A Photovoltaic Model Based Matched Load Operation Mode for Power Plants of Nanosatellite

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Abstract

The mode of matched load is the most effective mode that provides a maximum output power of power plants of nanosatellite. Therefore, it must be designed to be efficient and reliable to harvest the required power. There are two main operating scenarios of a nanosatellite in space, the first when the nanosatellite is stabilized with its photovoltaic (PV) array pointing to the sun and the second is when the nanosatellite experiences rotation and each PV array will face the sun for a short period. The rotation causes the satellite PV to face the sun at different angles which constantly change solar insolation level and temperature. In this work is achieved by introducing a method for tracking the maximum power point of photovoltaic panels with the help of a power coefficient for tracking the position of maximum power area and the next using one of the known direct of modified hill climbing. The proposed method allows increasing the average installed capacity utilization factor up to (36%-40%) of nanosatellite photovoltaic power plant.

Keywords: Nanosatellite, Electrical Power System, Matched Loading, Photovoltaic Panels, Battery, and Boost Converter

تشغيل الحمل المطابق القائم على النموذج الكهروضوئي لمحطات توليد الطاقة للأقمار نوع نانوستلايت

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بغداد – العراق

الخلاصـــة

وضِع الحمل المتطابق هو أكثر الطرق فعالية لتوفر طاقة إخراج قصوى لمحطات الطاقة للأقمار الصناعية النانويـــة. لذلك، يجب أن تكون مصممة لتكون فعالة وموثوقة لحصاد الطاقة المطلوبة. هناك نوعان من سيناريوهات التشغيل الرئيسية للقمر الصناعي في الفضاء. الأول عندما يكون القمر الصناعي النانوي مع الألواح الكهروضوئية موجهة إلى الشمس والثاني هو عندما يكون القمر الصناعي النانوي مع الألواح الكهروضوئية غير موجهة اي عندما يختبر القمر الصناعي الدوران وستواجه كل الألواح الكهروضوئية الشمس لفترة قصيرة. دوران الألواح الكهروضوئية للقمر الصناعي المواجهة للشمس في زوايا مختلفة يسبب الى تغير مستمر بشكل ثابت في مستوى الإشعاع الشمسي ودرجة الحرارة. في هذا العمل تم تحقيق ذلك بواسطة تقديم طريقة لتتبع نقطة الطاقة القصوى للوحات الكهروضوئية بمساعدة معامل القدرة لتتبع موضع منطقة الطاقة القصوى ومن ثم استخدام واحدة من طرق التتبع المباشره تسلق التل المعدلة. توفر الطريقة المقترحة والتي تسمح بزيادة معدل عامل الاستفادة من سعة القدرة لمحطة توليد الطاقـة الكهروضوئية النانوية ما يصل الى 36% و40%.

الكلمات المفتاحية: نانوستلايت ونظام القدرة الكهربائية والحمل المتطابق والالواح الفولطائية الضوئية والبطارية ومبدل رافع للجهد المستمر

Introduction

The modern forms of development of space technologies are the design, manufacture and operation of small and ultra-small satellites, so called nanosatellites technology has been significantly increased. Today's satellite power system is a key component of most constantly evolving nanosatellites power blocks and the main areas of improvement are solar cell efficiency, the use of more energy-efficient chemical batteries, more efficient control methods, which ensure the functioning of all devices. The satellite solar power especially photovoltaic (Solar) energy is gaining greater attention by the researchers. Point of maximum power (PMP) is the operating point, generated by the solar cell at a maximum point of the current-voltage (I-V) characteristic, in which the power plant operates in the matched load and therefore has a maximum output power. In conditions of orbital motion of the spacecraft with non-oriented panels its lighting and temperature are constantly changing, and that affects the position of the PMP. Extreme control of the spacecraft solar power plant is to continuously tracking point of the maximum power (TPMP) (Jasim and Shepetov 2017a). The following methods are now used to implement TPMP indirect methods based on the calculation the position of PMP with the help of the (I-V) characteristics database of photovoltaic panels for different levels of insolation and temperature, or on the use of mathematical functions on the basis of the previously obtained empirical data. The methods of this group include method of short circuit current coefficient (KI), method of open circuit voltage coefficient (KV), direct current voltage method and direct methods based on the instantaneous measurements of voltage and current values and the use of these measurements for calculation of the PMP position. The methods of this include the differentiation methods group, perturbation and observation method, incremental conductance method, hill climbing method. (Jasim and Shepetov 2016a) (Jasim and Shepetov 2017b). The main aim of this study is to find the method to increase the output power of solar power plants of nanosatellite with non-oriented panels.

Materials and Methods

Nanosatellite System

Nanosatellites are playing an important role gaining an increasing interest in the academic and industrial space communities, because they provide relatively fast and low-cost access to space and can be used as low-cost technology demonstrators for advanced space engineering concepts. The major difficulties with a nanosatellite design are the volume, mass, and power limitations (Vertat and Vobornik 2014). Over the past five years, nearly 910 such satellites have been launched, and only in 2020, there was announced the launch of another 449 nano satellites (Kulu, 2019). Figure (1) refers to the nanosatellites by announced launch years.

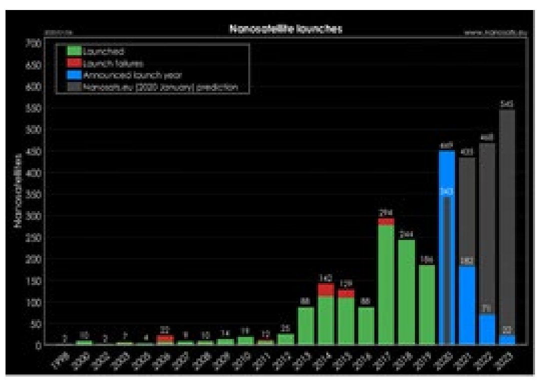

Figure (1) Nanosatellites by Announced Launch Years

Recently, nanosatellite development has begun to flow out of universities and into government agencies, the military, and industry. Research on the improvement of the small spacecraft power plant carried out in many countries. An example of one class of these very small satellites is the nanosatellite, (Figure 2).

