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The Design and Construction of a High Efficiency Satellite Electrical Power Supply System

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Abstract

In this paper, a high efficiency satellite electrical power supply system is proposed. The increased efficiency of the power supply system allows for downscaling of the solar array and battery weight, which are among the most important satellite design considerations. The satellite power supply system comprises two units, namely a generation unit and a storage unit. To increase the efficiency of the solar array, a maximum power point tracker (MPPT) is used in the power generation unit. In order to improve the MPPT performance, a novel algorithm is proposed on the basis of the hill climbing method. This method can track the main peak of the array power curve in satellites with long duration missions under unpredicted circumstances such as a part of the array being damaged or the presence of a shadow. A lithium-ion battery is utilized in the storage unit. An algorithm for calculating the optimal rate of battery charging is proposed where the battery is charged with the maximum possible efficiency considering the situation of the satellite. The proposed system is designed and manufactured. In addition, it is compared to the conventional power supply systems in similar satellites. Results show a 12% increase in the overall efficiency of the power supply system when compared to the conventional method.

Key words: Battery, High efficiency, MPPT, Satellite electrical power supply system, Solar array

I. INTRODUCTION

Since the beginning of the Space Age up until the present time, the majority of satellites have been utilizing solar cells and batteries to generate and store the required power. Batteries are basically heavy devices and solar panels occupy a vast area. Satellite designers should always aim for a tradeoff between the weight and volume of the electrical power supply (EPS) system and the operational requirements of the other subsystems and cargo. If a designer can make use of lighter batteries and smaller arrays by increasing the EPS efficiency, it becomes possible to enhance the operational quality and quantity of the load. To increase the efficiency of the electrical power generation unit, the maximum generable power in the solar array should be absorbed. To increase the efficiency of the energy storage system, the battery charge efficiency and charging route efficiency should be increased.

There exists a unique point in the voltage-power curve of the solar array called the maximum power point (MPP). If the operating point of the solar array is adjusted according to the MPP, the maximum power will be absorbed [1], [2]. In space missions, different factors affect the electrical characteristics of the array that lead to a MPP shift and consequently reduce the efficiency of the solar array. The factors affecting the shape of the electrical characteristic curve of an array are as follow:

A. Environmental conditions

As radiation increases, the short circuit current of the solar cell increases and an increased temperature reduces the open circuit voltage of the solar cell. These two phenomena cause MPP movement [3]. Fig. 1 shows the effect of radiation and temperature change on the voltage-power curve and the location of the MPP.

B. Shadow

If a part of an array is shadowed by the antenna or other satellite equipment, the voltage-power curve of the array will vary significantly and there will be as many peaks in the curve as the number of radiations [4].

C. Damage

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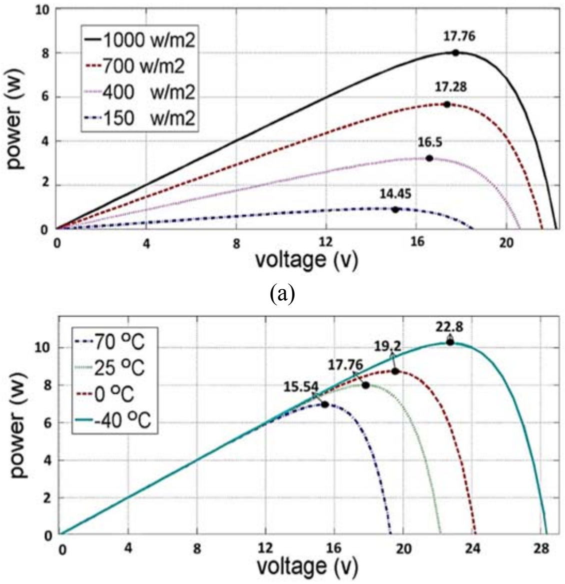


(a)

(b)

Fig. 1. MPP voltage variations in terms of (a) radiation and (b) temperature.

When the satellite experiences a high-energy flow of electrons, a huge potential difference is developed between the surfaces of the solar array and the satellite body. This results in an electrostatic discharge, which can damage a number of solar cells [5]. Like the previous case of shadows, there will be several peaks in the array power curve.

D. Weariness

The solar cells electrical characteristics deteriorate throughout the satellite mission as a result of collisions with space radiations. This causes a MPP shift [6].

In order for the operating point of a solar array to be at the MPP, a maximum power point tracker (MPPT) is employed. Various MPPT algorithms have been developed so far. However, the look-up table [7], curve adaptation [8], open-circuit voltage [9], and open-circuit current [10] methods have a low precision and they exhibit a huge error in the long run because they cannot determine the exact location of the MPP, and they work according to the array characteristic at the beginning of the mission. Today, search methods are utilized to determine the precise location of the MPP in different conditions. In the forced oscillation method [11], the MPP location is determined by comparing power and voltage waveforms. This method involves a highly complicated circuit that is inappropriate for space applications. The perturb and observe algorithm is proposed in [12] where the voltage corresponding to the maximum power is sought. The incremental conductance algorithm is proposed in [13]. This method works on the basis of the principle that $\frac{I_{PV}}{V_{PV}} = \frac{dI_{PV}}{dV_{PV}}$ in the MPP. The hill climbing algorithm was proposed in [14]. In this method, the duty cycle of the power converter can change one unit in any stage and the power is absorbed from the array compared to the previous stage. If power increases, the duty cycle changes to the previous direction and if power decreases, the duty cycle changes to the opposite direction. The most common MPPT method in space applications is the hill climbing method owing to its high precision, simple structure, direct investigation of power, high reliability, and independence from sensors such as radiation and temperature sensors [15, 16]. However, this method has three major defects:

1) Tracking local peaks of the solar array voltage-power curve
2) Oscillations around the MPP
3) Low speed

To overcome the disadvantages of the hill climbing method, [17] proposes a variable step-size hill climbing. In this method the response time and oscillations around the MPP are improved. However, the first problem has not been eliminated yet. If a shadow falls across or damage occurs to the solar array, which results in several local peaks, the variable step-size hill climbing tracks the nearest peak to the operating point. Therefore, if a local peak is located near the operating point, this method tracks the local peak.

