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V.Y. Romashko, L.M. Batrak, O.O. Abakumova

Features of the work of pulse regulators in the maximum power transmission mode, with the presence of an accumulator at their output

Introduction. *For the efficient use of non-traditional and renewable sources of electrical energy, it is necessary to ensure their operation at the maximum power point, which is possible if the load resistance is equal to the output resistance of the source. To match the load resistance with the output impedance of the source, a matching switching regulator is connected between the source and the load. Very often, the amount of energy received from such sources depends on external conditions. To ensure a uniform supply of electrical energy to the load, a battery operating in buffer mode is connected at the output of the switching regulator.* ***Problem.*** *In this case, the load of the switching regulator is the battery, and the input impedance of the regulator will perform the role of the load of the power source. This resistance depends on the voltage of the battery, the type of switching regulator and its mode of operation. In such cases, the maximum power extraction mode from the source can be provided by selecting the appropriate operating mode of the switching regulator. The* ***aim*** *of the work is to analyze the conditions and determine the modes under which the transfer of the maximum possible amount of electrical energy from the source to the battery is ensured, as well as the features of the switching regulator in these modes.* ***Methods.*** *For this purpose, the regulating characteristics of step-up and step-down switching regulators were determined and analyzed, taking into account the presence of an accumulator at their output. Taking into account that in the maximum power transmission mode, the output resistance of the source and the load resistance are of the same order of magnitude, when determining the regulating characteristics, the internal resistance of the source was taken into account.* ***Results.*** *As a result of the analysis of the obtained regulating characteristics, the conditions were determined under which the transfer of energy from the source to the battery is ensured, and the parameters of the operating mode of the switching regulator were determined, under which the maximum power will be taken from the source of electrical energy.* ***Novelty****. The originality of the work is the consideration of the internal resistance of the source of electrical energy in determining the regulating characteristics of pulse regulators.* ***Practical value****. The obtained results made it possible to indicate the appropriate range of battery voltages for different types of pulse regulators, as well as to give practical recommendations for choosing the mode of operation of the pulse regulator depending on its type, as well as the amount of voltage on the battery.* References 17, tables 1, figures 4.

Key words: **source output impedance, matching switching regulator, battery operation, maximum power transmission.**

Для ефективного використання нетрадиційних та відновлюваних джерел електричної енергії необхідно забезпечувати їх роботу в точці максимальної потужності, що можливо при рівності опору навантаження та вихідного опору джерела. Для узгодження опору навантаження з вихідним опором джерела між джерелом та навантаженням підключають узгоджувальний імпульсний регулятор. Досить часто кількість енергії, що отримують від подібних джерел, залежить від зовнішніх умов. Щоб забезпечити більш рівномірне надходження електричної енергії до навантаження, на виході імпульсного регулятора підключають акумулятор, що працює в буферному режимі. За таких умов навантаженням імпульсного регулятора є акумулятор, а роль навантаження джерела живлення виконуватиме вхідний опір регулятора. Цей опір залежить від величини напруги на акумуляторі, типу імпульсного регулятора та режиму його роботи. У таких випадках режим відбору максимальної потужності джерела може бути забезпечений шляхом вибору відповідного режиму роботи імпульсного регулятора. ***Метою*** *роботи є аналіз умов та визначення режимів, за яких забезпечується передача від джерела в акумулятор максимально можливої кількості електричної енергії, а також особливостей роботи імпульсного регулятора у зазначеному режимі. З цією метою було визначено та проаналізовано регулювальні характеристики імпульсних регуляторів підвищувального та понижувального типів з урахуванням наявності акумулятора на їх виході. Враховуючи, що у режимі передавання максимальної потужності вихідний опір джерела та опір навантаження є величинами одного порядку, при визначенні регулювальних характеристик враховувався внутрішній опір джерела. В результаті аналізу отриманих регулювальних характеристик було визначено умови, за яких забезпечується передавання енергії від джерела до акумулятора, а також визначено параметри режиму роботи імпульсного регулятора, за яких від джерела електричної енергії буде відбиратися максимальна потужність.* ***Оригінальністю*** *роботи є врахування внутрішнього опору джерела електричної енергії при визначенні регулювальних характеристик імпульсних регуляторів. Одержані* ***результати*** *дали можливість вказати доцільний діапазон напруг акумулятора для різних типів імпульсних регуляторів, а також дати практичні рекомендації щодо вибору режиму роботи імпульсного регулятора у залежності від його типу, а також величини напруги на акумуляторі.* Бібл. 17, табл. 1, рис. 4.

