UDC 621.314 **doi: 10.20998/2074-272X.2020.2.10**

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REGULATORY CHARACTERISTICS OF THE STEP-DOWN SWITCHING REGULATOR WHICH CHARGES THE BATTERY FROM THE SOLAR BATTERY

Problem.** An important element of autonomous power sources, built on the basis of solar batteries, is a battery, operating in a buffer mode. To extend the period of its use, it is necessary to ensure the appropriate modes of its charging and discharging, by regulating the charging and discharge currents. To ensure that maximum power can be transferred to the load in various operating modes, a matching switching regulator is included between the solar battery and the load. In the case of its application, it becomes possible to simultaneously regulate the charging current of the battery. For the most effective regulation of this current, it is necessary to know the regulatory characteristics of the regulator. **Goal.** The aim of the work is to determine and analyze the regulatory characteristics of the switching voltage regulator step-down type, which charges the battery from the solar battery. **Methodology.** Using the theory of switching voltage regulators, a relationship between the output characteristic of the source and the regulatory characteristic of the regulator are established. The graphs of the regulatory characteristics are carried out by the graphoanalytical method. **Results.** The dependence of the output current of the solar battery, from well as the current of the charged battery, on the relative time of the closed state of the key of the switching regulator are analyzes. A technique for constructing the regulatory characteristics of a switching regulator for a given type of output characteristic of a power source and operating voltage of a battery is proposed. For typical output characteristics of the solar battery, graphs of the regulatory characteristics of the switching regulator for various levels of illumination of the solar battery are constructed. When constructing the regulatory characteristics, the possibility of an intermittent current mode in the inductance of the switching regulator is taken into account. **Originality.** The results obtained make it possible to take into account the influence of the internal resistance of the power supply, in particular, substantially nonlinear, on the regulatory characteristics of the switching regulator. **Practical value.** The proposed technique can be used to determine the regulatory characteristics of other types of regulators, the power source of which has a non-linear output characteristic. Using the obtained regulatory characteristics, it is possible to determine the conditions under which maximum power will be transmitted from the solar battery to the battery. These characteristics can be used in the elaboration of solar battery charge controllers. References 8, figures 4.

Key words: **switching regulator, regulatory characteristic, solar battery, battery, internal resistance.**

Розглянуто підходи до визначення регулювальних характеристик імпульсного регулятора напруги понижувального типу, джерелом живлення якого є сонячна батарея, а навантаженням – акумулятор. Проаналізовано залежність регулювальних характеристик регулятора від типу вихідної характеристики джерела електроживлення з урахуванням нелінійності його внутрішнього опору. Запропоновано методику визначення регулювальної характеристики регулятора для заданого виду вихідної характеристики джерела, з урахуванням можливості виникнення режиму переривчастого струму в його індуктивності. Розроблено рекомендації щодо забезпечення можливості передавання максимально можливої потужності від сонячної батареї до акумулятора. Бібл. 8, рис. 4.

Ключові слова: **імпульсний регулятор, регулювальна характеристика, сонячна батарея, акумулятор, внутрішній опір.**

Рассмотрены подходы к определению регулировочных характеристик импульсного регулятора напряжения понижающего типа, источником питания которого является солнечная батарея, а нагрузкой – аккумулятор. Проанализирована зависимость регулировочных характеристик регулятора от типа выходной характеристики источника электропитания с учетом нелинейности его внутреннего сопротивления. Предложена методика определения регулировочной характеристики регулятора для заданного вида выходной характеристики источника, с учетом возможности возникновения режима прерывистого тока в его индуктивности. Разработаны рекомендации по обеспечению возможности передачи максимально возможной мощности от солнечной батареи к аккумулятору. Библ. 8, рис. 4.