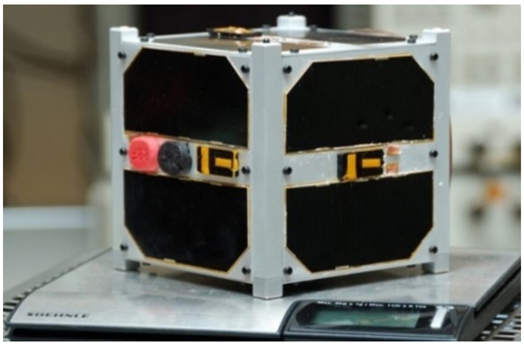

Figure (2) Nanosatellites

A CubeSat unit known as a "1U" Nano satellite, placed in low earth orbit (LEO) with the dimensions of a 10 cm3, weight less than 1.4 Kg and with a distance from 160 km up to 2000 km in an altitude. The basic of the satellite consists of many subsystems such as electrical power system (EPS), attitude determination control system (ADCS), on board computer system (OBCS), communication system (COMS) and payloads. The contents of the payload depend on the requirements of the mission (Angel-Rojas, *et al.,* 2017) (Mousavi, 2016) (Tresvig and Lindem 2014).

The main electrical power source for a nanosatellite are the solar panels that collect the sunlight and transform it to electrical energy, which is stored in the onboard batteries. Because of the motion of the nanosatellite along its orbit, the direction of the solar panels towards the sun varies continuously and hence the voltage generated is varying accordingly.

Matched Load Power System

Matching the power consumption level with the solar photovoltaic can make a great difference in the efficiency of power utilization. A source tracking power management strategy that maximizes the panel's total energy output under a given solar profile by load matching (Mousavi, 2016) (Tresvig and Lindem, 2014). Figure (3) shows a simple block diagram of the EPS components with a matched load control. The typical power system of a satellite consists of solar array unit, storage batteries unit and power conditioning and distribution unit.

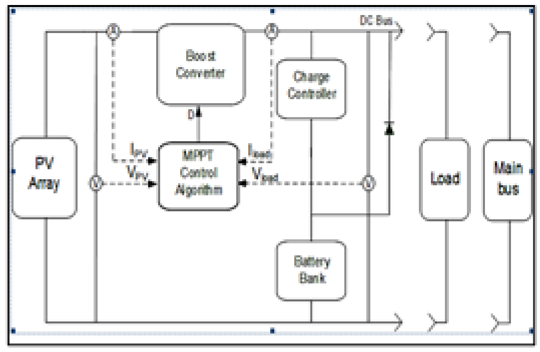

Figure (3) Simple Block Diagram of the EPS Components with a Matched Load Control

Mode of matched load, when the internal resistance of the source of electrical energy equal to the load resistance is the most effective mode that provides a maximum output power of power plants. The electrical matched load power system of the satellite has to provide a continuous power to other subsystems. The resistance of the load is constantly changing during the orbital motion. For providing mode of matched load,which the (I-V) characteristics of a solar cell and the load curve for a given resistive load is a straight line with slope equal to I/V=1/ RL where each point on the (I-V) curve corresponds to the load resistance (Thakurta, *et al*.,2019). Nanosatellite, as a separate class of spacecraft, has their own peculiarities.

First of all, it is the placement of photovoltaic panels on the sides of the satellite without their special positioning on the sun; the uniaxial orientation of the satellite relative to the earth or even the absence of orientation (Non-orientation). Hence, the main feature of the power plants of such nanosatellite it is a work in conditions of constant changes of the temperature and insolation photovoltaic panels during the orbital motion of the satellite (Moutaman, *et al*., 2016).

PV Array Modelling

For the proposed nanosatellite mission, are covered by solar cells on four sides. In each side with equipped with two triple junction connected in series from (Next Triple Junction XTJ) solar cells SpectroLab Company, a wholly owned subsidiary of Boeing Company, is the world's leading commercial supplier of high-efficiency multi-junction solar cells for space power systems, with 29.5% of efficiency at the beginning-of-life (BOL) (Data Sheets, www.spectrolab.com, 2020).

The key parameters from the XTJ datasheet, AM0, 1360 w/m^2, 28° are listed in Table (1). The model can also be used to extract the physical parameters for a given solar PV cell as a function of temperature and solar radiation (Azzouzi and Stork, 2014) (Bradaschia, *et al*., 2015). The simplest models are single-diode using a Matlab/Simulink model of a photovoltaic (PV) mathematical module. A PV module in the EPS of a satellite is used to convert sunlight into electrical energy. It is formed by connecting a number of PV cells in series-parallel combination to achieve the required system voltage and current (Spataru, *et al*., 2014) (Anku, *et al*., 2015).

Figure (4) shows the current-voltage (I-V) & power-voltage (P-V) characteristics of a solar cell. Thus, the I-V curve can be easily transformed to a load power curve using boost converter as shown in Figure (5) respectively. The single diode model (Bradaschia, *et al*., 2015) (Bellia, *et al*., 2014) is shown in Figure (6) widely used due to its simplicity. It consists of a current source, a diode, a series and a parallel resistor. The series resistor represents the ohmic loss, whose value is usually very small and the parallel resistor represents the leakage of the PV cell, whose value is usually very large (Jazayeri, *et al*.,2013) (Gopakumar, *et al*., 2015) (Skyttemyr, 2013) (Lim, *et al*., 2018).

