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A COMPREHENSIVE REVIEW OF POWER ELECTRONIC CONVERTER TOPOLOGIES FOR CUBESAT

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Abstract: CubeSats are designed to carry out space research by students of various universities. The electrical power system of CubeSat handles power generation, energy storage, and distribution to all other subsystems of CubeSat. Power Electronic Converters are used for power conversion as per the power budget. In this review paper, Various DC-DC converter topologies along with techniques used for controlling and maximum power point tracking have been discussed. The subsequent converter topologies need to focus on reliable efficient fault tolerance while reducing passive elements in the circuit.

Index Terms **- Electrical Power System, CubeSat, DC-DC converters.**

I. INTRODUCTION

CubeSat belongs to the family of nanosatellites, mainly built to carry out space research in Low Earth Orbit (LEO). The size of CubeSat (1U) resembles the size of the Rubik cube with sides 10cm*10cm*10cm. Similarly, mass is restricted to 1.33 kg per unit. These kinds of satellites operate at an altitude of 160km to 1000km. To operate these attitudes CubeSat must be designed to handle a harsh space environment.

The structure of the CubeSat is designed as per the mission. All subsystems must be tolerant to radiation and a wide range of temperatures. Unfortunately, there are the least chances of repairing it while in operation. Thus, CubeSat's each module and sub-modules should be reliable and efficient. In LEO, CubeSat components have a typical temperature lies between −40 to 80 °C [41]. The temperature control within the CubeSat is achieved by both passive and active thermal control units [42].

1.1 Electrical Power System

Power for the CubeSat can be generated by converting light, or chemical energy into electrical energy. Based on the mission of CubeSat Power budgeting is done. As per the power budget, EPS will be designed. Due to mass and size restrictions, Commercial off-the-shelf (COTS) components are often used for design fabrication. Since EPS powers the CubeSat and failure of which leads to catastrophic damage to the whole CubeSat.

1.2 Photo Voltaic Cell

Solar energy is preferred for CubeSat with a power demand of less than 1kW [30]. The major challenge is to utilize CubeSat's surface area effectively [32]. In earlier times, Silicon-based photovoltaic cells gained a major place in satellite power generation units. As technology progressed higher efficient multi-junction solar cells replaced silicon-based cells [31]. Solar cells are selected by considering the performance, economy, and efficiency of the cell along with the dimension of the cells. These cells built from In GaP/GaAs/Ge got efficiency ranging from 23% to 30%, which is double the efficiency of Si cells. Recent advancements include a spring-loaded solar array, arrays with thermal knife mechanism with deployment switch used to prevent operation before launching.

The Photovoltaic panels are either placed on the surface or deployed externally. The combination of these two types of mounting can also be seen [43]. Temperature and Solar Irradiance determine the panel power generation capability [44].

1.3 Power Storage Unit

The power storage unit is critical for space missions as it supplies power when PV panels fail during the eclipse. If the power storage unit fails to provide backup, then mission failure is guaranteed. Batteries are selected by considering power budget, mission life and thermal factors [11]. All components used in CubeSat must withstand a harsh space environment. Therefore, COTS batteries and their components passed through a rigorous test to check suitability for the space environment [33].

Table 1.1 Comparison of Battery Technology

Battery Parameters	Battery Chemistry →			
	NiCd	NiMH	Li-ion	LiPo
Discharge terminate voltage (V)	1.00	1.00	2.80	2.80
Charge terminate voltage (V)	1.55	1.55	4.20	4.2
Nominal discharge voltage (V)	1.25	1.25	3.70	3.70
Operational Temperature (° C)	-20 to 50	-10 to 50	-20 to 60	-20 to 60
Volumetric energy (Wh/l)	50-150	140-200	150-250	150-300
Gravimetric energy (Wh/kg)	40-60	30-80	100-200	130-250
Gravimetric Power (W/kg)	150-200	150-1000	200-500	>1000
Sensitivity to Overcharging	Medium	High	Very high	Very High
Disadvantages	Suffer memory effects	Less life cycle	Higher cost	Higher cost
Advantages	Good space heritage	Capable of high discharge currents	Higher voltage	Lighter

Until the 1980's Ni-Cd Batteries were the workhorse for CubeSat Power backup, which is then replaced by Ni-H2 batteries due to their long-life cycle and resiliency to abusive operating conditions [34]. Lithium-ion (Li-ion) batteries have become NASA's favorite choice after 2003 [34]. These batteries satisfied mass and volume restriction CubeSat and also provided high specific energy and energy density. Li-ion cell comes in different variants like coin cells and cylindrical cells. Coin cells acquire lesser volume, weight and low specific energy. Cylindrical cells got high energy density and specific energy. The major challenges are to develop an energy storage system to work at low temperatures. Usage of Lithium Polymer (Li-Po) batteries has also been observed to overcome a worse operating atmosphere [37].