Ключевые слова: **импульсный регулятор, регулировочная характеристика, солнечная батарея, аккумулятор, внутреннее сопротивление.**

Introduction. The scope of non-traditional and renewable sources of electricity is expanding every year. The peculiarity of such sources is the dependence of the amount of electricity produced by them on external conditions. Therefore, using similar sources, intermediate storage energy is used. As a storage device, batteries are often used [1, 2]. Rechargeable batteries have a limited life, which depends on the provision of appropriate charging and discharging modes [3, 4]. Battery life can be extended, if not rechargeable, as well as do not permit its deep discharge. In the process of charging the battery, it is desirable to be able to regulate the charge current according to a certain law [1, 2]. To provide these functions special devices – battery charge controllers are used [1, 4]. One of the components of such devices is the battery charge current regulator. As such a regulator it is advisable to use voltage switching regulators (SRs) [1, 5, 6]. As is known [7] in the case of operation of such a regulator on the battery, it will operate in the mode of regulation of the output current. In connection with this, such a regulator can be used to regulate the charging current of the battery. If necessary, maximum power output from the source can be provided.

The most important characteristic of any regulator is its regulatory characteristic. In the case of power from traditional electricity sources, it is often assumed that the load resistance is much greater than the internal resistance of the source. Therefore, when determining the regulatory characteristics, it is not taken into account, considering it to be zero [8]. Non-traditional and renewable energy sources often have limited power. Their internal resistance and load resistance are of one order of magnitude. In such cases, the internal resistance of the source will significantly affect the regulatory characteristics and must be taken into account.

In [7] the regulatory characteristics of a SR operation on the battery for cases where the power source is traditional and its internal resistance is close to linear are analyzed. However, the internal resistance of non-traditional and renewable electricity sources is often substantially non-linear. When using SR as a battery charging current regulator, it is important to know its regulatory characteristics.

The goal of the work is to develop a method for determining the regulatory characteristics of the switching voltage regulators for the case where the internal resistance of the power source is substantially nonlinear and the battery is connected at the output. Let's analyze the regulatory characteristics of the SR step-down type for the case when the power source is a solar battery (SB) and the battery is connected at its output.

The method of determining the regulatory characteristics. If the DC step-down SR (Fig. 1) operates in the continuous inductance L current mode, the average values of its input and output voltage are connected by the relation [8]

$$U_{out} = U_{in} t^*, \qquad (1)$$

where $t^* = t_{cl} / T$ is the relative time of the lock state of the switch S.

In the case where the internal resistance of the battery is much less than the internal resistance of the power source, it can be assumed that the output voltage of the SR coincides with the voltage of the battery, i.e. $U_{out} = E_a$.

Under these conditions, the input voltage of the SR will depend on the relative time t^*

$$U_{in} = U_{out} / t^* = E_a / t^*. \qquad (2)$$

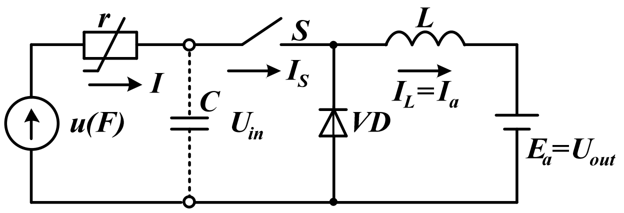

Fig. 1. Step-down switching regulator that charges the battery from the solar battery

If the input voltage source is considered perfect ($U_{in} = E$; $r = 0$), steady-state operation mode of the SR will be possible only at a fixed value t^*

$$t^* = E_a / E, \qquad (3)$$

and the output current of the SR is uncertain and depends on the previous mode of operation of the SR.

For $t^* > E_a / E$ the output current will increase indefinitely, and for $t^* < E_a / E$ the SR goes into the mode of intermittent current of the inductance L.

In real power supply sources that have a certain internal resistance r, the output voltage does not remain constant and varies according to their load characteristics. In such cases, the system will be in equilibrium at a given t^* only at a certain value of the current I consumed from the source.