In this paper, a new MPPT algorithm based on the hill climbing method is proposed in which the defects of the previous methods are corrected. In the proposed method, the power is initially measured in different areas of the voltage-power curve of the array. The area with highest power is selected as the main peak range. Afterward, the method moves toward the MPP using the hill climbing method. Once the MPP is reached, the points nearby are investigated and the operating point is lain precisely on the MPP so that the power loss due to oscillations near the MPP are prevented. The proposed method enjoys a higher speed, precision, and efficiency when compared to the previous methods. In addition, when there are several peaks in the voltage-power curve of the array, it can track the main peak of the array characteristic curve.

The efficiency of the energy storage unit substantially affects the determination of the battery capacity and size as well as the solar array size. The higher the efficiency of the storage system, the lower the need for energy generation. Consequently, the solar array dimensions decrease. The efficiency of the storage unit depends on the charger efficiency and the battery efficiency. Numerous methods have been proposed for increasing the efficiency of the storage unit. A battery charger with a high efficiency in which a ZVS converter is used for reducing switching loss is presented in [18]. A battery charger with a boost ZVT converter is put forward in [19]. A ZCS converter is adopted in [20] in order to reduce switching loss. These methods merely increase the charger efficiency and do not affect the battery efficiency. A very influential parameter in charging efficiency is the battery-charging rate. The results of the experiments carried out in this study demonstrate that adjusting the battery-charging rate can increase battery efficiency. On this basis, an algorithm is presented that can increase charging efficiency to the maximum possible value by selecting the optimal charging rate. The proposed algorithm can increase the battery charging efficiency rate up to 99%.

A satellite EPS is proposed that can absorb the maximum power from an array and deliver it to consumer loads with the highest efficiency possible. The proposed algorithm can pass by local peaks in different conditions, placing the operating point of the solar array precisely on the MPP. Moreover, the charger switching loss is brought to a minimum value using a soft switching technique and the efficiency of the charging is increased by selecting the optimal charging rate. Finally, the proposed design is manufactured. Furthermore, using practical experiments, the superiority of the proposed method over the conventional method in satellites is verified under different conditions of a space mission.

II. THE PROPOSED EPS

The satellite EPS topology is of the PPT type with an unadjusted voltage. The overall plan of the system is illustrated in Fig. 2. This system comprises two parts:

- Power generation unit
- Power storage unit

A buck DC-DC converter is used in the power generation unit for adjusting the operating point of the solar array. MPPT measures the voltage and current of the array and adjusts the duty cycle of the PWM signal applied to the converter in a way that, if required, the maximum possible power can be absorbed from the array. In the power storage unit, when the generated power exceeds the consumption demand, the battery is charged by the charger. On the other hand, when consumed power exceeds the maximum array power or when there is an eclipse, the battery is connected to the main bus, via the discharge diode, and supplies the required power.

A. Power Generation Unit

The proposed MPPT algorithm is depicted in Fig. 3, where D is the duty cycle of the power converter, P_{PV} is the array power, V_{PV} is the array voltage, and I_{PV} is the array current. This algorithm consists of five sections as described below.

Section 1- Finding the Main Peak

As noted earlier, in the hill climbing method and in the other search-based methods, if there are several peaks in the curve, local peaks may be tracked. This remarkably decreases the generation unit efficiency. Since system access is impossible in space systems and the characteristic of a solar array vary during the mission, it is impossible to predict the location of the main peak and it may be placed anywhere in the array characteristic curve. As a result, it is recommended that the array voltage-power curve be divided into several parts and that the power be measured in each part to identify the main peak location. Thus, searching for the MPP may start from the part with the highest power. In the proposed algorithm, it is assumed at first that D=1. Therefore, the array voltage is at its minimum value. At this stage, the array voltage and current are measured and the power is calculated. Then, D is subtracted as much as α at each stage. It is investigated at each stage whether the absorbed power is the maximum. If the power exceeds that in the previous regions, the duty cycle and power of that region are saved. Having examined all of the regions, the proposed algorithm sets the duty cycle to be equal to that of the region with the highest power. In this manner, the control system passes by local peaks and searches for the MPP in the vicinity of the main peak. The value of α should be smaller than 1/number of modules, because in the worst situation, the number of local peaks is equal to number of modules.

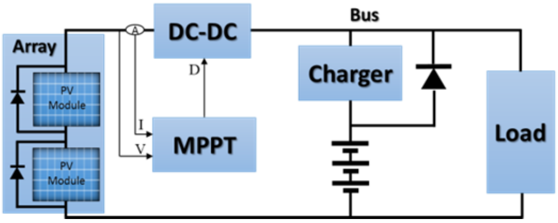


Fig. 2. Satellite EPS schematic.