Advancements in supercapacitors are intended to develop low-temperature performance characteristics with high specific energies. The combination of Li-ion and super capacitors into a single storage unit supplies higher specific energy and handles overload conditions. Extended Battery life is another advantage of this kind of combination. CSUNSat1 is a 2U CubeSat deployed in space to check the hybrid energy storage system [38]. Successful mission CSUNSat1 opened doors for further research [39].

1.4 Power Conditioning Unit

The power Control Unit (PCU) regulates PV panels, batteries and load. Efficient power extraction is much needed to extract power from solar panels thus Maximum Power Point Tracking (MPPT) techniques are implemented.

II. Classification of Electrical Power System

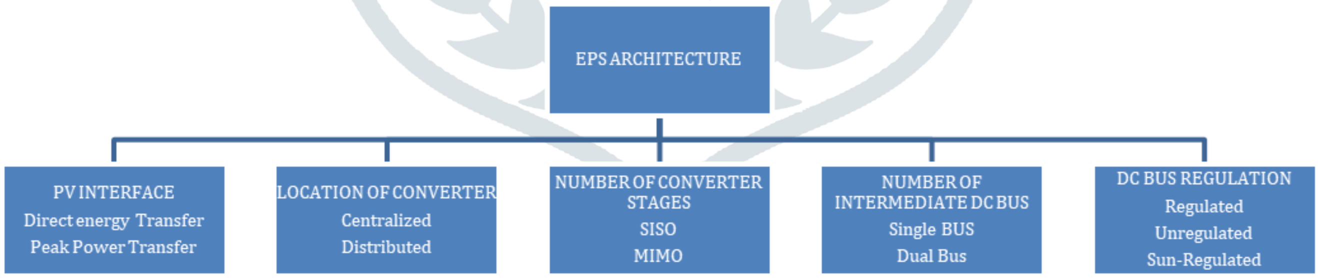

Fig. 2.1 Classification of EPS Architecture

EPS architecture can be categorized based on PV interface, bus voltage regulation, power converter location and number of conversion stages as depicted in Figure 2.1. Based on the PV panel interface EPS architecture is divided into Direct Energy Transfer (DET) and Peak Power Transfer (PPT).

1.Direct Energy Transfer:

Diodes are connected in series with PV panels to transfer energy directly to either storage or load. To avoid over-current shunt regulators are connected but underutilization of PV panels is the prime drawback of this interface.

2.Peak Power Transfer:

PV panel is integrated with choppers to achieve MPPT.

The Digital microcontroller (MCU) or analog controllers can be used for this task [46]. MCUs are robust, simple and flexible but they may fail due to radiation.

The EPS architectures are again classified into Centralized and decentralized architectures as per the location of power converters.

1.Centralized architecture:
Power converter and controllers are mounted in the single PCB which connects to all submodules. In this architecture, the component requires less space and hence compact design can be achieved. Even though it has a simple architecture failure of one component may result in total failure of EPS [47].
2.Decentralized architectures:
In this architecture, the power converters are laid near individual subsystems. In [2], behind PV panels the MPPT converters are deployed which saves space for other components. The advantages of these architectures are redundancy, modularity, and reusability for multiple missions [49].

Depending on the number of power conversion stages, the EPS architectures are classified as Single-stage and Multistage architectures.
1.Single-stage Power converters:
The single conversion stage is employed to get Multiple Input Multiple Output (MIMO). Advantages are higher conversion efficiency, fewer components used, and leaves smaller footprint. Disadvantages are complex control systems and lower performance under various operating conditions. It has a lot of scope for research.
2.Multistage Power Converters:
Single Input Single Output (SISO) based conversion got simple control and better performance compared to single-stage architecture. However, the main downside is higher component count and losses due to multiple stages.

