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Obtaining the maximum power from the source using step-up and step-down type pulse regulators that work on battery

Introduction. *Pulse regulators are widely used to match the output resistance of the source with the load resistance in order to ensure the possibility of taking maximum power when the value of the load resistance changes.* ***Problem.*** *In the case of using non-traditional and renewable sources of electrical energy, for a more uniform supply of energy to the load, a battery is often connected to the output of the pulse regulator, which works in buffer mode. In such cases, the load for the pulse regulator will be the battery itself, and the role of the source load will be performed by the input resistance of the regulator. To ensure the mode of operation of the pulse regulator, in which the maximum power will be transmitted from the source to the load, it is necessary to know the regulating characteristics of the regulator. There are works that analyze the regulating characteristics of step-up and step-down pulse regulators, which are used to match the load with the output resistance of the source. At the same time, for the same purpose, pulse regulators of the step-up and step-down type can be used.* ***Goal.*** *The purpose of the work is to analyze the features of the operation of step-up and step-down type pulse regulators in the mode of maximum power transmission from the source to the battery, as well as to determine the conditions under which it is possible and appropriate to use such regulators for the specified purpose.* ***Methodology.*** *The regulating characteristics of step-up and step-down type pulse regulators with sequential and parallel switching on of the controlled key were determined and analyzed, taking into account the presence of a battery at their output.* ***Results****. It is shown that the transfer of energy from the source to the battery is possible only under certain modes of operation of the regulator, which depend on the type of regulator, as well as the amount of voltage on the battery. The conditions under which it is possible to draw the maximum power from the source are determined.* ***Originality.*** *Since the output resistance of the source and the load resistance are of the same order in the maximum power selection mode, the internal resistance of the power source was taken into account when determining the regulating characteristics of the regulators.* ***Practical value.*** *The obtained results made it possible to formulate practical recommendations for a justified choice of the regulator's operating modes, depending on its type and the value of voltage on the battery.* References 15, tables 1, figures 4.

Key words: **source output impedance, matching pulse regulator, battery operation, maximum power transmission, step-up and step-down type regulators.**

Проаналізовано регулювальні характеристики імпульсних регуляторів підвищувально-понижувального типу з урахуванням внутрішнього опору джерела живлення, за умови підключення акумулятора на їх виході. Показано, що за наявності акумулятора, регулятори напруги працюватимуть у режимі регулювання струму заряджання акумулятора. При цьому діапазон регулювання відносного часу замкненого стану ключа буде обмеженим. Дано рекомендації щодо вибору режимів роботи регулятора, за яких забезпечується передавання енергії від джерела до акумулятора, в залежності від схеми регулятора, а також значення напруги на акумуляторі. Визначено умови, за яких забезпечується передавання максимальної потужності від джерела живлення до акумулятора. Бібл. 15, табл. 1, рис. 4.

Ключові слова: **вихідний опір джерела, узгоджувальний імпульсний регулятор, робота на акумулятор, передавання максимальної потужності, регулятори підвищувально-понижувального типу.**

Introduction. When using different types of non-traditional and renewable sources, they strive to obtain the maximum possible amount of electrical energy. For this, the operating point of the source must be at the point of maximum power (MP) on its output characteristic. However, this mode of operation of the source is possible only in the case when the output resistance of the source r coincides with the resistance of its load R [1, 2].

To ensure the possibility of selecting MP from the source in a wide range of changes in the load resistance, a pulse regulator (PR) is switched on between the source and the load, which matches the output resistance of the source with the load resistance [3-6]. In such cases, the role of the source load will be performed by the input resistance of the regulator $R_e = f(R, t^*)$, which is a function of the load resistance of the regulator R, as well as the relative time of the closed state of the regulator key $t^* = t_{closed} / T$ during the period of operation of the key T. By changing the parameter t^* it is possible to ensure the fulfillment of the condition $R_e = r$ in a wide range of changes in the load resistance R.

