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Step-up/step-down regulators in maximum power transmission mode

Introduction. *Switching DC voltage regulators are traditionally used to regulate and stabilize the voltage on the load. Due to the widespread use of non-traditional and renewable sources of electricity, there is a need to select from them the maximum possible amount of electricity. As is known, the maximum power from the power supply to the load will be transmitted provided that the output resistance of the source is equal to the load resistance. If this condition is not met, a matching switching regulator is switched on between the power supply and the load. Most often, for the purpose of matching, pulse regulators of step-up or step-down types are used.* ***Problem.*** *The operation of regulators in the matching mode has a number of features, in comparison with the modes of regulation and stabilization of the output voltage. Thus, since in the maximum power transmission mode the output resistance of the source and the resistance of the load are values of the same order, in any calculation the internal resistance of the source must be taken into account. There are works in which features of work of regulators of step-up and step-down types in a mode of transfer of the maximum power are analyzed. In addition to these types of pulse regulators, there are regulators of step-up/step-down types, which are relatively rarely used for this purpose. First of all it is connected with insufficiently studied abilities of work of such regulators in the specified mode.* ***Goal.*** *The aim of the work is to analyze the features of the operation of pulse regulators of step-up/step-down types in the mode of transmission of maximum power from the power supply to the load, as well as to determine the conditions under which it is possible and appropriate to work in this mode.* ***Methodology.*** *In the work, taking into account the internal resistance of the power supply, the regulation characteristics of the basic circuit of the pulse regulator of the step-up/step-down type are analyzed. The conditions under which the transfer of maximum power from the power supply to the load is ensured are determined.* ***Results.*** *It is shown that the existing variants of the circuits of regulators of the step-up/step-down type can be obtained from the basic circuit by applying the rules of construction of dual electric circuits. Consequently, the basic calculated relations for such circuits can be obtained from the calculated relations of the basic circuit using the principle of duality.* ***Originality.*** *A method for determining and studying the regulation characteristics of pulse regulators, taking into account the internal resistance of the power supply.* ***Practical value.*** *The obtained results allow to determine the conditions under which it is possible and expedient to operate different circuits of regulators in the mode of transmission of maximum power from the power supply to the load. Based on these results, recommendations are given for selecting a suitable range for changing the relative time of the closed state of the controlled switch, depending on the type of power supply used, as well as the method of connecting the controlled switch in the regulator circuit.* References 14, tables 3, figures 8.

Key words: **step-up/step-down regulator, regulation characteristics, maximum power transmission**.

З урахуванням внутрішнього опору джерела живлення проаналізовано регулювальні характеристики імпульсних регуляторів підвищувально-понижувального типу. Визначено умови, за яких забезпечується передавання максимальної потужності від джерела живлення до навантаження. Дано рекомендації щодо вибору доцільного діапазону зміни відносного часу замкненого стану керованого ключа регулятора , у залежності від типу джерело живлення, а також способу підключення керованого ключа в імпульсному регуляторі. Бібл. 14, табл. 3, рис. 8.

Ключові слова: **регулятор підвищувально-понижувального типу, регулювальні характеристики; передавання максимальної потужності.**

Introduction. DC pulse regulators (PRs) are traditionally used to regulate and stabilize the load voltage [1]. With the expansion of the use of non-traditional and renewable energy sources, there is a need to extract from them the maximum possible amount of electricity. As is known [2], the maximum power from the power supply to the load will be transmitted only if the output resistance of the source r is equal to the resistance of its load R. To ensure maximum power transmission in cases where $R \neq r$, between the source and load they connect the PR which matches the output resistance of the source with the resistance of its load. In the presence of the PR, the role of the load source R will be performed by its input resistance. This resistance depends on the load resistance of the regulator R_{LD} as well as the relative time of the closed (open) state of the controlled key t^*: $R = f(R_{LD}, t^*)$. By changing the parameter t^*, it is possible to ensure the condition $R = r$, i.e. the condition of transmitting maximum power from source to load R_{LD}.