Table (1) Solar Cell XTJ Characteristics

Parameter	Symbol	Unit	Value
Short Circuit Current Density	Jsc	(mA/cm^2)	17.77
Short Circuit Current	ISC	(mA)	1.06
Open Voltage Current	VOC	(V)	2.39
Area of The Cell	A	(cm^2)	59.65
Series Resistance	Rs	(Ω)	0.001
Parallel Resistance	Rp	(Ω)	360
Average Efficiency	η	(%)	29.5
Voltage at Maximum Power	Vmpp	(V)	2.12
Current at Maximum Power	Impp	(A)	1.02
Ideality Factor	N	-	1.77

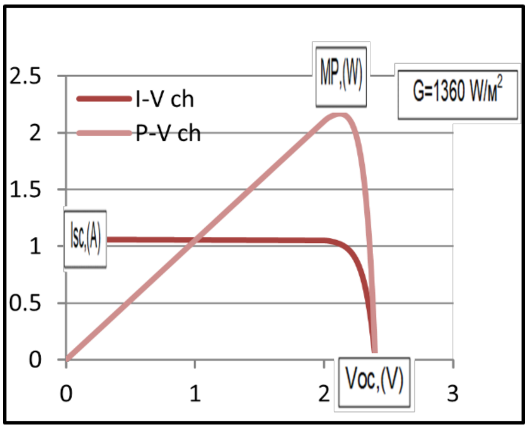

Figure (4) Characteristics of the Model of XTJ Solar Cell Company Spectro Lab

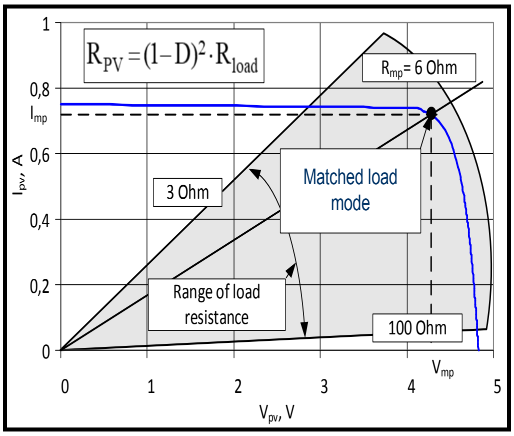

Figure (5) Load Matching Diagram with Internal Resistance of Power Source Based on PV

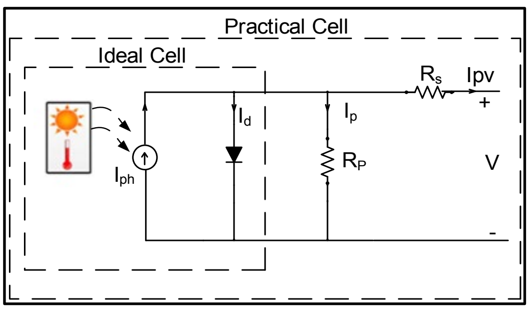

Figure (6) Single Diode PV Model

To simulate the suggested PV system, it is necessary to have a mathematical model to express a typical (I-V) characteristic of PV arrays. The model is a system of equations linking together current and voltage of the PV depending on light conditions and temperature. A single exponential model considered as the most popular model for solar cells describes the relationship between voltage and current (Bellia, *et al*., 2014) (Jazayeri, *et al.*, 2013). This relationship given by a PV module is written as Equation (1).

$$Ipv = I_{ph} - I_s \cdot \left[\exp\left(\frac{q\,(Vpv+Ipv\cdot R_S)}{nK_B\,T}\right) - 1\right] - \frac{(Vpv+Ipv\cdot R_S)}{R_p} \qquad (1)$$

Where I_{PV}, I_{ph}, I_s, q, V_{PV}, n, K_B, T, R_S and R_P are PV cell output current, photovoltaic current or light-generated current, diode saturation current, electron charge ($1.6 \cdot 10^{-19}$ C) PV cell output voltage, ideality factor, Boltzmann constant ($1.38\cdot10^{-23}$ J/K), temperature of the cell, series resistance and parallel resistance respectively. In Eq. (1), since the value of RP is very high, the fraction of $(V_{pv}+I_{pv}R_S)/R_P$ approach the zero. Therefore, in a good approximation, the equation above is converted to the following equation:

$$Ipv = I_{ph} - I_s \,.\, e^{\left(\frac{q(Vpv+Ipv.R_S)}{nK_BT}\right)-1} \qquad (2)$$

From here we can conclude the main factors influencing the voltage of the solar cell are the temperature through the thermal voltage (VT) as in equation (3).

$$V_T = n\frac{K_BT}{q} \qquad (3)$$

Equation (2) is called the current equation of the solar cell. Thus, if the PV module contains the N_S series cells and the RP resistance is infinity, the equations related to the voltage and the power are obtained, respectively, by Eq. (4) and (5) (Jazayeri, *et al*.,2013).

$$Vpv = N_SV_T \cdot \ln\left(\frac{N_PIph - Ipv + N_PIs}{Is}\right) - IpvRs\,) \qquad (4)$$

$$Ppv = Vpv \cdot Ipv \qquad (5)$$

Battery Technology

A power plant also usually includes a battery bank E_{bat}, which is the one of the most important components of the EPS (Gopakumar, *et al*., 2015) (Skyttemyr, 2013) (Lim, *et al*., 2018). The successful selection and sizing of the battery technology and the battery capacity ensure the high performance of the satellite during the eclipse time and the peak demand time. The extra energy is stored in Lithium-Polymer (Li-Po) batteries is selected for our nanosat, which is connected through the discharge or the charge-discharge device (Charger). The Li-Po battery can be found in Table (2).