Section 2- Investigating Abrupt Changes in Power

Generally, if the array characteristic curve undergoes a substantial change, the maximum output power changes and the MPP point moves. For instance, when a system is absorbing the maximum power and one of the solar panels is suddenly shadowed, the maximum power decreases and the new maximum power point moves far from the operating point. Altogether, these two events considerably decrease the output power at the moment of the change in the array characteristic. As a matter of fact, when there is a shadow or damage, the output power changes. If the power change is smaller than $p_{PV}(t)$/number of modules, main peak will stay in its present region. On the other hand, if the power change is bigger than $p_{PV}(t)$/number of modules, main peak will move to another region. Hence, the proposed algorithm checks whether the power change is larger than $(\beta \times p_{PV}(t))$ or not. β is obtained via the following formula:

$$\beta = 1/\, number\ of\ modules \qquad (1)$$

In the proposed algorithm, it is considered that if the power change is bigger than $(\beta \times p_{PV}(t))$, the regions of Section 1 are examined again. Therefore, the maximum possible power from the array will always be absorbed. In this method, the control system works without using temperature or radiation sensors. In addition, it can identify changes in the array characteristic curve merely by assessing the output power value of the array.

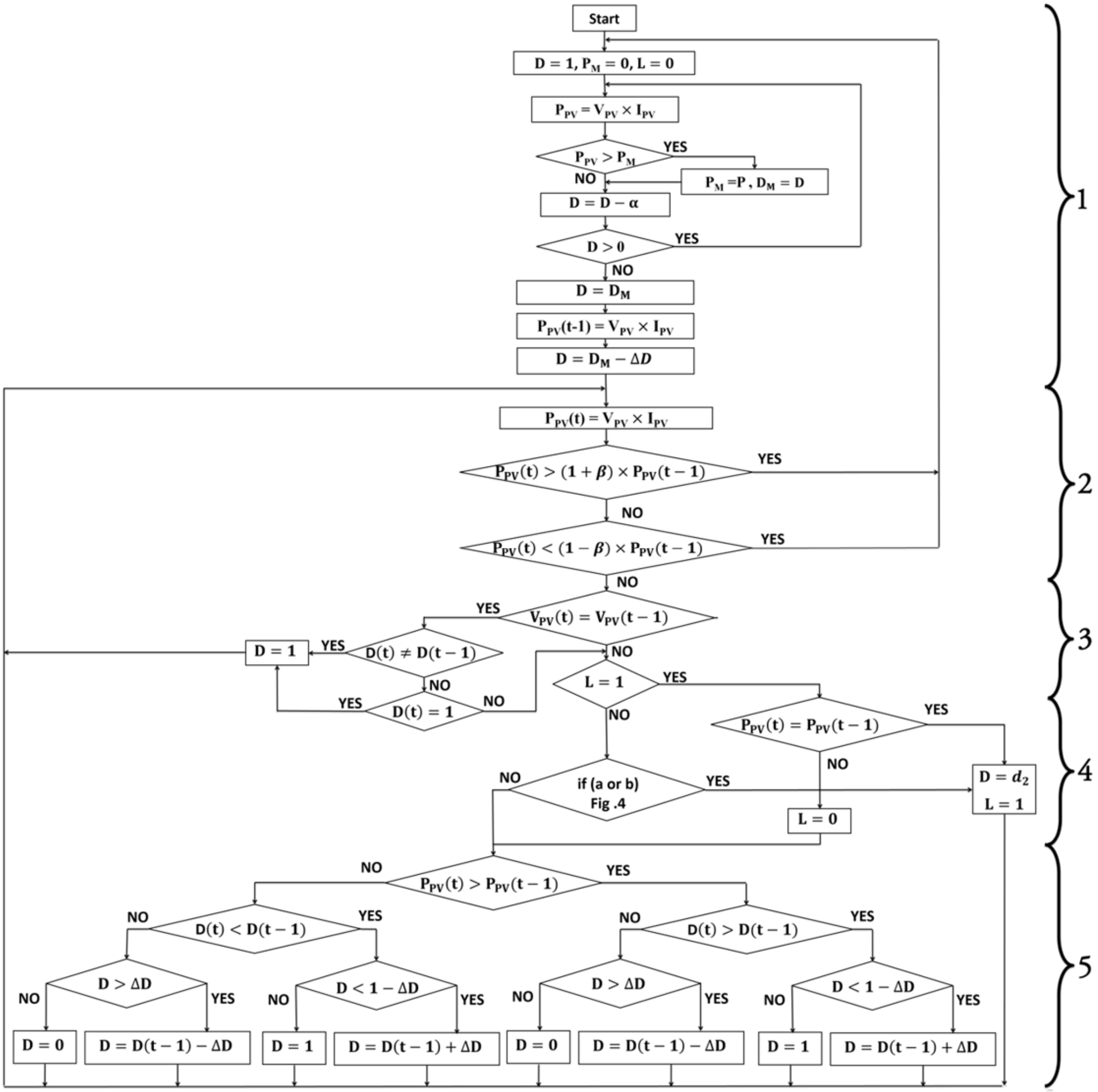


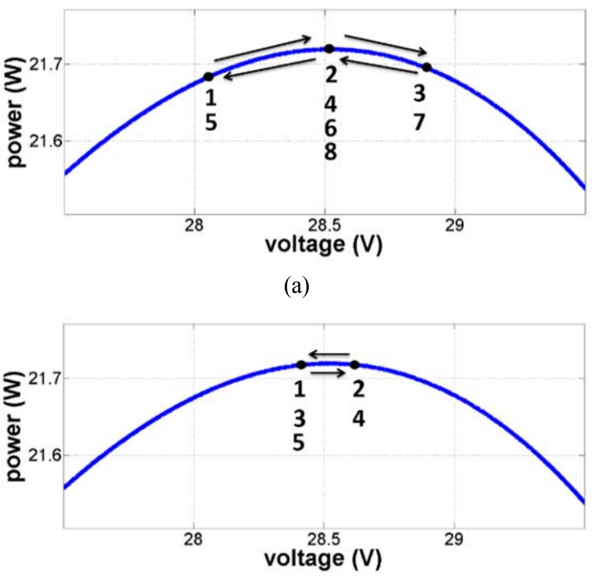
Fig. 3. Proposed MPPT algorithm.