Linear internal resistance of the source. Let the internal resistance r of the source E be linear. Then its output voltage will be determined by the known relationship [8]

$$U = U_{in} = E - I \cdot r. \qquad (4)$$

Therefore, the average value of current consumed from source E can be determined by equating (2) and (4)

$$E - I \cdot r = E_a / t^*,$$

wherefrom

$$I = \frac{E - E_a / t^*}{r} = \frac{E \cdot t^* - E_a}{r \cdot t^*}. \qquad (5)$$

If the capacitor C is absent ($C = 0$) at the SR input, a pulsed current will be consumed from the source E, the average value of which *at the interval* t^* will coincide with the average value *at the period* of the charging current of the battery $I_a = I_L$. Therefore, in this case, the regulatory characteristic for the battery charging current will look like

$$I_a = \frac{E \cdot t^* - E_a}{r \cdot t^*}. \qquad (6)$$

However, if a capacitor C of sufficient capacitance ($C \neq 0$) is placed at the input of the SR, the output current of source I becomes continuous. In such cases, the average values of the currents I and I_a will be related by the relationship [7]

$$I_a = I / t^*. \qquad (7)$$

Therefore, in the presence of capacitor C, the regulatory characteristic of the SR (Fig. 1) will look like

$$I_a = \frac{E \cdot t^* - E_a}{r \cdot t^{*2}}. \qquad (8)$$

The obtained regulatory characteristics (6) and (8) coincide with the characteristics obtained in [8] otherwise by other considerations.

Nonlinear internal resistance of the source. The solar battery, as a power source, is characterized by a *substantially nonlinear* internal resistance. Its output voltage will depend on the external conditions as well as on the output current. In the presence of an E_a battery at the output of the SR operation in the of continuous-current mode of the reactor L, the condition of equilibrium must necessarily be satisfied

$$U_{SB} = E_a / t^*. \qquad (9)$$

The voltage value of the selected battery E_a will determine the minimum possible voltage at which it is still possible to transfer energy from the SB to the battery

$$U_{SB\min} = E_a. \qquad (10)$$

According to (9), the SR in this mode of operation will operate with $t^* = 1$. In case of decrease in $t^* < 1$, the output voltage of the SB must increase, which, under the existing external conditions, may result from a decrease in its output current. Therefore, in the case of a given illumination of the SB F, the maximum current will be taken away from it provided that $t^* = 1$. If $t^* < 1$ decreases, the output voltage of the SB will increase and the output current will decrease. At a certain value of

$t^* = t^*_{\min}$ the output current of the SB becomes zero, and output voltage becomes the idle voltage U_{oc}. Since condition (9) is required for the system under consideration, it is possible to determine a minimum relative switch-locking time $t^*_{\min}$ that will correspond to the SB operation in the idle mode at maximum illumination

$$t^*_{\min} = E_a / U_{oc\max} = E^*_a . \qquad (11)$$

We draw the voltage of the selected battery E^*_a on the voltage axis of the typical normalized output characteristics of the SB (Fig. 2). This voltage will determine the minimum possible voltage at the output of the SB. According to the presented characteristics, the maximum possible output voltage of the SB corresponds to the voltage of the SB in the idle mode with maximum illumination F_1. For the selected battery with voltage E_a, from (11) we determine the relative time $t^*_{\min}$ that will correspond to the specified mode of operation. If, now, parallel to the voltage axis, the axis of relative time t^* is drown and to point on it the obtained values $t^*_{\max} = 1$ corresponding to the voltage $U_{SB\min} = E_a$, and $t^*_{\min}$, and corresponding to the voltage of the SB $U_{oc\max}$, we obtain the dependence of the output current of the SB on the relative time of the closed state of the switch t^*.

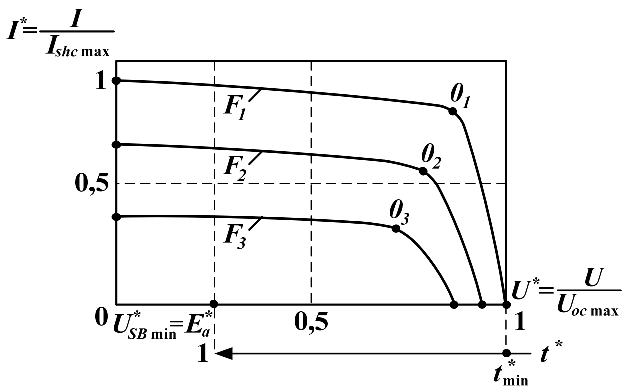

Fig. 2. Typical normalized output characteristics of the SB

It is obvious that in these graphs the directions of growth of the parameters t^* та U^* are opposite.