In practice, for the purpose of coordination, up or down PRs are most often used [3-5]. The operation of regulators in the matching mode has a number of features compared to the mode of regulation and stabilization of the output voltage. In particular, since in the maximum power transmission mode the output source resistance and the load resistance are of the same order, the internal resistance of the source must be obligatory taken into account in any calculation. In the existing literature [1, 9], when determining the control characteristics of the PRs which operate in the mode of stabilization of the output voltage, it is believed that the internal resistance is much lower than the load resistance. Therefore, the internal resistance of the source is not taken into account. In addition, the internal resistance of the source will affect the coefficient of utilization of electrical energy of the source, and hence the overall efficiency of the system power supply – pulse regulator. In [6] the peculiarities of the operation of the up and down PR in the mode of transmission of maximum power from the power supply to the load are analyzed in detail. In addition to these types of PRs, there are step-up/step-down regulators [7-9] which are relatively rarely used for this purpose. This is primarily due to insufficient study of the features of such regulators in this mode.

The goal of the work is to analyze the features of the step-up/step-down PR in the mode of transmission of maximum power from the power supply to the load, and to determine the conditions under which it is possible and appropriate to operate in this mode.

Analysis of regulatory characteristics. The most important characteristics of any regulator are its regulatory characteristics. In the case of power supply from real sources of electrical energy, due to the presence of internal resistance, the regulatory characteristics will depend on the load resistance. In this regard, the properties of the regulator are described by a family of its regulatory characteristics which determine for different values of load the resistance R_{LD}. Let us analyze the regulatory characteristics of the classical circuit of the step-up/step-down PR (Fig. 1) [9].

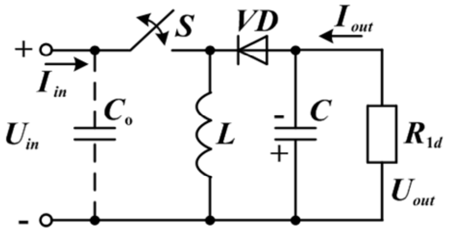


Fig. 1. Basic circuit of the step-up/step-down PR

For simplicity, we assume that the internal resistance of the source r is linear, and the losses in the PR elements are insignificant. To describe the regulatory characteristics, we will use relative values [9].

According to [10], the regulatory characteristic of the PR (Fig. 1) is described by this expression

$$U^* = \frac{t^*\left(1-t^*\right)}{\left(1-t^*\right)^2 + r^* t^*}, \qquad (1)$$

where $U^* = U/U_{oc}$; $r^* = r/R_{LD}$; $t^* = t_{cl}/T$; U_{oc} is the source's no-load voltage; t_{cl} is the duration of the no-load state of the key S in the period T.

Figure 2 presents a family of regulatory characteristics for several fixed values of relative resistance r^*. The same graph shows the regulatory characteristic for the case of power supply from an ideal voltage source (r^* = 0). Let us analyze the obtained characteristics. For an ideal voltage source (r^* = 0), with increasing parameter t^* the output voltage U^* will increase indefinitely. In the case of real sources ($r^* \neq 0$), at $t^* = 0$ and $t^* = 1$, the output voltage will be zero, as there is no energy transfer from source to load. At a certain value of the parameter $t^* = t_m^*$, the output voltage, and hence the output power reaches the maximum value P_{max}. The question arises: does this mode of operation correspond to the mode of transmission of maximum power from source to load?