The amount of energy coming from non-conventional and renewable sources often depends on external conditions. Therefore, to ensure a more uniform supply of energy to the load, a battery is switched on at the PR output, which operates in buffer mode. In such cases, the PR load will be the battery itself, and the source load will be the input resistance of the regulator. Transmission of MP from the source to the battery can be ensured by choosing the appropriate operating mode of the PR [5, 7, 8].

In [9], the conditions under which it is possible and expedient to transfer the MP from the source to the battery using step-up and step-down PRs, as well as the peculiarities of the operation of these regulators in the specified mode, were analyzed. To match the output resistance of the source with the load, well-known PR circuits of the step-up-step type can also be used [10-12].

The goal of the work is to analyze the peculiarities of the step-up and step-down PRs operation in the mode of MP transmission from the source to the battery, as well as to determine the conditions under which it is possible and expedient to use such regulators with the indicated purpose.

Circuits of regulators. Let's consider those variants of IP circuits of the step-up and step-down type, which provide the possibility of sampling MP from the power source [13]. The corresponding circuits of the regulators are presented in Fig. 1, 2.

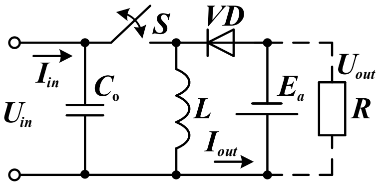

Fig. 1. Regulator of the step-up and step-down type with serial key activation

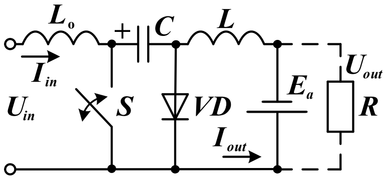

Fig. 2. Regulator of the step-up and step-down type with parallel key activation

We determine and analyze the control characteristics of these regulators, with the help of which the PR operating mode can be determined, in which the MP will be selected from the power source. Since in the MP selection mode, the load resistance and the output resistance of the source are values of the same order, when determining the control characteristics of the regulators, we will take into account the internal resistance of the source, considering it to be *linear*.

The regulator of the step-up and step-down type with serial activation of the key (Fig. 1). If the losses in the elements of the PR circuit are not taken into account, in the continuous current mode of the inductance L, the conditions will always be fulfilled [12]

$$U_{out} = U_{in} \frac{t^*}{1-t^*}; \quad I_{out} = I_{in} \frac{1-t^*}{t^*}. \tag{1}$$

If it is assumed that the internal resistance of the battery is much smaller than the internal resistance of the source, it can be argued that during the regulation process, the output voltage of the regulator will remain practically unchanged and will be equal to the voltage on the battery $U_{out} = E_a$. Therefore, in order for the system to be in a state of equilibrium during the regulation process, the input voltage of the regulator must be equal to

$$U_{in} = U_{out} \frac{1-t^*}{t^*} = E_a \frac{1-t^*}{t^*}, \tag{2}$$

where $t^* = t_{closed} / T$ is the relative time of the closed state of the key S in the period T, t_{closed} is the duration of the closed state of the key.

Due to the presence of the internal resistance of the source, the input voltage of the regulator will change with changes in the consumed current and will be determined by the output characteristic of the source [12]

$$U_{in} = U_{oc} - I_{out} r, \tag{3}$$

where U_{oc} is the no-load voltage of the power source.

Thus, in a state of equilibrium, conditions (2), (3) must be fulfilled simultaneously

$$U_{oc} - I_{in} r = E_a \frac{1-t^*}{t^*}, \tag{4}$$

or moving to relative units [12]

$$1 - I_{in}^* = E_a^* \frac{1-t^*}{t^*}, \tag{5}$$

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

Taking into account that the no-load voltage of the source, as well as the battery voltage, are fixed, by changing the parameter t^*, we will thereby adjust the input and, accordingly, the output current of the regulator

$$I_{in}^* = 1 - E_a^* \frac{1-t^*}{t^*}. \tag{6}$$

Taking into account (1)

$$I_{out}^* = I_{in}^* \frac{1-t^*}{t^*} = \left[1 - E_a^* \frac{1-t^*}{t^*}\right] \frac{1-t^*}{t^*}. \tag{7}$$

Therefore, (6), (7) are the regulating characteristics of PR according to the circuit (Fig. 1).