Section 3- Stopping Switching in Case of a Decreased Consumption Load

During the day, when the solar array is tasked with supplying the consumed power, sometimes the consumed power is less than the maximum array power. In this case, there is no longer a need for absorbing the maximum power. Rather, the power should be absorbed from the array in accordance with the consumed power. In this case, the array operating point in the voltage power curve is to the right of the MPP, and its location merely depends on the consumed power, and changing the duty cycle does not affect this location. This feature is utilized in the proposed algorithm in this manner so that if the duty cycle changes at any stage and the array voltage remains constant, the system realizes that the consumed power is below the array maximum power and sets the duty cycle equal to 1 (D=1). Thus, there would be no switching in the power switch and the array would be directly connected to the load. This method eliminates switching loss and increases the efficiency of the converter at times of low consumption.

Section 4- Eliminating Oscillation

One of the defects of the search-based MPPT methods is oscillations around the MPP that reduces efficiency at the steady state of the system. By studying the behavior of the hill climbing algorithm and the results of experiments revealed that as the operating point reaches the MPP, one of the two cases shown in Fig. 4 occurs. In the normal case, the operating point starts to oscillate at three points as shown in case (a). Case (b) may occur due to two reasons: either the MPP is located between those two points or the measurement unit is unable to identify the absorbed power difference. The algorithm compares the recorded duty cycles of case (a) and



(a)

(b)

Fig. 4. Different oscillation modes around MPP. (a) Three-point. (b) Two-point.

case (b) to find out which one has occurred.

If case (a) or (b) takes place, the control system selects point number 2 as the MPP point and generates the corresponding duty cycle, and L changes to one. Therefore, the control system keeps the array operating point on the MPP unless the array MPP moves. In this case, whenever the array characteristic curve changes, the MPP point moves, which causes a change in the absorbed power. Hence, the absorbed power is always examined. When the power absorbed from the array makes the slightest change, L changes to zero. As a result, the new MPP location will be sought by running the hill climbing algorithm.

Section 5- Hill Climbing

The hill climbing method is used in this section to search for the MPP, where the range of the MPP is sought by investigating power variations and the duty cycle. ΔD is the value of change in the duty cycle in each stage.

B. Power Storage Unit

A lithium-ion battery was adopted for storing energy. This battery is charged using the constant-current constant-voltage charging method. Batteries generally have limitations in the charging rate considering their characteristics and production method. Batteries are typically charged with the maximum possible current that does not damage the battery. However, charging efficiency is low in this case because it considerably depends on the charging rate. The reason behind this is the internal resistance of the battery. Thus, the charging rate cannot easily be considered as a constant value. Fig. 5 demonstrates practical experimental results of battery charging efficiency at different charging rates. The results indicate that the lower the charging rate, the higher the charging efficiency, and that it may be increased up to 99% with a 0.1C rate. The more the charging rate increases, the greater the loss in the internal resistance of the battery. This occurs at almost at the same rate. As a result, charging should be performed using the least possible current rate.

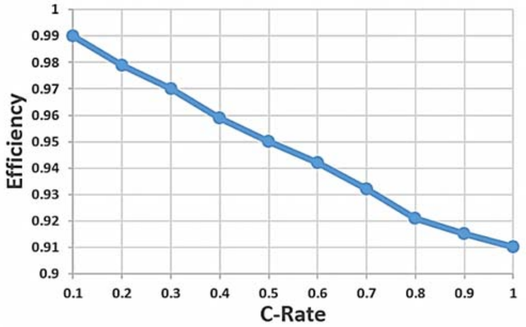


Fig. 5. Battery efficiency in terms of charging rate.

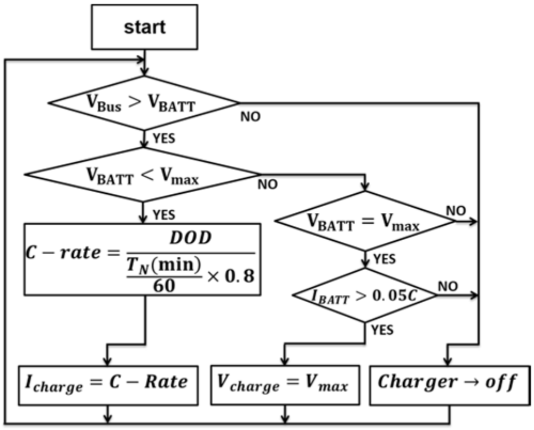


Fig. 6. Battery charger proposed algorithm.