Ключові слова: **вихідний опір джерела, узгоджувальний імпульсний регулятор, робота на акумулятор, передавання максимальної потужності.**

Introduction. In connection with the significant spread of non-traditional and renewable sources, the task of obtaining the maximum possible amount of electrical energy from them arises. For this, the operating point of the power source must be at the maximum power point (MPP). As is known [1-4], such a mode of operation of the source will be provided under the condition that the resistance of the load R coincides with the output resistance of the source r. If $R \neq r$, in order to ensure the possibility of taking maximum power from the source, a pulse regulator (PR) is switched on between the source and the load, which matches the resistance of the load with the output resistance of the source. Today, the main method of taking maximum power from non-traditional and renewable sources is the use of various algorithms to search for MPP of the source [5-10]. Most of these algorithms consist in periodically changing the duration of the locked state of the PR key and, depending on the consequences of such a change, adjusting this duration in the direction of decrease or increase. The main disadvantage of such methods is that at the time of start-up or a sudden change in external conditions, when the coordinates of the MPP are unknown, its search may take a certain amount of time, during which a certain amount of energy will not be received from the source. Moreover, in the process of searching for MPP, there may be cases when the duration of the locked state of the key will change in the opposite direction from the required one, which will increase the amount of under-received energy. Supplementing the existing algorithms with analytical methods for determining the MPP makes it possible to significantly speed up its search and reduce the amount of electricity not received from the source.

Quite often, the amount of energy coming from non-traditional and renewable sources depends on external conditions. Therefore, to ensure a more uniform supply of energy to the load, a battery is connected to the PR output, which operates in buffer mode [11-13]. In such cases, the PR load will be the battery itself, and the role of the source load will be performed by the input resistance of the regulator. The mode of selection from the source of maximum power can be ensured by selecting the appropriate operating mode of the PR.

The goal of the work is to analyze the conditions under which it is possible and expedient to transfer the maximum possible amount of electrical energy from the power source to the battery, as well as the features of PR operation in this mode.

To do this, it is necessary to determine and analyze the control characteristics of the regulator, taking into account the internal resistance of its power source. Let's consider these questions on the example of PR circuits of step-down and step-up types, which are most often used to match the output resistance of the power source with the load resistance.

Determination and analysis of regulatory characteristics. Since we are interested in extracting the maximum power from the power source, we will consider those variants of PR circuits that provide this possibility [14]. The corresponding circuits of step-down and step-up regulators are presented in Fig. 1, 2.

We will assume that the internal resistance of the source r is linear, and the internal resistance of the battery is much smaller compared to the internal resistance of the source. We will determine and analyze the control characteristics of the regulator circuits presented in Fig. 1, 2.

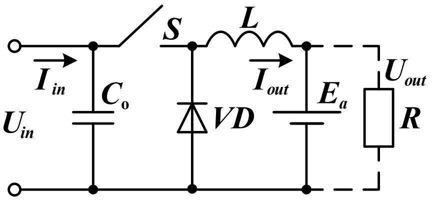

Fig. 1. Circuit of the step-down regulator

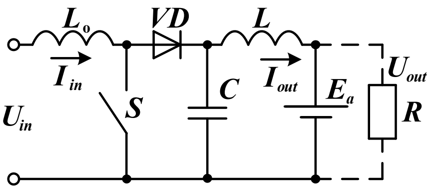

Fig. 2. Circuit of the step-up regulator

Step-down type regulator. If losses in the elements of the PR circuit are not taken into account, for the regulator (Fig. 1) in the mode of continuous inductance current, the conditions will always be fulfilled [15]

$$U_{out} = U_{in} t^* ; \; I_{out} = I_{in} / t^* , \quad (1)$$

where $t^* = t_c/T$ is the relative time of the locked state of the key S.

Taking into account that the internal resistance of the battery is much smaller than the internal resistance of the source, we can assume that during the adjustment process the output voltage of the regulator remains almost unchanged and is equal to $U_{out} = E_a$. Therefore, in order for the system to be in a state of equilibrium in the process of regulation, the input voltage of the regulator must be

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

In real power sources, due to the presence of internal resistance in them, the input voltage of the regulator will change due to changes in the current consumed by the source. In the case of linear internal resistance of the source, its output voltage (PR input voltage U_{in}) will be determined by the output characteristic of the source

$$U_{in} = U_{oc} - I_{in} r , \quad (3)$$

where U_{oc} is the open-circuit voltage of the power source.