Table (2) Li-Po Battery Cell Characteristics

Nominal Voltage	3.5	V
Typical Capacity	1.25	Ah
Charge Voltage	4.2	V
Width	42.5	mm
Length	73.5	mm
Thickness	5.4	mm
Typical Weight	32	g
Max. Charge Current	2.5	A

Power Conditioning and Distribution Unit

This unit is the part of the EPS where the harvested power from the solar array is conditioning to be stored in the battery bank, and to be distributed to subsystems. To convert the energy collected by the solar panels into usable voltages, an energy conversion system has to be used. The power regulator (PR) has two main functions (Lim, *et al*., 2018) (Gonzalez, *et al*., 2014). The first one is to match the solar array and the load to obtain the maximum power available from the array. Even when the solar cells receive the maximum irradiance, the power generated from them can be the minimum if there is a load mismatch ($R_{in} \neq R_L$). The second function of the PR is to prevent the batteries from overcharging by controlling the power generated by the solar array according to their charge state. Most CubeSat use one of the two following systems: direct energy transfer (DET) and maximum power point tracking (MPPT). Both can achieve a load matching to obtain maximum power from the solar array. However, DET it operates the PV arrays at a fixed point to transfer power from PV array to the satellite main bus while MPPT can continuously track the maximum power point. Both techniques of solar regulators can be used in a modular approach (Lim, *et al*., 2018) (Gonzalez, *et al*., 2014). MPPT aims to maximize the produced power from the power source by controlling its operating conditions using power regulator unit (PRU). Complexity in the design and relatively lower efficiency are the disadvantages of the MPPT architecture.

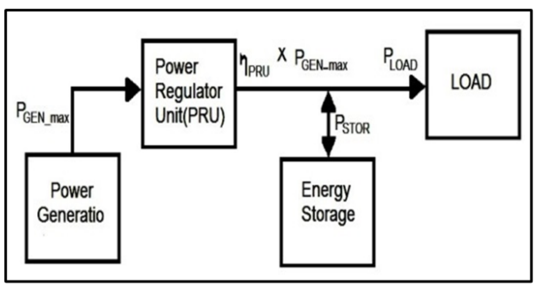

Figure (7) Simplified MPPT Architecture

Figure (7) shows MPPT architecture (Gonzalez, *et al*., 2014) (Hamidi, *et al*., 2020). We chose to implement MPPT because it offers several advantages compared to DET. Firstly, MPPT allows the use of solar arrays with different voltage levels, thus it can be used in different EPS. Secondly, the power output of each solar array will be optimized even for different radiation and temperature. Thus, MPPT is optimal when installed in satellites using body mounted solar cells, in which each side experiences different conditions. This is equivalent to having a distributed photovoltaic system. However, if a PV array is partially shaded, the conventional MPPT techniques track local MPP and fail to track global MPP. Also, if modules with different optimal currents are connected in series-parallel local MPPs occur in the P-V curves and conventional MPPT techniques fail to search global maxima. The MPPT ensure impedance matching between the PV generator and the load for maximum power transfer by controlling the duty cycle of boost converter. Solar radiation, load impedance and module temperature are the three factors which affect the maximum power extraction from solar PV module. It is known that the implementation of algorithms for constructing of load diagram, even for the simplest CubeSAT type nanosatellite, may require considerable computations on a typical modern computer. Therefore, there is a need to improve the methods of MPPT in order to find a reliable global tracking for maximum power in order to ensure the match load (ML) mode of nanosatellite power plant (Jasim and Shepetov,2017a) (Jasim and Shepetov, 2017c).

Shading Effects on PV Panels

Partial shading problem in solar panels to detect the global maximum power point that can be used in Nano-satellite system. Shading can occur due to several factors such as orbital motion. The shading can be broadly classified into two types:

a) Uniform Shading

b) Non- uniform/ Partial

The effect of partial shading on few cells is more detrimental to the solar panel operation when compared to uniform shading case. Partial shading is a vital issue for the following reasons (Farh and Eltamaly, 2020) (Jasim and Shepetov, 2016b) (Koutroulis and Blaabjerg, 2012):

1- Shaded cells can have unpleasant consequences and begin to consuming power instead of generating power, which leads to a complete loss of output power.

2- Loss of power in individual shaded cells can lead to local heating and temperature rise, which affects the surrounding cells. An increase in temperature causes thermal pressure on the entire module and causes hot spots and local defects that can lead to failure of the entire array. In under extreme cases of shading, the reverse bias of a solar cell may exceed its breakdown voltage. In such cases, the cell is completely damaged, develops cracks and an open circuit can occur at the serial branch where the cell is connected. However, in different lighting and temperature of panels, which is characteristic for nanosatellite, the watt-volt characteristic of PV can have curve with several maxima, which positions constantly change in the process of orbital motion Figure (8).

In such conditions, existing methods lose their effectiveness, since they can choose as an operating point a local, rather than global, maximum power. Therefore, existing methods of providing the matched load (Extreme Regulation) of solar photovoltaic power plants require improvement in order to constantly guarantee the choice of a global maximum power for reliable and efficient illumination of PV panels of nanosatellite operation in conditions of different illumination of PV panels of nanosatellite.