The proposed algorithm of the storage unit is shown in Fig. 6, where V_{BUS} is the satellite main supply bus voltage, V_{BATT} and I_{BATT} are the measured voltage and current of the battery, respectively, V_{max} is the battery maximum voltage, T_N is the time remaining until an eclipse, C is the battery capacity in ampere-hours, D is the duty cycle of the charger converter, and V_{charge} and I_{charge} are charger voltage and current, respectively. In the proposed algorithm, it is initially investigated whether the EPS can supply energy to the charger. Charging begins when battery voltage is lower than the maximum level and the bus voltage exceeds the battery voltage. It has been demonstrated in [6] that the time remaining to an eclipse (T_N) can be calculated by the following equations:

$$P = 1.658669 \times 10^{-4} \times (637.14 + H)^{\frac{3}{2}} \tag{2}$$

$$\cos\left(\frac{\Phi}{2}\right) = \frac{\cos\rho}{\cos\beta_s} \tag{3}$$

$$T_E = P\left(\frac{\Phi}{360}\right) \tag{4}$$

$$T_N = P - T_E - T \tag{5}$$

Where P is the orbit period in minutes, H is the altitude of the satellite in kilometers, Φ is the rotation angel, ρ is

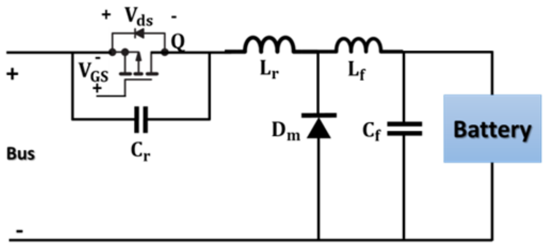


Fig. 7. Charger circuit.

the angular radius of the earth, β_s is the angle of the sun above the orbit plane, T_E is the duration of the eclipse, and T is the time of the satellite which is reset at the beginning of the day.

To increase battery efficiency, the minimum charging rate is calculated in the constant-current mode using Eq. (6).

$$C-rate=\frac{DOD}{\frac{T_N\,(min)}{60}\times 0.8} \qquad (6)$$

Since 20% of the charging duration is performed in the constant-voltage mode, the T_N value is multiplied by 0.8. At first, the battery is charged using the optimal charging rate in the constant-current mode. When battery voltage reaches its maximum value, charging by the use of the constant-voltage mode begins. At this stage, the voltage of the battery terminals is set on V_{max}. When the charging current reaches 5% of the nominal value, the charging process stops. This algorithm reduces the losses in the battery. Therefore, the heat of the battery will be decreased during the charge, which increases the lifetime of battery. Additionally, since the battery is charged by the minimum charging rate, the lifetime of the electrical components will be increased.

High-frequency converters are used in satellites in order to reduce the charger volume and weight and to reduce the charger current oscillations. However, the more the switching frequency increases, the more the converter switching loss and electromagnetic noise increase. To solve this problem, a ZVS converter is utilized as shown in Fig. 7, where the capacitor C_r and the inductor L_r are used for bringing about switching conditions at zero voltage.

III. EXPERIMENTAL STUDY

The manufactured EPS, together with the solar modules and the battery are illustrated in Fig. 8. Table I shows the system characteristics. The solar array consists of two solar modules connected in series and a battery consisting of three lithium-ion cells connected in series. The values of the MPPT algorithm parameters are listed in Table II. In this section, the proposed EPS is compared to the conventional EPS used in satellites according to the scenario defined in Fig. 9 by means of a practical experiment. The hill climbing method is used in the conventional EPS to absorb the maximum power from the solar array and a buck power converter via the constant-current constant-voltage charging method where a 1C charging rate charges the battery.

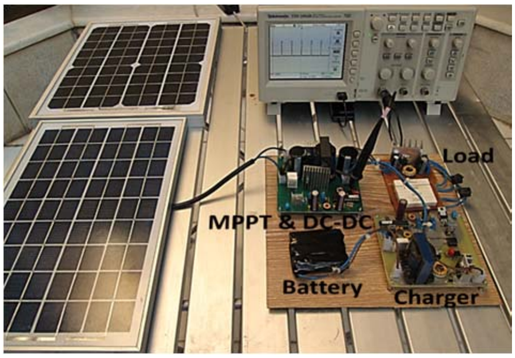


Fig. 8. Proposed EPS manufactured.

TABLE I

PRACTICAL SYSTEM CHARACTERISTICS

Item	Value
Open circuit voltage of pv	37.2 V
Short circuit current of pv	0.6 A
Maximum battery voltage	12.6 V
Capacity of battery	2 Ah