For greater clarity and ease of use, in Fig. 3 for the case $E^*_a = 0{,}4$ the same graphs are constructed with the conventional axis direction of the coordinate system.

Figure 3,*a* presents the dependence of the average value of the SB current on the relative time t^*, and Fig. 3,*b* shows the regulatory characteristics $I^*_a = f(t^*)$ for the absence ($C = 0$) and the presence ($C \neq 0$) of the capacitor C at the output of the SB.

If the capacitor C is absent ($C = 0$), the SB will operate in the pulsed mode in which the average value of the current of the SB *at the interval* t^* coincides with the average value of the charging current of the battery I_a *at the period* T. Therefore, for this mode the regulatory characteristics for the current of the SB I (Fig. 3,*a*) and the charging current of the battery I_a (Fig. 3,*b*) will coincide. However, in this operation mode, the maximum possible amount of electricity cannot be drawn from the SB. Therefore, it is not appropriate to use this mode of operation to charge batteries from the SB.

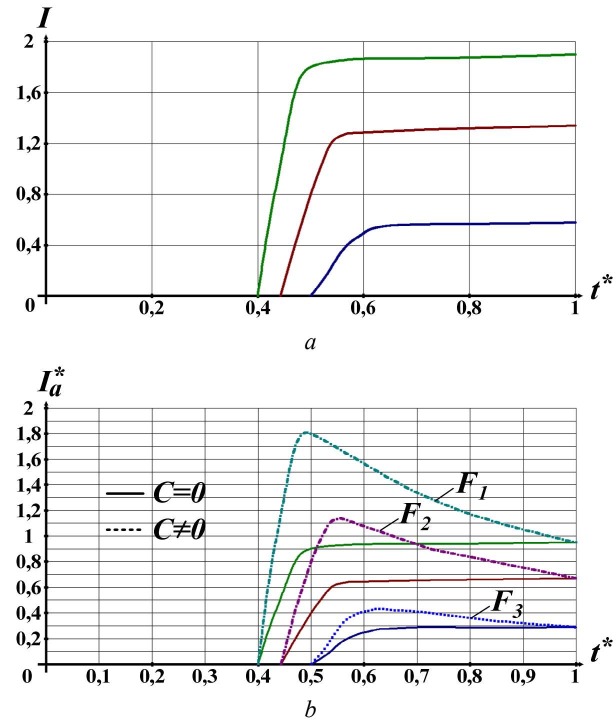

Fig. 3. Regulatory characteristics: *a*) of the current of the solar battery; *b*) of the battery charging current

If a capacitor C of sufficiently large capacitance ($C \neq 0$) is placed at the output of the SB, the current of the SB becomes continuous and its average value is related to the average value of the battery charging current by the relationship (7). Under such conditions, the maximum possible power will be transmitted from the SB operating at the maximum power point (MP) to the E_a battery (Fig. 3,*b*).

If $t^* < t^*_{MP}$ decreases, the charging current of the battery I_a will drop rapidly and at $t^* = t^*_{\min}$ it should be zero. However, in the real world, at a certain value of $t^* = t^*_{cr} > t^*_{\min}$, the SR goes into the intermittent-current reactor L mode, in which with decreasing t^* in the range $(t^*_{cr}...0)$, the average charging current of the battery I_a will gradually drop from the initial value $I^*_{acr} = I^*_a(t^*_{cr})$ to zero. To determine the numerical values of t^*_{cr}, we can use the methodology discussed in [7]. For example, in the case of $E^*_a = 0{,}4$ at the maximum illumination F_1, depending on the inductance of the reactor L, the numerical value of t^*_{cr} lies in the range (0.406 ... 0.41).

Figure 4 is a graph of the regulatory characteristic $I^*_a = f(t^*)$ taking into account the possibility of the mode of intermittent current of the reactor L. The regulatory characteristics for other (smaller) levels of illumination F will have the similar character.