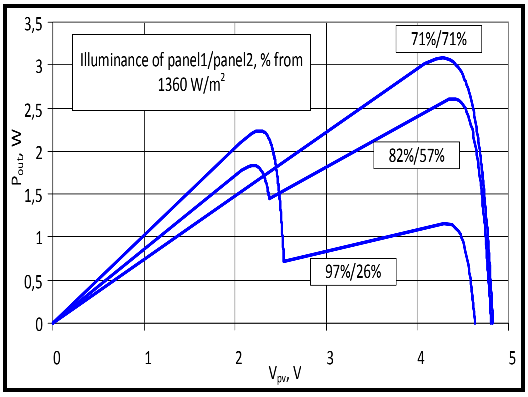

Figure (8) The Relation Between Output Power and Terminal Voltage for Transformation of the Power Curve in the Orbital Motion with Multi-directional Panel

Direct Current Boost Converter

Boost converter which are used in solar power plants and function on the basis of photovoltaic, including as part of nanosatellite, have been presented. MPPT uses the direct current converter for a different purpose regulating the input voltage at the PV module's MPP and providing load matching for the maximum power transfer. PV Array is connected with the direct current converter (boost converter as in Table (3), which has different dependence of the output voltage (V_{out}) on the duty cycle D and the input voltage (V_{in}), can be used in solar power plants (Yadav, 2012) (Jasim and Shepetov, 2017d).

Table (3) Parameters of Boost Converter

Parameter	Value
Input Capacitor, Cin (μf)	47
Output Capacitor, Co (μf)	70
Inductance, L (mH)	3
Switching Frequency, F(kHz)	5

$$V_{out} = \frac{V_{in}}{1-D} \tag{6}$$

$$R_{PV} = (1-D)^2 . R_{load} \tag{7}$$

Boost converter, which is controlled by pulse-width modulation (PWM). The required duty cycle of control pulses D is determined by the MPPT unit, which performs extreme regulation through tracking the maximum power point by operating the values of current and voltage at the input and output of the power converter see Table (3). The goal of the MPPT is to match the impedance of load to the optimal impedance of PV module. The output voltage of the power plant is directed to its own separate load, or to the main bus in the case of parallel operation with the power utility system, which has greater power. As implies, its typical application is to convert low input voltage to a high output voltage. Consequently, direct current converters of the boost type were considered in the future as the most shown suitable for nanosatellite because buck converter has lower efficiency than boost but buck-boost has the greater mass ratio, so we used here boost converter. The equivalent resistance seen from the source is the ratio of input source voltage and input current and duty cycle of the boost converter (Jasim and Shepetov, 2017a).

$$D = 1 - \sqrt{\frac{R_{PV}}{R_L}} \tag{8}$$

From the above equation, we can say that the value of input impedance of the boost converter and load impedance can be matched by controlling the duty cycle. The range of R_{PV} values for boost converters as shown in the following Figure (9), here (Consider $R_{in} = R_{PV}$, $R_o = R_L$). When R_{in} matches with that of R_{mp} ($R_L = R_{mp}$), the maximum power transfer from PV to the load will occur. Moreover, if the system is required to operate at or near the MPPs of the solar array without changing the load resistance, the resistance seen from the converter input side (Can be Adjusted by Changing the Duty Cycle) needs to match the load resistance.

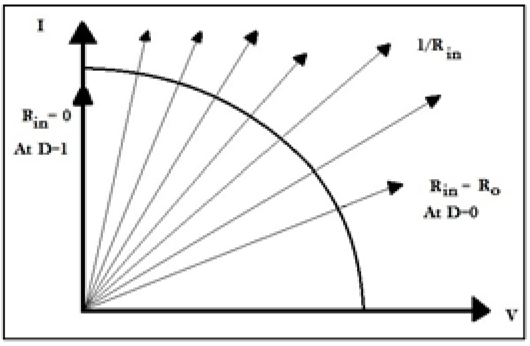

Figure (9) the Range of Rin Values for Boost Converters

When R_{in} increases, the operating point moves along the I-V curve from left to right as shown in Figure (9). It can be observed that there is specific value of Rin called optimal resistance (R_{mp}), which operates at the MPP of the PV. The dc-dc converters are widely used in photovoltaic generating systems as an interface between PV module and the load. These converters must be chosen to be able to match the maximum power point (MPP) of PV module when climatic conditions change. So, dc-dc converter must be used with MPPT controller in order to reduce losses in the global PV system (Yadav, 2012) (Jasim and Shepetov, 2016) (Jasim and Shepetov, 2017a).

Space Solar Power Load Matching under Different Light Panels

It is to be mentioned that the conversion efficiency of the solar PV type XTJ since the module efficiency is low; it is desirable to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and insolation conditions. Hence, maximization of power improves the utilization of the solar PV module. A maximum power point tracker (MPPT) is used for extracting the maximum power from the solar PV module and transferring that power to the load. According to the maximum power transfer theory, the power delivered to the load is a maximum when the source internal impedance matches the load impedance. A dc-dc converter (step up) can be used to serve the purpose of transferring maximum power from the solar PV module to the load. A dc-dc converter acts as an interface between the load and the solar PV module. In the work the method of TPMP was used, based on the gradient (Modified Hill Climbing Method) search of the point of the matched load (Jasim and Shepetov, 2017e). The method is to find the necessary incremental duty cycle of the control pulses ΔD by the formula:

$$\Delta D_i = \frac{P_i - P_{i-1}}{D_i - D_{i-1}} \times \frac{2}{P_i + P_{i-1}} \times \frac{1}{K_{sc}} \quad (9)$$

Where Pi, Pi-1 - Present and previous measured values output power; D_i, D_{i-1} – the present and previous values of duty cycle pulses; K_{sc} – scaling coefficients. To ensure the stability of the algorithm the incremental value is limited to the interval (-0.1:0.1).

$$\Delta D_i = \begin{cases} -0.1 & \text{if } \Delta D_i \le -0.1 \\ \Delta D_i & \text{if } -0.1 \le \Delta D_i < 0.1 \\ 0.1 & \text{if } \Delta D_{i+1} \ge 0.1 \end{cases} \quad (10)$$

The algorithm of the implementation of the proposed method of tracking PMP is presented in Figure (10).