III. SURVEY ON POWER CONVERSION TOPOLOGIES

In the initial stages of development, On Semiconductor-based low dropout regulator chips have been used but the efficiency of the converter was 40% thus there is a need for an advanced topology design which will meet design criteria [29]. When it comes to switching converters boost converter-based topologies are used for space applications [28]. Conventional boost converter provides higher reliability and can be designed with a smaller number of components. Whereas a two-inductor boost converter will provide continuous input & output currents. Besides, a boost converter with ripple cancellation topology reduces the mass of passive elements. Even though such converters have got added advantages yet they are far from perfect due to the increased number of semiconductor devices [28].

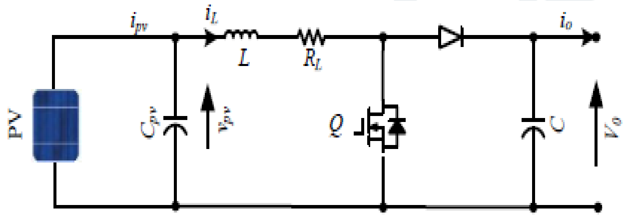

Fig. 3.1 Boost Converter [1].

Samrat Acharya et al. [1] implemented boost converter as shown in Figure 3.1 that will be connected to PV cells to step up the voltage from 4.8V to 7.4 V to match bus voltage. The triple junction PV cells with an efficiency of 30% will be the primary power source of CubeSat. Perturb and Observe (P&O) MPPT algorithm is implemented to track maximum power from PV cells. The lithium-ion battery is connected to a 7.4V bus. The proportion-integral-derivative (PID) Controller is designed by performing a small signal analysis to control the duty cycle.

Amarendra Edpuganti et al. [2] proposed a single inductor-based multiport converter which consists of half-bridge modules connected in series replacing inductors in the converter. P & O based MPPT converter and proportional-integral (PI) controller are used. Efficiency is low and complexity in Gate driver circuits due to higher switch count.

V. Pooler et al. [3] used LT3479 boost converter IC which feeds LT3652 MPPT IC. The MPPT IC provides low temperature protection. Li-Ion batteries made of four cells are used for energy storage. DS2782 IC-s are used for battery monitoring. While selecting PV panels higher efficiency and higher fill factor have to be selected. Based on power requirement hybrid series-parallel module connection is employed. Boost converter is connected to the solar panel to get constant bus voltage. The expected features from the converter are efficiency higher than 85%, soft start and simplicity. A battery charging module is used unlike the Schottky diode to limit reverse current [4].

Rohit Joshi et al. [5] conducted experiments using switching regulators and linear regulators for the Iinusat-1 nanosatellite. LM2576 IC switching regulator has been used to step up the voltage. Experimental results show that switching regulators can produce higher efficiency when compared to linear regulators.

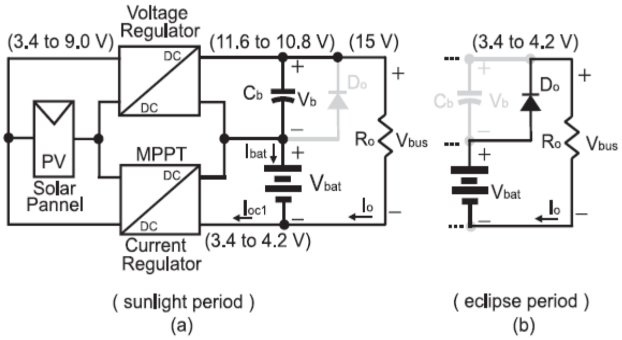

Fig. 3.2 Boost converter with stacked capacitors [6].

Everson Mattos et al. [6] proposed boost converter and battery charging converter connected to a stack of output capacitors as illustrated in Figure 3.2. The battery charge current reference is provided by the P&O algorithm and controlled by the PID controller.

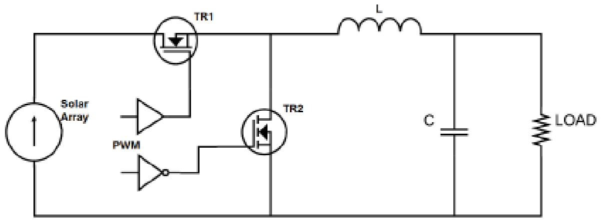

Fig.3.3 Synchronous Buck Converter [7].

