total capacity of 3000 mAh. The battery system integrates cell monitoring, passive balancing, and thermal control functions [13].

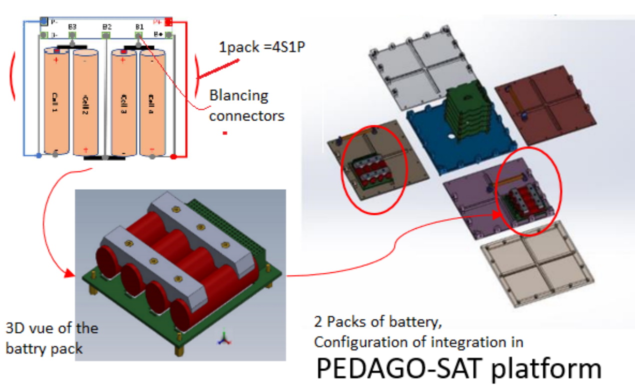

Fig. 9. Battery pack assembling configuration [9].

Note that the PEDAGO-SAT platform is frequently connected to an Electrical Ground Support Equipment (EGSE) unit supplying a stabilized laboratory power source. Under this configuration, the energy storage system is mainly used to support functional testing. Consequently, increasing the number of parallel cells (nP) to guarantee a minimum depth of discharge (DoD), as required in flight missions, is not necessary in this case [1]. In addition, a battery simulator implemented using a switch is envisaged to emulate battery behavior during specific test scenarios.

XI. Simulation of Solar Panel & MPPT Module Characteristic

To analyze and visualize the voltage, current, and power curves delivered by the photovoltaic panels, as well as the behavior of the main DC/DC converter and the chosen maximum power point tracking (MPPT) algorithm, we used MATLAB-Simulink. This software allowed us to accurately simulate the expected operation of our solar generator. As a first step, we implemented a selected converter controlled by a tracking method to regulate the converter's operation. For the PEDAGOSAT's EPS, and in order extend the range of power operating cases and converter topologies to be addressed for reinforcing the educational and research stadies aspect of the platform, several configurations have been implemented through the reconfiguration and interconnection of photovoltaic panels under voltage or current mismatch conditions and combined with dynamic changes in converter topology(buck, boost, or buck–boost converters). Fig 10 illustrates one of the simulation case studies investigated, namely the boost converter configuration.

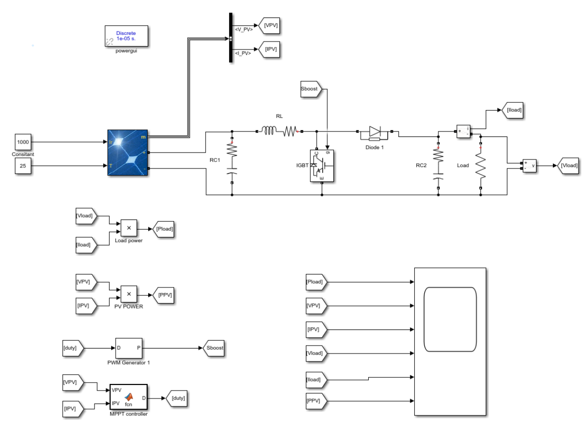

Fig. 10. EPS MATLAB-Simulink implementation [11].

XII. Implementation & Characterization tests

To validate the sizing of the DC-DC converter configuration and the MPPT approach selected for implementation, preliminary tests were carried out on a test bench. The work involved implementing the chosen Buck converter architecture using laboratory components and development boards. Measurement instruments, a laboratory power supply simulating satellite power generation conditions, and an electronic load ,see Fig.11, representing the typical consumption of a space system were used to closely replicate real operational conditions. In addition to validating the electrical behavior, this prototyping phase also served as a basis for transitioning toward the final EPS design. The results obtained from the test bench allow the identification of critical components and performance constraints, which guide the selection of Commercial Off-The-Shelf (COTS) components suitable for integration into the finale model. Particular attention is given to components that can withstand the space environment. Consequently, the selected COTS devices must undergo a dedicated qualification campaign to ensure reliability and compliance with mission requirements before being incorporated into the final EPS architecture.

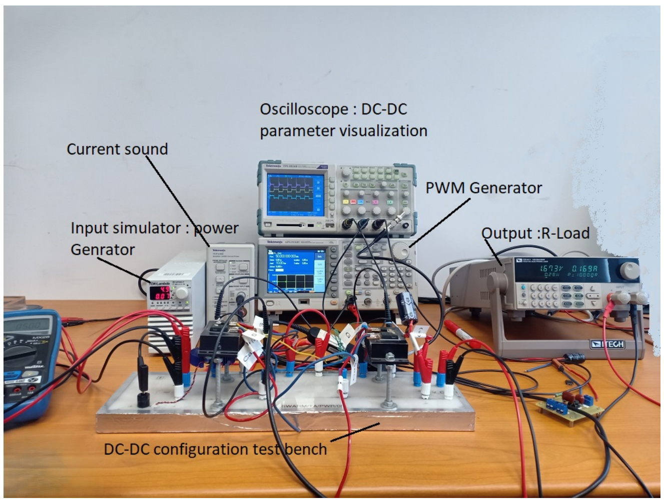

Fig. 11. Test bench used to validate the design.

CONCLUSION

The work carried out has progressively brought us closer to the final solutions to be adopted on the design of the Electrical Power System (EPS) for the PEDAGOSAT nanosatellite. The study progressively leads to the selection and development of the main EPS subsystems, including solar panel configuration, maximum power point tracking (MPPT) algorithms, DC–DC converters, and load-switching architecture, which will ultimately be integrated into the satellite's power system.

The methodology for selecting solar cells was based on key electrical parameters, ensuring adequate power generation, current uniformity for series connection, and voltage compatibility with the EPS requirements. Compact solutions that combine the MPPT function and buck conversion into a single unit are also investigated. However, the final design is intentionally based on a modular architecture to provide an educational platform for students and newly recruited engineers, allowing them to explore and understand each technical function independently.

For the power distribution unit (PDU), switch-load ICs were chosen to provide precise On/Off control of the loads while enabling a low-cost development of the PDU, ensuring reliable power management across the satellite subsystems. In this context, the Perturb and Observe (P&O) algorithm was investigated for maximum power point tracking, several DC/DC converters were considered and simulated. To facilitate analysis and understanding of their operating principles, a buck converter was implemented using discrete basic components. This approach ensures both functional performance and pedagogical value in the proposed EPS design for the PEDAGOSAT nanosatellite. Future work will focus on investigating additional operating cases and validating them in order to develop reconfigurable solution.

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