The regulator of the step-up and step-down type with parallel activation of the key (Fig. 2). For this circuit in the continuous current mode of the inductance L_0, a relationship is valid [12]

$$U_{out} = U_{in} = \frac{1-t^*}{t^*}; \quad I_{out} = I_{in} \frac{t^*}{1-t^*}, \tag{8}$$

where $t^* = t_{open} / T$; t_{open} is the duration of the open state of the key S during the period T.

Therefore, in the steady state of operation, the input voltage of the regulator should be

$$U_{in} = U_{out} \frac{t^*}{1-t^*} = E_a \frac{t^*}{1-t^*}. \tag{9}$$

In order for the system to be in a state of equilibrium, the condition must be fulfilled

$$E_a \frac{t^*}{1-t^*} = 1 - I_{in} r, \tag{10}$$

or in relative units

$$E_a^* \frac{t^*}{1-t^*} = 1 - I_{in}^*. \tag{11}$$

Therefore, the control characteristics of the PR according to the circuit (Fig. 2) will look like this

$$I_{in}^* = \left[1 - E_a^* \frac{t^*}{1-t^*}\right]; \tag{12}$$

$$I_{out}^* = \left[1 - E_a^* \frac{t^*}{1-t^*}\right] \frac{t^*}{1-t^*}. \tag{13}$$

Thus, if there is a battery at the output, the regulators under consideration will operate in the mode of regulating the input and output current (battery charging current). At the same time, the output voltage of the regulators will remain almost constant and equal to the battery voltage.

Analysis of control characteristics of regulators. If there is a battery at the output, the PR will operate in the battery charging current regulation mode. In the case of $t^* = 0$, the power source and the load are disconnected from each other and there will be no energy transfer to the battery. If $t^* > 0$, to ensure the transfer of energy from the source to the battery, the condition $I_{in} > 0$ must be fulfilled. For the circuit (Fig. 1), taking into account (6), this condition takes the form

$$\left[1-E_a^*\frac{1-t^*}{t^*}\right]>0\,, \qquad (14)$$

and for the circuit (Fig. 2)

$$\left[1-E_a^*\frac{t^*}{1-t^*}\right]>0\,. \qquad (15)$$

Taking into account that, in general, the parameter t^* can vary in the range [0...1], taking into account (14), (15), we come to the conclusion that in the presence of a battery, the permissible range of changes in the parameter t^* will be limited. For the circuit (Fig. 1), the permissible change of the parameter lies in the range

$$1\ge t^*>\frac{E_a^*}{E_a^*+1}, \qquad (16)$$

and for the circuit (Fig. 2)

$$0<t^*<\frac{1}{1+E_a^*}\,. \qquad (17)$$

Therefore, the higher the voltage on the battery E_a^*, the more limited the permissible range of regulation of the parameter t^* in the PR will be. At the same time, the analysis of (16), (17) shows that the battery voltage can be both higher and lower than the no-load voltage of the power source U_{oc}.

As is known [1], in the case of linear internal resistance of the power source, at the MP point, the relative value of its output current (input current of the PR) should be $I_{in}^*=0.5$.

Therefore, the condition of MP selection from the source for the regulator circuit (Fig. 1) will look like this

$$1-E_a^*\frac{1-t^*}{t^*}=0.5, \qquad (18)$$

and for the circuit (Fig. 2)

$$1-E_a^*\frac{t^*}{1-t^*}=0.5. \qquad (19)$$

Thus, the MP will be transmitted from the source to the load under the condition that $t^*=t_{MP}^*$, where for the regulator circuit (Fig. 1)

$$t_{MP}^*=\frac{E_a^*}{E_a^*+0,5}, \qquad (20)$$

and for the circuit (Fig. 2)

$$t_{MP}^*=\frac{0,5}{0,5+E_a^*}\,. \qquad (21)$$

The regulatory characteristics of the considered circuits presented in Fig. 3, 4, confirm the results of the analysis carried out. The main properties of these circuits are similar. However, if for the circuit (Fig. 1) the permissible regulation range is limited to the left [$t_{\min}$ ... 1], then for the circuit (Fig. 2) it is limited to the right [0 ... $t_{\max}$]. This is a consequence of the duality of the circuits of the considered regulators [13].