TABLE II

PARAMETERS USED FOR MPPT ALGORITHM

parameter	Value
ΔD	0.01
α	0.2
β	0.5

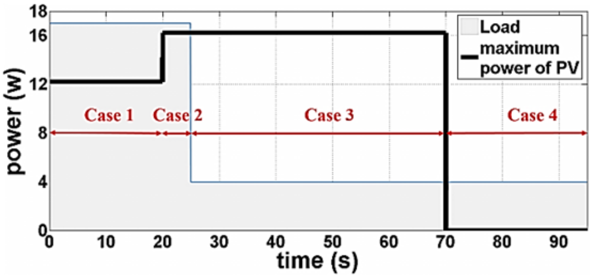
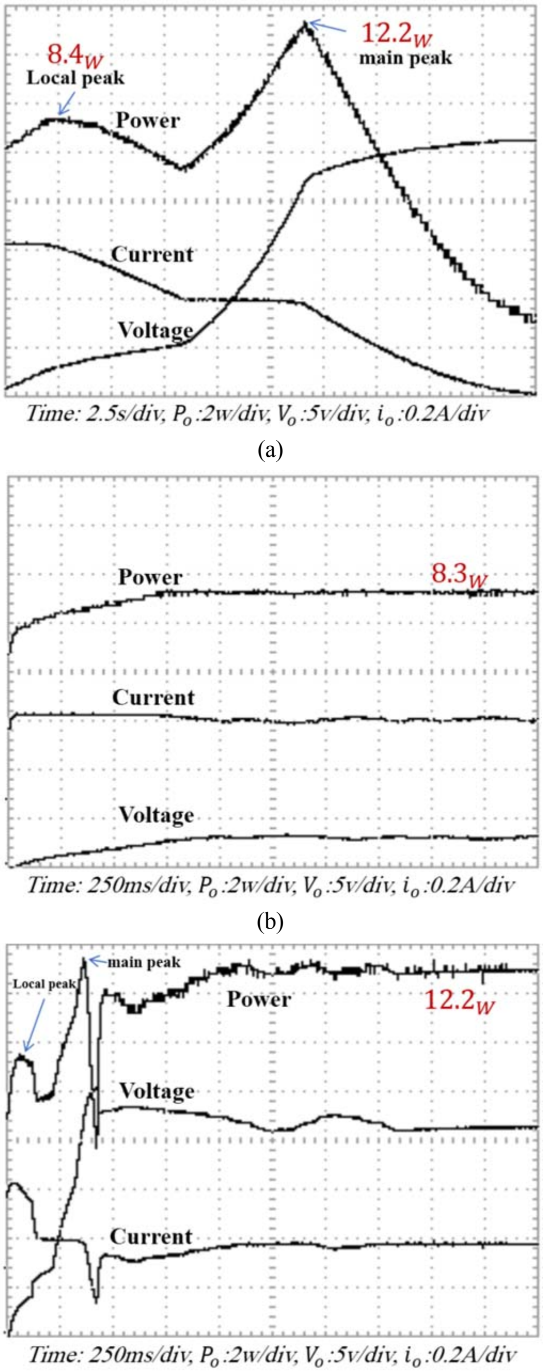


Fig. 9. Load power consumption curve and array maximum power in the orbit of the satellite around the Earth.

The scenario defined in Fig. 9 is adapted from a satellite at an altitude of 500km from the Earth surface. During the period of the experiment, the day lasts 70 minutes and the eclipse lasts 25 minutes. Fig. 9 depicts the load power consumption and the array maximum power at any moment. Four cases occur for the EPS in this scenario.

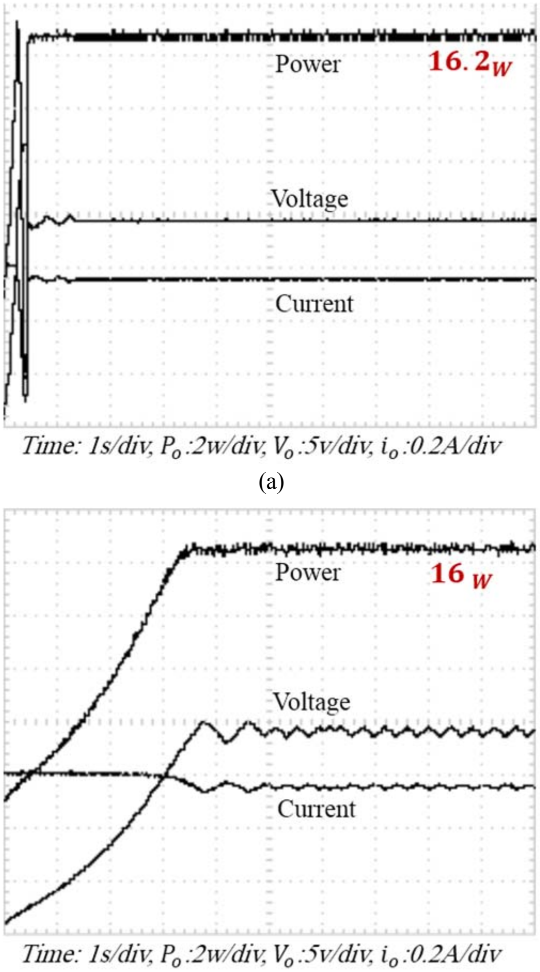
Case 1: During the first 20 minutes of the day, the load power consumption is 17 W and the satellite is positioned so that one of the modules is shadowed by the satellite antenna. The array voltage, current, and power curves in this position and by changing the duty cycle from zero up to one are given in Fig. 10(a). There are two peaks in the power curve. The power of the main peak is 12.2 W and that of the local peak is 8.4 W. In Fig. 10(b-c), the performance of the proposed



(c)

Fig. 10. Experiment results of Case 1. (a) Array power, current, and voltage curves by changing the duty cycle from zero up to one. (b) Hill climbing method. (c) Proposed method.

method can be observed in comparison with the hill climbing method. Having examined the different regions of the power curve, the proposed method selects a region that contains the highest power. Then it reaches the MPP in five stages of search. After two stages of oscillation, it places the operating point on the main peak and absorbs 12.2 W of power from the array. Meanwhile, in the hill climbing method, the local peak is searched for and 8.3 W of power is absorbed from the array owing to the oscillation around it. In this case, the battery supplies the extra power consumption.



(b)

Fig. 11. Experiment results in Case 2 (a) proposed method (b) hill climbing method.

Case 2: The solar array is not shadowed between the 20th and 25th minutes and it has a peak with a power of 16.2 W. The load power consumption during this time is 17 W. Fig. 11 shows the performance of the proposed method in comparison with that of the hill climbing method. The proposed method reaches the MPP 7 times faster. After two stages of oscillation, it places the operating point on the exact location of the MPP and absorbs 16.2 W of power. Meanwhile, in the hill climbing method, the operating point always oscillates around the MPP in the steady state and 16 W of power are absorbed. In this case, the extra power consumption is supplied by the battery.