Jesus Gonzalez et al. [7] proposed the usage of synchronous buck converter for CubeSat as seen in the Figure 3.3. LiFePO4 batteries of two stacks have been used. By considering various operating conditions efficiency of buck converter is calculated for various cases to get higher efficiency both in theory and practical [7].

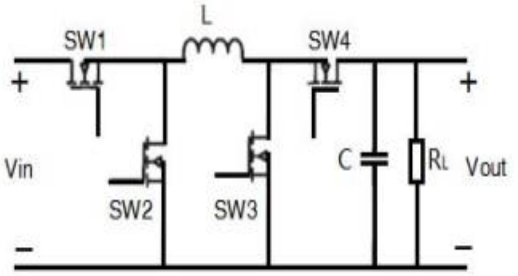

Fig. 3.4 Four Switch Buck-Boost Converter [8].

Mihir Shah et al. [8] implemented four-switch buck-boost converter (FSBB) as shown in Figure 3.4 along with an advanced controller to achieve stable results in power conversion and control. The proposed topology is working in real-time thus reliable operation can be expected. Experimental results confirmed that Solar cells supplied power to the load very efficiently.

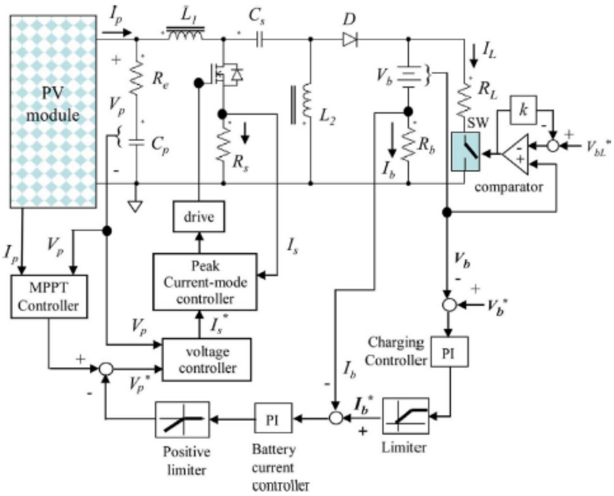

Fig.3.5 SEPIC Converter [10].

Li Peng et al. [9] implemented synchronous buck-boost converter topology using GaN FETs (Gallium Nitride Field Effect Transistor) to get higher efficiency. Digital controllers like MPPT controllers and closed loop Fixed digital point load converters are implemented.

Padma Priya S et al. [10] proposed SEPIC converter for CubeSat as detailed in Figure 3.5. The major advantage of this converter is its main energy storage element coupling capacitor. Based on the PV power generation, the Battery State of Charge, and load controllers are designed to operate.

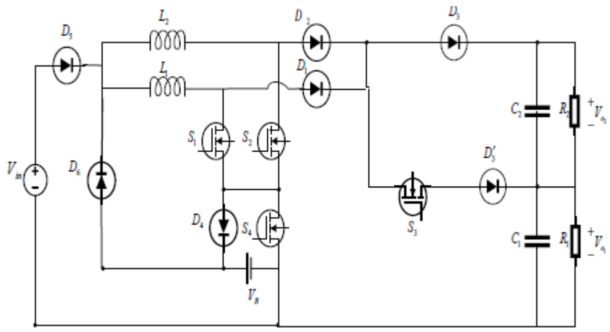

Fig.3.6 Interleaved Boost Converter [11].

Jafar Gholami Gorji et al. [11] proposed Dual input dual output (DIDO) interleaved boost converter as shown in Figure 3.6. The major advantage of this topology is reduced input source ripple current and grounded battery bases hence the noise battery life will be extended.

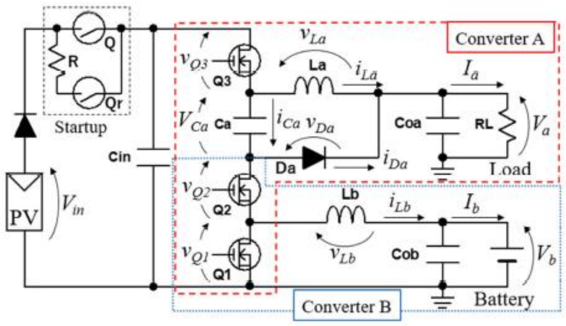

Fig. 3.7 Three Port Converter [12].