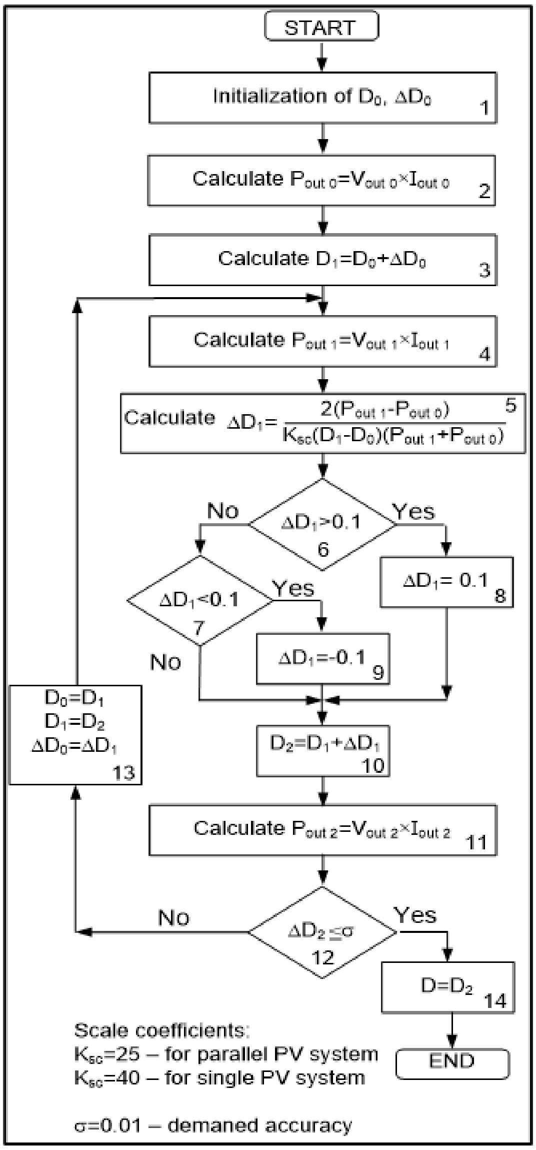

Figure (10) the Algorithm of the Proposed Method of the Tracking of PMP

However, this method in its pure form like the other mentioned methods does not provide reliable of tracking PMP if on the graphic chart P_{out} (D) there are the several maximums that may take place under the different lighting conditions and equilibrium temperature of several photovoltaic panels, which work at the same time. In this case, there is a need for a reliable choice of the starting point D so that it was near global maximum Pout (D), after which it will ensure a safe ascend into PMP. In this work, it was modeled to change the illumination or insolation of panels for the nanosatellite of the widely used standard CubeSat. The panels P1, P2, P4 and P6 are located on four sides of the cube Figure (11) and are connected in series in order to provide the necessary output voltage.

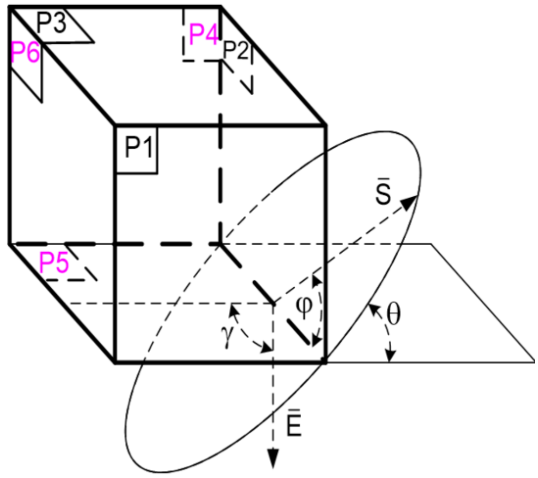

Figure (11) Design Model used for Calculate the Lighting of the CubeSat type

Where G_S = 1360 W/m^2 – the density of light flux under normal lighting panel, φ – The position of panel's type CubeSat nanosatellite relative to sun angles and θ– The Inclination angle of sun plane relative to satellite biased plane. The equilibrium temperature of the panels was calculated as Equation (12) (Radu, *et al*., 2002). Nanosatellite panels. $\bar{S}$ - Sun direction vector, $\bar{E}$ - Earth direction vector. At each moment, two panels are illuminated. Illumination panel defined following the cosine law as Equation (11).

$$\begin{aligned} G_{P1} &= G_s \cdot \cos\varphi, \\ G_{P2} &= G_s \cdot \cos\theta \cdot \sin\varphi \end{aligned} \qquad (11)$$

Where T_i - temperature of i-th panel; $\underline{\alpha}$ = 0.84 - the average coefficient of absorption of solar radiation; G_{ea} = 406 W/m^2 – albedo of the Earth; G_{ei} = 237 W/m^2 – the flow of infrared radiation from the Earth; ε_c = 0.84 – the average emissivity for solar cells sides; ε_a = 0.3 – the average emissivity for equipment sides; σ=5,67·10^{-8} W/m^2/K^4 – Stefan-

Boltzmann constant, bi – the function from the angle γ, which describes the position of a panel relative to the Earth, supposed bi to equal one.

$$T_i = \sqrt[4]{\frac{\bar{\alpha}\cdot(G_{Pi}+b_i(G_{ea}+G_{ei}))}{(4\cdot\bar{\varepsilon}_c+2\cdot\bar{\varepsilon}_a)\cdot\sigma}} \quad (12)$$

Where Ti - temperature of i-th panel; $\bar{\alpha}$= 0.84 – the average coefficient of absorption of solar radiation; G_{ea} = 406 W/m^2 – albedo of the Earth; G_{ei} = 237 W/m^2 – the flow of infrared radiation from the Earth; $\bar{\varepsilon}_c$ = 0,84 – the average emissivity for solar cells sides; $\bar{\varepsilon}_a$= 0.3 – the average emissivity for equipment sides; σ=5,67·10^{-8} W/m^2/K^4 – Stefan-Boltzmann constant, b_i – the function from the angle γ, which describes the position of a panel relative to the Earth, supposed bi to equal one.