Case 3: The solar array is still not shadowed between the 25th and 70th minutes and it has a peak with a power of 16.2 W. The load power consumption is 4 W. As a result, the generation unit sets the duty cycle of the power converter equal to 1 in order to avoid switching loss. The battery depth of discharge is DOD=15%, and the time remaining to eclipse is $T_N = 45\text{min}$. According to the obtained results, the

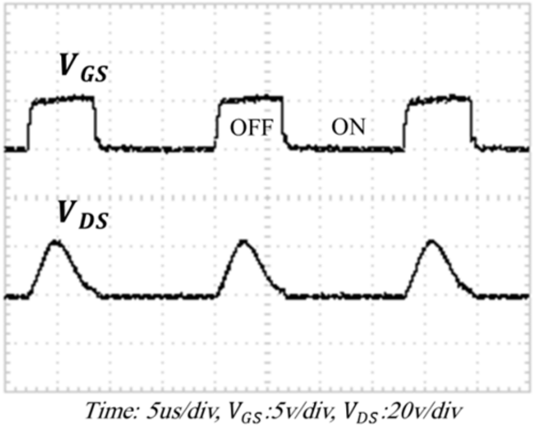


Fig. 12. V_{DS} and V_{GS} curves of the charger power switch.

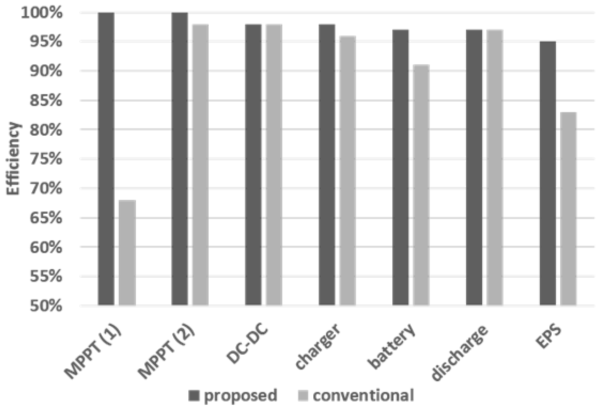


Fig. 13. Comparison between the efficiency of the proposed system and that of the conventional one.

proposed charger charges the battery with a rate of 0.25C and an efficiency of 97%. Meanwhile, with the conventional system, the battery is charged with a rate of 1C and an efficiency of 91%. The gain-source voltage curve and the drain-source voltage curve of the proposed charger power switch are shown in Fig. 12. As can be seen, switching has been performed at zero voltage at both the disconnection moment and at the connection moment. The efficiency of this charger was shown to be 98%, while the charger efficiency without using the ZVS method is 96%.

Case 4: The satellite is in eclipse between the 70th and 95th minutes. The battery from the discharge diode route supplies the load power consumption. The discharge route efficiency in both systems is 0.97%.

Throughout all of the experiment stages, the power of the different parts of the proposed EPS and the conventional EPS are measured and the efficiency of each part is calculated as per the formulas expressed in Table III.

TABLE III

EFFICIENCY OF DIFFERENT PARTS OF THE SYSTEM

Conventional	Proposed	Efficiency Equation	
68%-98%	100%	$\frac{P_a}{p_{max}} \times 100$	$\boldsymbol{\eta_{MPPT}}$
98%	98%	$\frac{P_{out-a}}{p_a} \times 100$	$\boldsymbol{\eta_{DC-DC}}$
96%	98%	$\frac{P_{out-charger}}{p_{in-charger}} \times 100$	$\boldsymbol{\eta_{charger}}$
91%	97%	$\frac{w_{out-battery}}{w_{in-battery}} \times 100$	$\boldsymbol{\eta_{battery}}$
97%	97%	$\frac{P_{out-discharger}}{p_{in-discharger}} \times 100$	$\boldsymbol{\eta_{dishtarge}}$
83%	95%	$\frac{w_{out-EPS}}{w_{out-EPS} + W_{loss}} \times 100$	$\boldsymbol{\eta_{EPS}}$

where η_{MPPT} is the MPPT unit efficiency, P_a is the power absorbed from the array, p_{max} is the solar array maximum power, η_{DC-DC} is the efficiency of the generation unit power converter, P_{out-a} is the output power of the generation unit power converter, $\eta_{charger}$ is the charger efficiency, $p_{in-charger}$ is the charger input power, $p_{out-charger}$ is the charger output power, $\eta_{battery}$ is the battery efficiency, $w_{in-battery}$ is the battery input energy, $w_{out-battery}$ is the battery output energy, $\eta_{discharge}$ is the battery discharge route efficiency, $P_{in-discharger}$ is the discharge route input power, $P_{out-discharger}$ is the discharge route output power, η_{EPS} is the EPS total efficiency, $w_{out-EPS}$ is the EPS energy output, and W_{loss} is the energy lost in the satellite EPS.

By tracking the main peak and eliminating oscillations, the proposed method increased the MPPT efficiency by as much as 32% in Case 1. In Case 2, the proposed method increased the MPPT efficiency by as much as 2% by eliminating oscillations. The charger efficiency increased 2% thanks to employing the ZVS converter. By selecting the optimal charging rate, the battery efficiency increased 6%. Altogether, the proposed method has been able to increase the EPS total efficiency by as much as 12%.

IV. CONCLUSION

A high-efficiency satellite EPS was designed and manufactured. As a power supply for satellites, the proposed system was compared to the conventional system through a practical experimental implementation. The superiority of the proposed system in terms of efficiency and performance under different circumstances was demonstrated with scientific arguments and practical experiments. Given the obtained results, the proposed power generation unit passes by local peaks and places the solar array operating point precisely on the main peak, preventing power oscillations. The proposed algorithm sets the duty cycle equal to one at times of low consumption, thereby averting switching loss. This increases both the lifetime of the electronic parts and the efficiency. By adopting the optimal charging rate selection algorithm, the storage unit increases the battery-charging efficiency to the maximum possible value. Furthermore, the ZVS charger has increased the charging route efficiency by as much as 2% when compared to hard switching chargers. Fig. 13 shows practical experiment results in the form of a diagram. Altogether, by using the methods presented for the generation and storage units has led to a 12% increase in the satellite EPS efficiency according to the defined scenario.