Hikaru Nagata et al. [12] proposed a novel nonisolated Three Port Converter with unidirectional as well as bidirectional pulse width modulation as shown in Figure 3.7. The Hill climbing method is implemented to track MPP. The miniaturized inductor has been used. Due to integrated techniques system is simpler with fewer switch counts. To reduce voltage stress of switches capacitors connected in series. Reliability and narrow operating are critical drawbacks as the system is complex.

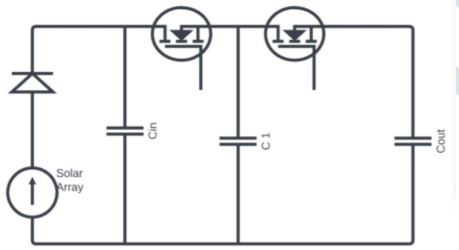

Fig.3.8 Switched Capacitor Buck Converter [13].

Pradeep K et al. [13] proposed hybrid switched capacitor topology as depicted in Figure 3.8. Using pulse-width modulating technique closed-loop control is achieved.

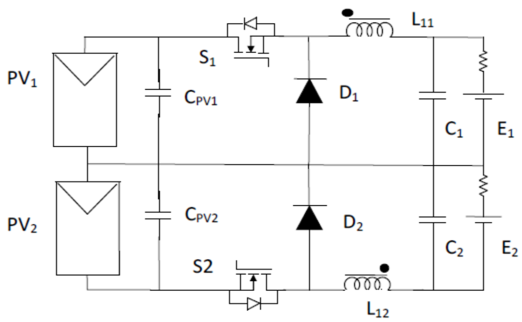

Fig. 3.9. Buck Converter with Coupled Inductor [14].

Jatin Faujdar et al. [14] proposed buck converter with coupled inductors to reduce ripple current and components count. Incremental Conductance (InC) MPPT technique is used. Fast computing microcontrollers are used as controllers.

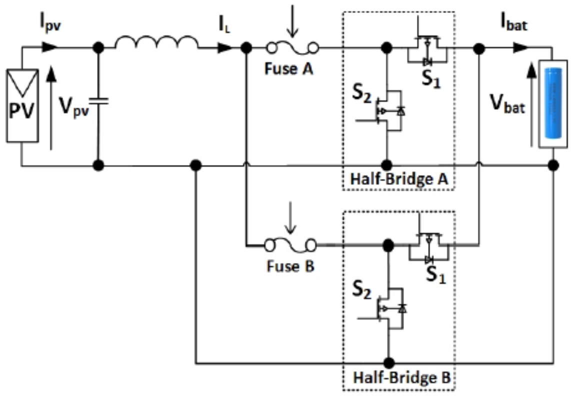

Fig.3.10 Fault Tolerant Converter [15].

Amarendra Edpuganti et al. [15] introduced fault Tolerant Topology as depicted in Figure 3.10. By utilizing available free space behind the PV panels and a smaller footprint GaN FETs switches are used for converters to reduce weight. The fault diagnosis system activates during faults. Converters have been designed to reduce the electrical and thermal stresses of semiconductor devices and also to provide over-current protection.

IV. COMPARATIVE STATEMENT

PV panels were placed on the six faces of CubeSat. Based on EPS architectures converters are implemented. Mostly a set of panels gets one converter which corresponds to three sets of panels and three converters to step up the voltage to match the intermediate bus voltage.

Since solar PV depends on irradiance as well as temperature, when it comes to CubeSat irradiance mismatch is the major concern. As there is a 100 % mismatch in irradiance due to the spinning of CubeSat in its orbit and also temperature variation got its effect on PV cell. Extracting maximum power efficiently from the panels gets tougher due to this.

Form the inception of CubeSat, PV array remained as an obvious choice for primary source of energy. In-order to get maximum power from panel perturb and observe techniques are being employed along with MPPT. To get the higher efficiency and regulated output closed loop control of switch mode converters are being used. Boost converters with PI/PID controllers are the commonly used closed loop switching converter. Whereas to charge the battery, SOC-based charging and over-current/short circuit protection techniques is implemented.