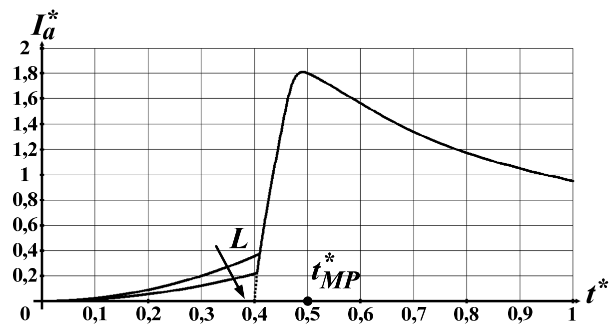

Fig. 4. Regulatory characteristic of the battery charging current taking into account the occurrence of the mode of intermittent current of inductance L

The analysis of the obtained regulatory characteristics shows the following:

1) in case of charging of the battery from the SB with the use of the step-down voltage SR, in order to allow the maximum amount of energy to be drawn from the SB, a capacitor C of a sufficiently large capacitance must be installed at its output;

2) the regulatory characteristics for the battery charging current are substantially nonlinear;

3) with a change in t^* in the range from t_{MP}^* to 0, the charging current of the battery I_a decreases rapidly, and in a large part of this range the SR will operate in the mode of intermittent current of the reactor L;

4) with a change in t^* in the range from t_{MP}^* to 1, the current I_a will decrease more smoothly. The SR will operate in continuous current mode of the reactor L. However, in this case the range of current regulation is limited.

Conclusions. A developed technique for determining the regulatory characteristics of switching voltage regulators for the case when the power source is a solar battery and the battery connected at the output can be used for other types of renewable and non-traditional sources with nonlinear internal resistance.

REFERENCES

1. Osaretin C.A., Edeko F.O. Design and implementation of a solar charge controller with variable output. *Electrical and electronic engineering*, 2015, vol. 12, no. 2, pp. 40-50.

2. Haq I.N., Leksono E., Iqbal M., Sodami F.X.N., Nugraha, Kurniadi D., Yuliarto B. Development of battery management system for cell monitoring and protection. *2014 International Conference on Electrical Engineering and Computer Science (ICEECS)*, Kuta, Nov. 2014, pp. 203-208. **doi: 10.1109/ICEECS.2014.7045246**.

3. Krieger E.M., Arnold C.B. Effects of undercharge and internal loss on the rate dependence of battery charge storage efficiency. *Journal of Power Sources*, 2012, vol. 210, pp. 286-291. **doi: 10.1016/j.jpowsour.2012.03.029.**

4. Ashiquzzaman M., Afroze N., Hossain J.M., Zobayer U., Hossain M.M. Cost effective solar charge controller using microcontroller. *Canadian Journal on Electrical and Electronics Engineering*, 2011, vol. 2, no. 12, pp. 572-576.

5. Romashko V.Y., Matching device load from the source of electrical energy. *Energy saving. Power engineering. Energy audit*, 2013, no. 8 (114), vol. 1, pp. 67-74.

6. Vieira J.A.B, Mota A.M. Implementation of a stand-alone photovoltaic lighting system with MPPT battery charging and LED current control. *2010 IEEE International Conference on Control Applications*, Sep. 2010, pp. 185-190. **doi: 10.1109/CCA.2010.5611257.**

7. Romashko V., Batrak L. Regulation characteristics of the step-down switching regulator which operates on a rechargeable battery. *Bulletin of the National Technical University «KhPI» Series: New solutions in modern technologies*, 2019, no. 10 (1335), pp. 30-37. **doi: 10.20998/2413-4295.2019.10.04.**

8. Goncharov Y.P., Budonny O.V., Morozov V.G., Panasenko M.V, Romashko V.Y., Rudenko V.S. *Peretovyuvalna technicala. Navchalnyi posibnyk. Ch. 2* [Power conversion equipment. Part 2]. Kharkiv, Folio Publ., 2000. 360 p.

Received 29.11.2019

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How to cite this article:
Romashko V.Ya., Batrak L.M., Abakumova O.O. Regulatory characteristics of the step-down switching regulator which charges the battery from the solar battery. *Electrical engineering & electromechanics*, 2020, no.2, pp. 64-67. **doi: 10.20998/2074-272X.2020.2.10.**