REFERENCES

[1] K. Ishaque and Z. Salam, "A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition," *Renewable and Sustainable Energy Reviews*, Vol. 19, No. 1, pp. 475-488, Mar. 2013.

[2] V. Salas, E. Olias, A. Barrado, and A. Lazaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems," *Solar energy materials and solar cells*, Vol. 90, No. 11, pp. 1555-1578, Jul. 2006.

[3] J. Ramos Hernanz, J. Campayo Martín, I. Zamora Belver, J. Larrañaga Lesaka, E. Zulueta Guerrero, and E. Puelles Pérez, "Modelling of photovoltaic module," in *International Conference on Renewable Energies and Power Quality*, pp. 1-5, 2010.

[4] B. N. Alajmi, K. H. Ahmed, S. J. Finney, and B. W. Williams, "A maximum power point tracking technique for partially shaded photovoltaic systems in microgrids," *IEEE Trans. Ind. Electron.*, Vol. 60, No. 4, pp. 1596-1606, Apr. 2013.

[5] H. Masui, T. Endo, K. Toyoda, M. Cho, F. K. Wong, B. Hoang, and T. Redick, "Electrostatic discharge tests of solar array coupons with different string-to-string gaps without RTV adhesive grout," *IEEE Trans. Plasma Sci.*, Vol. 40, No. 2, pp. 351-358, Feb. 2012.

[6] W. J. Larson and J. R. Wertz, *Space Mission Analysis and Design*, Microcosm press, Chap. 5, 7, and 11, 2005.

[7] H. E.-S. A. Ibrahim, F. F. Houssiny, H. M. Z. El-Din, and M. El-Shibini, "Microcomputer controlled buck regulator for maximum power point tracker for DC pumping system operates from photovoltaic system," in *Fuzzy Systems Conference Proceedings*, Vol. 1, pp. 406-411, 1999.

[8] H. Andrei, T. Ivanovici, G. Predusca, E. Diaconu, and P. Andrei, "Curve fitting method for modeling and analysis of photovoltaic cells characteristics," in *Proceedings of 2012 IEEE International Conference on Automation, Quality and Testing, Robotics*, pp. 307-312, 2012.

[9] M. A. Masoum, H. Dehbonei, and E. F. Fuchs, "Theoretical and experimental analyses of photovoltaic systems with voltageand current-based maximum power-point tracking," *IEEE Trans. Energy convers.*, Vol. 17, No. 4, pp. 514-522, Dec. 2002.

[10] T. Noguchi, S. Togashi, and R. Nakamoto, "Short-current pulse-based maximum-power-point tracking method for multiple photovoltaic-and-converter module system," *IEEE Trans. Ind. Electron.*, Vol. 49, No. 1, pp. 217-223, Feb. 2002.

[11] K. Tse, H. S. Chung, S. Hui, and M. Ho, "A novel maximum power point tracking technique for PV panels," in *Power Electronics Specialists Conference*, Vol. 4, pp. 1970-1975, 2001.

[12] M. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications," *IEEE Trans. Sustain. Energy*, Vol. 3, No. 1, pp. 21-33, Jan. 2012.

[13] A. Safari and S. Mekhilef, "Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter," *IEEE Trans. Ind. Electron.*, Vol. 58, No. 4, pp. 1154-1161, Apr. 2011.

[14] H. Al-Atrash, I. Batarseh, and K. Rustom, "Statistical modeling of DSP-based hill-climbing MPPT algorithms in noisy environments," in *Applied Power Electronics Conference and Exposition*, Vol. 3, pp. 1773-1777, 2005.

[15] S. B. Kjaer, "Evaluation of the hill climbing and the incremental conductance maximum power point trackers for photovoltaic power systems," *IEEE Trans. Energy Convers.*, Vol. 27, No. 4, pp. 922-929, Dec. 2012.

[16] H. Al-Atrash, I. Batarseh, and K. Rustom, "Effect of measurement noise and bias on hill-climbing MPPT algorithms," *IEEE Trans. Aerosp. Electron. Syst.*, Vol. 46, No. 2, pp. 745-760, Apr. 2010.

[17] S. Abuzed, M. P. Foster, and D. Stone, "Variable PWM step-size for modified Hill climbing MPPT PV converter," in *IET International conference on Power Electronic*, Vol. 7, pp. 1-6, 2014.

[18] C.-M. Wang, C.-H. Lin, and H.-Y. Lin, "High-efficiency and low-stress ZVS-PWM bidirectional DC/DC converter for battery charger," in *Industrial Electronics and Applications Conference (ICIEA)*, pp. 1185-1190, 2011.

[19] Y.-L. Ke, Y.-C. Chuang, and M.-S. Chen, "Implementation of high-efficiency battery charger with a zero-voltage-transition pulse-width-modulated boost converter," in *Industrial & Commercial Power Systems Technical Conference*, pp. 1-9, 2009.

[20] Y.-C. Chuang and Y.-L. Ke, "High efficiency battery charger with a buck zero-current-switching pulse-width-modulated converter," *IET Power Electron.*, Vol. 1, No. 4, pp. 433-444, Dec. 2008.

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