Therefore, in the state of equilibrium, (2), (3) must be fulfilled simultaneously

$$U_{oc} - I_{in} r = E_a / t^* , \quad (4)$$

or in relative units [15]

$$1 - I_{in}^* = E_a^* / t^* , \quad (5)$$

where $I_{in}^* = I_{in} / I_{sc}$; $U^* = U / U_{oc}$; $E_a^* = E_a / U_{oc}$; $I_{sc} = U_{oc} / r$ is the short-circuit current of the source.

Taking into account that the open-circuit voltage of the source, as well as the battery voltage, are fixed values, as a result of changes in the parameter t^*, the input and, accordingly, the output current of the regulator will be adjusted

$$I_{in}^* = \left[1 - E_a^* / t^* \right] . \quad (6)$$

Taking into account (1)

$$I_{out}^* = I_{in}^* / t^* = \left[1 - E_a^* / t^* \right] \cdot \frac{1}{t^*} . \quad (7)$$

Therefore, the control characteristics of PR (Fig. 1) are described by (6), (7). Let's analyze the obtained characteristics.

According to (6), to ensure the transfer of energy from the power source to the battery ($I_{in} > 0$), the condition must be fulfilled

$$\left[1 - E_a^* / t^* \right] > 0 , \quad (8)$$

or

$$t^* > E_a^* . \quad (9)$$

Considering the physical content of the parameter t^*, we conclude that it can vary within a limited range

$$1 \ge t^* > E_a^* , \quad (10)$$

and the battery voltage cannot be greater than the open-circuit voltage of the power source. The lower the battery voltage E_a^*, the wider the permissible range of adjustment of the parameter t^*.

As is known [16], in the case of linear internal resistance of the source, its MPP has coordinates $I^* = 0,5$; $U^* = 0,5$. Taking into account that $I^* = I_{in}^*$ of the regulator, the condition for taking the maximum power from the source according to (6), takes the form

$$\left[1 - E_a^* / t^*\right] = 0,5 . \quad (11)$$

Thus, the maximum power from the source to the battery will be transferred provided that $t^* = t_{MP}^*$, where

$$t_{MP}^* = 2E_a^* . \quad (12)$$

Taking into account that t^* = [0...1], we conclude that the maximum power from the source to the battery can be transferred only if

$$E_a^* \leq 0,5 . \quad (13)$$

Step-up type regulator. For this regulator (Fig. 2), in the mode of continuous inductance current, the following relations are valid

$$U_{out} = U_{in} / t^* ; \quad I_{out} = I_{in} t^* , \quad (14)$$

where $t^* = t_{open} / T$; t_{open} is the duration of the unlocked state of the key *S* on the period *T*. So, in steady state, the input voltage of the regulator should be

$$U_{in} = U_{out} t^* = E_a t^* . \quad (15)$$

The system will be in a state of equilibrium under the condition

$$E_a t^* = U_{sc} - I_{in} r . \quad (16)$$

In relative units, this condition will look like

$$E_a^* t^* = 1 - I_{in}^* . \quad (17)$$

Therefore, the control characteristics of the PR of the step-up type (Fig. 2) will be as follows

$$I_{in}^* = \left[1 - E_a^* \cdot t^*\right]; \quad (18)$$

$$I_{out}^* = \left[1 - E_a^* \cdot t^*\right] t^* . \quad (19)$$

According to (18), the condition of energy transfer from the source to the battery ($I_{in}^* > 0$) will have the form

$$I_{in}^* = \left[1 - E_a^* \cdot t^*\right] > 0 , \quad (20)$$

that is, the parameter t^* can vary in the range

$$0 < t^* < 1 / E_a^* . \quad (21)$$

So, for this regulator, the battery voltage, theoretically, can be both higher and lower than the open-circuit voltage of the source. However, in the case of $E_a^* > 1$, the permissible range of adjustment of the parameter t^* will be limited. The stronger the inequality $E_a^* > 1$ is fulfilled, the narrower the permissible parameter t^* adjustment range will be.