Nowadays, space debris has become a matter of concern as it has the potential to damage other functioning satellites. In order to minimize space debris, the satellite design should be compact, particularly with a smaller number of passive components, and achieving this is easier said than done. Since, inductor and switch have a larger footprint in causing space debris it is advisable to use wide band gap semiconductor and operating converter at the higher switching frequency

If PV supplies a higher voltage than bus voltage, step down topology can be implemented instead of step-up topologies. A synchronous buck converter has got higher efficiency. Also, buck boost converter is another type of converter that can be seen in CubeSat EPS

SEPIC converter is a type of buck-boost converter got many pros compared to single-stage converters but coupled inductor is a major disadvantage. As three converters are required for CubeSat, number of switches count and passive elements also increases. Topologies discussed so far gave unidirectional conversion functionality. To overcome these disadvantages research is being focused on multiport converters with bidirectional capability.

Multi input multi output interleaved boost converter is two staged converter which has got bidirectional input for connecting the battery. Reduction in ripple current is the major advantage of this topology. Many other Multi-input multi-output topologies can be observed for CubeSat, like three port converters. As the number of converter stages increases overall losses reduce but controlling gets more complex.

Hybrid converters usage has been observed to reduce the count of inductors. Hybrid converters can be derived using capacitors or connecting fuses to obtain fault-tolerant topologies to achieve higher reliability.

Among most MPPT techniques, hill climbing techniques are simpler and require less computational power. The most commonly used algorithms are P & O and Incremental Conductance. Advanced techniques like fuzzy logic control, and neural network is currently trending research topics. Sensor’s requirement for MPPT depends on complexity, cost, speed of convergence, temperature range, and required hardware differs as per the selected MPPT technique. Most of these methods yield a local maximum with approximated MPP but not maximum output. Soft Computing based MPPT tracking is more efficient compared to traditional tracking techniques but requires much computational power and the system becomes complex.

Table 4.1 Comparative Table

No	Proposed Converter	MPPT	Controller	No. of Switches	No of Diodes	No of L's	No of C's	Efficiency (%)
[1]	Boost	P&O	PI	8	8	1	2	94 -96
[2]	Boost	P&O	PID	3	3	1	2	95
[3]	Boost	P&O-LT3652 MPPT IC	Battery monitoring DS2782 IC, and TPS2420 IC for over current and short circuit protection	6	6	2	2	--
[4]	Boost LM2576 and linear regulator IC's MC7805, MC7812	--	MAX471 current sensing. LM35 temperature sensing, Atmega128A1	1	1	1	1	85
[5]	Boost-SPV1040	--	BQ24002 SOC monitor, feedback based on voltage, current and temperature sensors.	1	1	1	1	78-85
[6]	Boost converter with stacked capacitor	P&O	PID	1	1	1	2	--
[7]	Synchronous Buck		Battery Charge Regulator	2	1	1	1	98
[8]	Four switch buck-boost converter	--	MSP430 series MCU	4	0	1	1	--
[9]	Synchronous buck boost	Digital MPPT	FDPOL, the current sensor	4	-	1	1	--
[10]	SEPIC	P & O	various	1	2	2	2	90-95
[11]	Interleaved Boost	--	--	4	7	2	2	--
[12]	Three Port Converter	P&O	PI	3	0	2	4	97.3
[13]	Switched capacitor	Panel voltage and temp	PWM controller	2	0	0	2	--
[14]	Buck with coupled inductors	InC	Current control, Battery Management System	2	2	1	2	--
[15]	N-1 redundant MPPT	P&O	Microcontroller, Gate drivers	4	4	1	1	--

V. CONCLUSION

In this paper, various power electronic converter topologies used for CubeSat have been reviewed. While selecting converter topology, it needs to be chosen in such a way that it will leave a smaller footprint in space. Converter topology should focus on minimizing the dimensions, power losses, and cost. It must be reliable and efficient. Multiport converters are gaining much importance for nanosatellite applications. Out of many MPPT algorithms, the best algorithm has to be chosen which gives fast and efficient tracking of maximum power from the PV panel. From the control point of view, designing a soft-switching control strategy with high reliability and efficiency is necessary. Maintaining temperature for battery operation also need to be taken care of. The future scope of MPPT lies in PV irradiance forecasting, which could be done to determine a better-suited MPPT technique for space application.

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