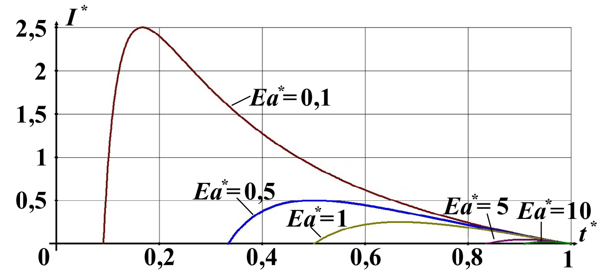

Fig. 3. Regulatory characteristics of PR with serial key activation

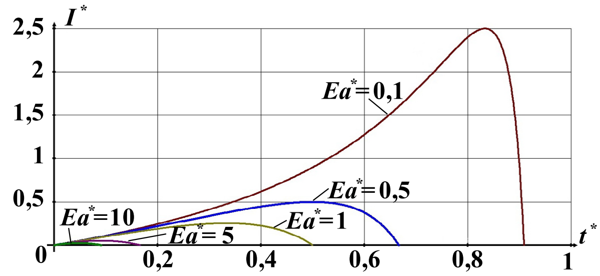

Fig. 4. Regulatory characteristics of PR with parallel key activation

To compare the properties of the four main PR circuits Table 1 shows their main features when operating in the MP transmission mode from the power source to the battery, namely:

- condition of energy transfer from the source to the battery;
- condition of MP selection from the source;
- reasonable battery voltage E_a change range.

Table 1

Conditions of energy transfer from the source to the battery

No.	Regulator type	Energy transfer condition	Condition of MP selection	Reasonable range of change of E_a^*
1	Step-down	$t^*>E_a^*$	$t_{MP}^*=2E_a^*$	$0{,}1\le E_a^*\le 0{,}5$
2	Step-up	$t^*<1/E_a^*$	$t_{MP}^*=1/2E_a^*$	$0{,}5\le E_a^*\le 5$
3	Step-up and step-down (Fig. 1)	$t^*>\frac{E_a^*}{1+E_a^*}$	$t_{MP}^*=\frac{E_a^*}{E_a^*+0{,}5}$	$0{,}1\le E_a^*\le 5$
4	Step-up and step-down (Fig. 2)	$t^*<\frac{1}{1+E_a^*}$	$t_{MP}^*=\frac{0{,}5}{0{,}5+E_a^*}$	$0{,}1\le E_a^*\le 5$

Today, there are modified versions of step-up and step-down PR circuits that differ from the considered ones by the polarity of the output voltage (ZETA and SEPIC converters) [14, 15]. Changing the polarity of the output voltage is achieved by the appropriate construction of the output circuit of the regulator. However, since the main properties of the regulator are determined by the method of construction of its input circuit, and first of all by the method of connecting the controlled key *S*, the obtained results will be valid for the corresponding types of modified circuits of the step-up and step-down type regulators.

Conclusions.

1. If there is a battery at the output, the pulse voltage regulators will operate in the current regulator mode.

2. The nature of the regulation characteristic and the permissible range of regulation depend on the type of regulator and the value of the voltage on the battery.

3. The maximum power from the source will be selected at a certain value of the parameter $t^* = t^*_{MP}$, which is determined by the type of regulator and the value of the voltage on the battery.

4. The pulse regulator of the step-up and step-down type, in comparison with separately the step-up and step-down type regulators, have the widest permissible range of changes in the relative voltage on the battery.