Results and Discussion

The current study depends on the results of changing azimuth angle φ of nanosatellite from 0°– 45° and 90°– 45° at θ=0°. To calculate parameters of insolation and temperature of panels are shown in Table (4) and (5) respectively.

Table (4) Estimated Parameters of the Insolation and Temperature of Nanosatellite with the Sun *φ* =0°– 45°, θ=0°

Azimuth angle	φ	Gp_1, W/m^2	Gp_2, W/m^2	Tp_1, K	Tp_2, K
A	0°	1360	0	294	221
B	5°	1355	119	294	231
C	10°	1339	236	293	239
D	15°	1314	352	293	247
E	20°	1278	465	291	254
F	25°	1233	575	289	260
G	30°	1178	680	287	265
H	35°	1114	780	285	270
I	40°	1042	874	282	274
J	45°	962	962	278	278

Table (5) Estimated Parameters of the Insolation and Temperature of Nanosatellite with the Sun *φ* =90°– 45°, θ=0°

Azimuth angle	φ	Gp_1, W/m^2	Gp_2, W/m^2	Tp_1, K	Tp_2, K
A	90°	0	1360	221	294
B	85°	119	1355	231	294
C	80°	236	1339	239	293
D	75°	352	1314	247	293
E	70°	465	1278	254	291
F	65°	575	1233	260	289
G	60°	680	1178	265	287
H	55°	780	1114	270	285
I	50°	874	1042	274	282
J	45°	962	962	278	278

From changing azimuth angle φ of nanosatellite from 0°–45° at θ=0°, estimated power-voltage characteristic of the PV of the nanosatellite for different positions of the panels relative to the sun is presented in Figure (12). It can be seen that besides the positions corresponding to the angles φ =0° to φ =45°, the power curve has global and local maximum.

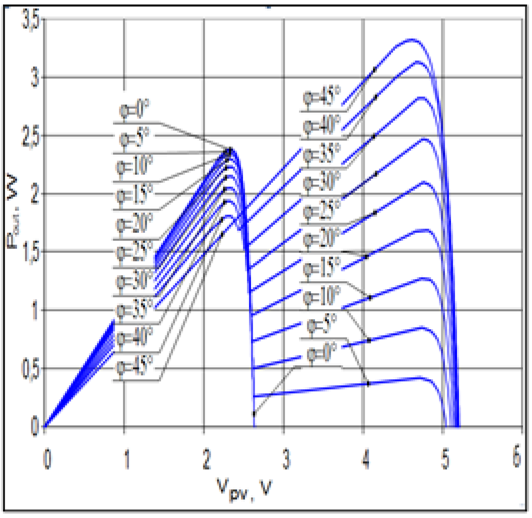

Figure (12) Dependence on the Output Power from Voltages for Different Positions of Panels Type Nanosatellite Relative to the Sun Direction, θ=0°.

To identify the position of the global power maximum there was first proposed using the power coefficient K_P. In Figure (13) by dependency on K_P from duty cycle pulses of dc-dc converter for the angle of inclination θ=0°.

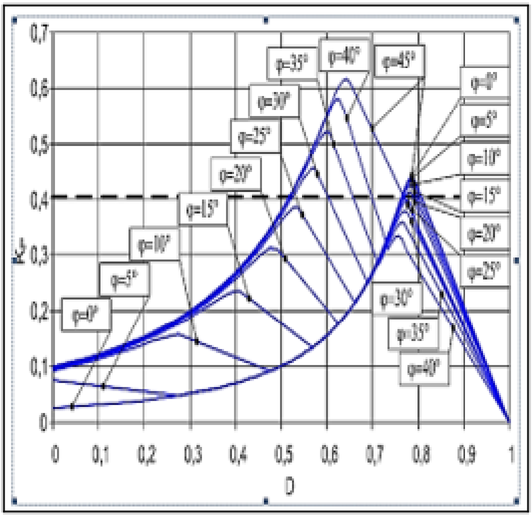

Figure (13) Shows Dependency on KP from Duty Cycle Pulses D of Boost Converter for Different Positions of Panels Relative to the Sun Direction, θ=0°

K_P, which is multiplication of the open circuit voltage coefficient K_V (the ratio of actual voltage to open circuit voltage V_{OC}) and the short circuit current coefficient of K_I (the ratio of the actual current to short circuit current I_{SC}) defined as Equation (13):

$$K_P = K_V.K_I = \frac{V_{pv}.I_{pv}}{V_{oc}.I_{sc}} = \frac{P_{pv}}{V_{oc}.I_{sc}} \quad (13)$$

In Figure (13) by dependency on K_P from duty cycle pulses of dc-dc converter for the angle of inclination θ=0°. Also, Figure (13) shows the coefficient K_P capacities for local maxima always less than a certain value to the global maxima of the same value. Then the algorithm for identification the position global maximum in this case lies in setting the initial value D = 0.8 – 0.9. Figure (13), then with the decrease of D with constant step 0.05 to achieve fulfillment of the condition $K_P \geq K_{P\ bound}$. After that, the controller can be found around of the global maximum area, which can be reached with the help of one of the known direct methods for tracking MPP. Taking into account the above mentioned, block 1 in Figure (10), needs to be modernized as shown in Figure (14).