The condition of taking from the source of maximum power will be as follows

$$\left[1 - E_a^* t^*\right] = 0,5 . \quad (22)$$

So,

$$t_{MP}^* = 1 / 2E_a^* . \quad (23)$$

Taking into account (23), the maximum power can be taken from the source only if

$$E_a^* \geq 0,5 , \quad (24)$$

that is, the battery voltage can be both higher and lower than the open-circuit voltage of the source. Figures 3, 4 present graphs of the family of control characteristics of the considered regulators for different values of the relative voltage on the battery E_a^* . These graphs confirm the results of the analysis carried out.

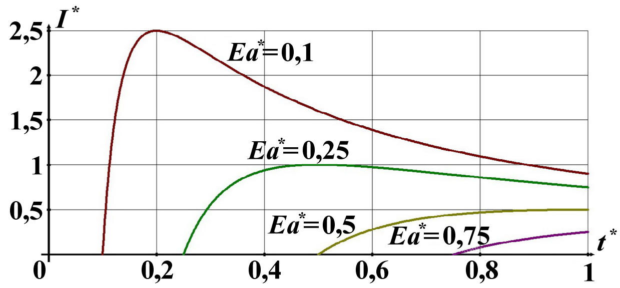

Fig. 3. Regulatory characteristics of the step-down regulator for different values of the relative voltage on the battery

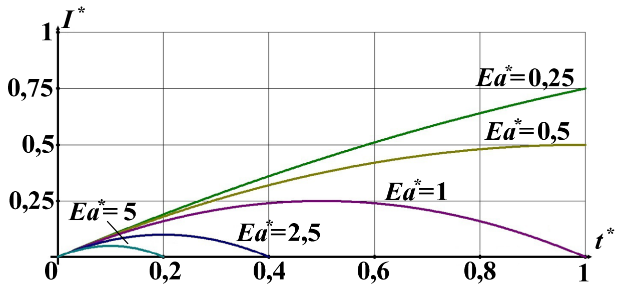

Fig. 4. Regulatory characteristics of the step-up regulator for different values of the relative voltage on the battery

Table 1 shows the conditions under which it is possible to transfer energy from the power source to the battery in the case of PR operation in the mode of *continuous* inductance current.

The parameter t_{MP}^* for which the maximum power is taken from the power source is provided, as well as the reasonable range of changing the parameter E_a^* is suggested.

Table 1

Pulse regulator	The condition for energy taking from the source	The condition for taking the maximum power	Appropriate range of change in E_a^*
Step-down type (Fig. 1)	$t^* > E_a^*$	$t_{MP}^* = 2E_a^*$	$0,1 \leq E_a^* \leq 0,5$
Step-up type (Fig. 2)	$t^* < 1 / E_a^*$	$t_{MP}^* = 1/2E_a^*$	$0,5 \leq E_a^* \leq 5$

In the case of switching the regulator to the *intermittent* inductance current mode, it becomes possible to adjust the parameter t^* in the full range [0...1]. However, in this mode, the battery charging current is insignificant [17]. Therefore, it is advisable not to use this mode for charging the battery, but to compensate for its self-discharge in the charged state.

Conclusions.

1. If there is a battery at the output, the PR will operate in the input and, accordingly, output current (battery charging current) regulator mode.

2. The regulatory characteristic of the current will depend on the ratio of the numerical values of the battery voltage and the open-circuit voltage of the source E_a^*.

3. In the mode of continuous inductance current, the permissible range of adjustment of the parameter t^* is limited and depends on the type of regulator, as well as the numerical value of the parameter E_a^*.

4. The output current of the regulator (output power of the source) reaches its maximum value at a certain value of the parameter $t^* = t_{MP}^*$, which is a function of the parameter E_a^*, as well as the type of PR.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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V.Y. Romashko[1], *Doctor of Technical Science, Professor,*
L.M. Batrak[1], *PhD, Assistant Professor,*
O.O. Abakumova[1], *PhD, Assistant Professor,*
[1] National Technical University of Ukraine
«Igor Sikorsky Kyiv Polytechnic Institute»,
37, Prospect Beresteiskyi, Kyiv-56, 03056, Ukraine,
e-mail: rvy90593-eds@lll.kpi.ua;
batrakln5@gmail.com (Corresponding Author);
e.o.abakumova@gmail.com

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