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

REFERENCES

1. Panchenko S.V., Ananieva O.M., Babaev M.M. *Theory of electric and magnetic circuits. Textbook*. Kharkiv, UkrDUZT Publ., 2020. 246 p. (Ukr).

2. Louarem S., Kebbab F.Z., Salhi H., Nouri H. A comparative study of maximum power point tracking techniques for a photovoltaic grid-connected system. *Electrical Engineering & Electromechanics*, 2022, no. 4, pp. 27-33. doi: https://doi.org/10.20998/2074-272X.2022.4.04.

3. Twaha S., Zhu J., Yan Y., Li B., Huang K. Performance analysis of thermoelectric generator using DC-DC converter with incremental conductance based maximum power point tracking. *Energy for Sustainable Development*, 2017, vol. 37, pp. 86-98. doi: https://doi.org/10.1016/j.esd.2017.01.003.

4. Olalla C., Clement D., Rodriguez M., Maksimovic D. Architectures and Control of Submodule Integrated DC–DC Converters for Photovoltaic Applications. *IEEE Transactions on Power Electronics*, 2013, vol. 28, no. 6, pp. 2980-2997. doi: https://doi.org/10.1109/TPEL.2012.2219073.

5. Anandhi T.S., PremKumar S. Application of DC-DC boost converter for solar powered traffic light with battery backup. *Indian Journal of Science and Technology*, 2015, vol. 8, no. 32, pp. 1-5. doi: https://doi.org/10.17485/ijst/2015/v8i32/84408.

6. Tseng S.-Y., Wang H.-Y. A Photovoltaic Power System Using a High Step-up Converter for DC Load Applications. *Energies*, 2013, vol. 6, no. 2, pp. 1068-1100. doi: https://doi.org/10.3390/en6021068.

7. 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: https://doi.org/10.1016/j.jpowsour.2012.03.029.

8. 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*, 2010, pp. 185-190. doi: https://doi.org/10.1109/CCA.2010.5611257.

9. Romashko V.Y., Batrak L.M., Abakumova O.O. Features of the work of pulse regulators in the maximum power transmission mode, with the presence of an accumulator at their output. *Electrical Engineering & Electromechanics*, 2023, no. 6, pp. 63-66. doi: https://doi.org/10.20998/2074-272X.2023.6.11.

10. Dinniyah F.S., Wahab W., Alif M. Simulation of Buck-Boost Converter for Solar Panels using PID Controller. *Energy Procedia*, 2017, vol. 115, pp. 102-113. doi: https://doi.org/10.1016/j.egypro.2017.05.011.

11. Shayeghi H., Pourjafar S., Sedaghati F. A Buck-Boost Converter; Design, Analysis and Implementation Suggested for Renewable Energy Systems. *Iranian Journal of Electrical and Electronic Engineering*, 2021, vol. 17, no. 2, p. 1862. doi: https://doi.org/10.22068/IJEEE.17.2.1862.

12. Goncharov Y.P., Budonny O.V., Morozov V.G., Panasenko M.V., Romashko V.Y., Rudenko V.S. *Power conversion equipment. Text book. Part 2.* Kharkiv, Folio Publ., 2000. 360 p. (Ukr).

13. Romashko V.Y., Batrak L.M., Abakumova O.O. Step-up/step-down regulators in maximum power transmission mode. *Electrical Engineering & Electromechanics*, 2022, no. 2, pp. 18-22. doi: https://doi.org/10.20998/2074-272X.2022.2.03.

14. Soedibyo, Amri B., Ashari M. The comparative study of Buck-boost, Cuk, Sepic and Zeta converters for maximum power point tracking photovoltaic using P&O method. *2015 2nd International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, 2015, pp. 327-332. doi: https://doi.org/10.1109/ICITACEE.2015.7437823.

15. Chavan F.T., Mopari S.S., Swami P.S. Performance analysis of SEPIC and zeta converter for power quality improvement. *International Journal of Scientific and Technology Research*, 2019, vol. 8, no. 12, pp. 1925-1929.

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