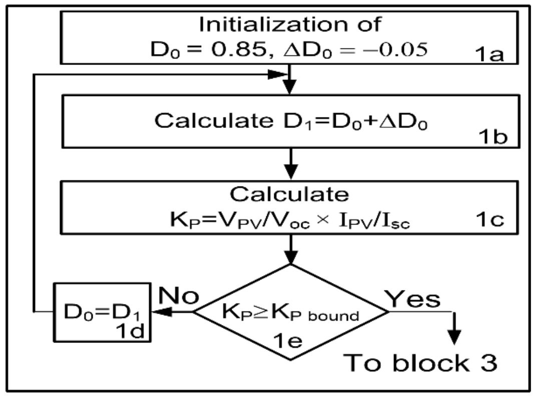

Figure (14) Modernization of MPP Algorithm for Reliable Reaching or Tracking Around of the Global Maximum area

For PV cells of this type, as shown in Figure (15), the bounding value of KP bound is 0.404. In the general case, this value depends on the magnitude of fill factor of a specific photovoltaic and is 0.447 from its magnitude as shown in Figure (16).

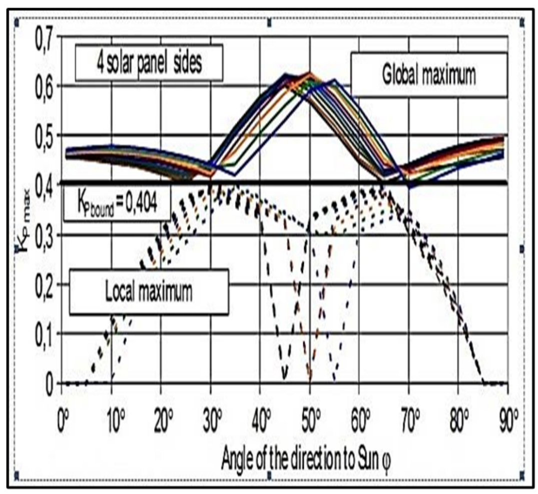

Figure (15) The Values of Power Coefficient KP for Global and Local Maximum for the Different Panels Relative to the Sun Direction, θ=0°– 45°

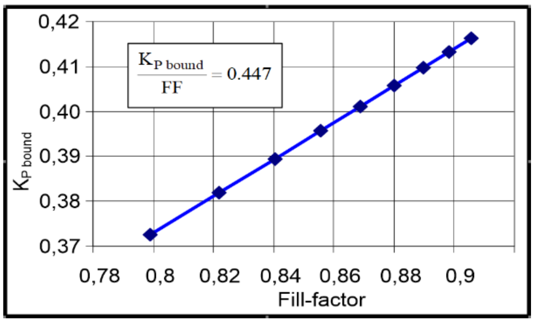

Figure (16) Dependence of the Bounding Value of the Power Coefficient on the Fill Factor of the PV Cell

Using the power coefficient K_p in combination with direct method TPMP to track the point of maximum power allows to provide the mode of matched load for all positions of satellite relative to the sun at the expense of guaranteed identification of the neighborhood of the global maximum power. In Figure (17) shows calculated depending on output power related to the installed capacity (installed Capacity Utilization Factor - ICUF) for different angles towards the sun.

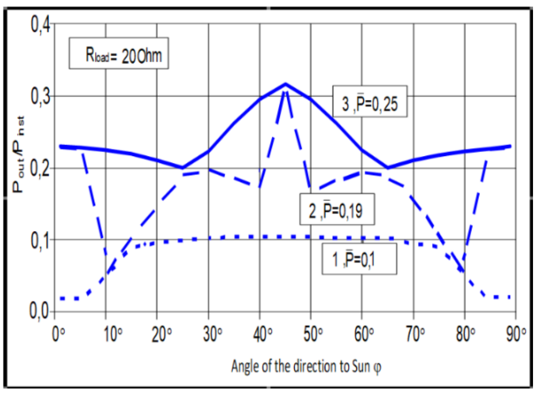

Figure (17) The Relative Output Power at Different Positions of Solar Panels Relative to Sun for Mismatched Load (1), Matched Load Without Power Coefficient Control (2), Matched Load with Using the Power Coefficient (3), θ=0

Conclusion

- In the work an important scientific task of increasing the output power of solar power plants of spacecraft with non-oriented panels of photovoltaic cells in conditions of different illumination of these panels due to providing the mode of the matched load of solar power systems of nanosatellites is solved by the improvement of the method of finding the point of maximum power of a photovoltaic panel with more reliable identification of the global maximum of power.
- An indirect method of TPMP of a photovoltaic panel operating in conditions of different illumination of panels is improved by using a power coefficient representing a product of the open circuit voltage coefficient and short circuit current coefficient, which provides a reliable identification of the global maximum of the power of the photovoltaic panels in conditions for the presence of several local maximum and the mode of matched load of solar power systems of a nanosatellite.
- The proposed method of providing the matched load mode with using the power coefficient can increase the average installed capacity utilization factor up to (36 - 40%) under different illumination of panels.
- The mathematical model of solar photovoltaic power plant with extreme power control, which is conducted with the help of pulse-width modulation and a simulation of the solar power plant with a dc-dc converter, is developed.
- Development methods for tracking the point of maximum power of a solar PV plant based on a hybrid of direct and advanced indirect methods of tracking the position of the point of maximum power in the conditions of the existence of several highs on the volt-watt characteristic of the photovoltaic panels of the nanosatellite, which allows uniquely determine the position of the global maximum of power and avoid

power losses that may occur when one of the local maximums is selected relative to the use existing methods.

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