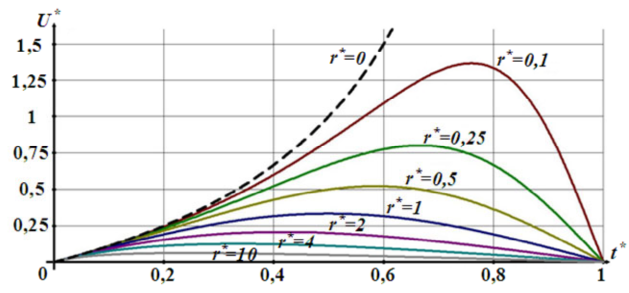


Fig. 2. Regulatory characteristics in the absence of the storage capacitor C_0

As is known [2], in the case of linear internal resistance of the source, its point of maximum power (PMP) has the coordinates $U_{MP}^* = 0.5$; $I_{MP}^* = 0.5$. Therefore, the maximum possible output power of such a source is $P_{MP}^* = U_{MP}^* \cdot I_{MP}^* = 0.25$. The output power of the regulator, at the point of maximum output voltage (Fig. 2), can be determined by the formula $P_{max}^* = U_{max}^{*2} / R_{LD}^* = U_{max}^{*2} \cdot r^*$. The test shows that for any value of the parameter r^* $P_{max}^* < P_{MP}^*$. Therefore, this circuit, for any value of the parameter r^*, does not provide the ability to transfer maximum power from source to load. This is due to the fact that energy is taken from the source only when the key S is closed, i.e. in discrete portions. If the key S is permanently closed (t^*=1), the power supply will operate in short circuit mode, as a result of which energy from the source to the load will not be received. To ensure the continuity of energy extraction from the source, it is necessary to install a storage capacity C_0 of sufficient value at the input of the PR (Fig. 1). Due to the redistribution of currents, in the presence of C_0, the regulatory characteristic will be described by the following expression

$$U^* = \frac{t^*\left(1-t^*\right)}{\left(1-t^*\right)^2 + r^* t^{*2}}. \qquad (2)$$

For this case, the graphs of the regulatory characteristics are presented in Fig. 3.

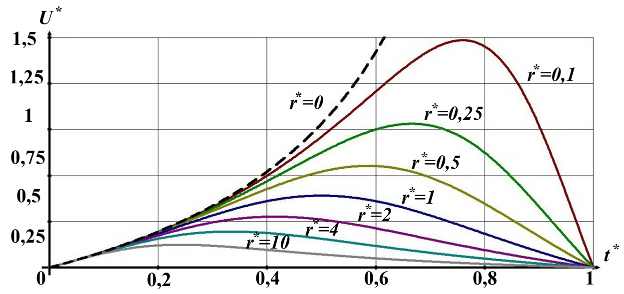


Fig. 3. Regulatory characteristics in the presence of the storage capacitor C_0

The test shows that the output power at the points of maximum output voltage of any of these graphs corresponds to the maximum output power of the source

$$P_{max}^* = P_{MP}^* = 0.25. \qquad (3)$$

Therefore, in the presence of capacity C_0, the step-up/step-down regulator provides the possibility of transmission from the source to the load of the maximum possible power. To do this, it is necessary to provide a certain value of the parameter $t^* = t_{MP}^*$. Determine the conditions under which the maximum possible power will be transmitted from the source to the load.

As is known [9], the input and output parameters of the step-up/step-down PR (Fig. 1) are related by the relationships

$$U_{out}^* = U_{in}^* \cdot \frac{t^*}{1-t^*}; \quad I_{out}^* = I_{in}^* \cdot \frac{1-t^*}{t^*}. \qquad (4)$$

Taking into account that at the linear internal resistance of the source, its output voltage and output current in the PMP $U^*_{MP} = 0.5$; $I^*_{MP} = 0.5$, we can write that in the case of the source operation in the PMP the output voltage and current of the PR

$$U^*_{out} = 0.5 \cdot \frac{t^*}{1-t^*}; \quad I^*_{out} = 0.5 \cdot \frac{1-t^*}{t^*}. \qquad (5)$$

On the other hand, $U^*_{out} = I^*_{out} R^*_{LD}$, i.e.

$$U^*_{out} = 0.5 \cdot \frac{1-t^*}{t^*} R^*_{LD}. \qquad (6)$$

Equating (5) and (6) we obtain

$$0.5 \cdot \frac{t^*}{1-t^*} = 0.5 \cdot \frac{1-t^*}{t^*} R^*_{LD}$$

or

$$t^{*2} / R^*_{LD} = t^{*2} r^* = (1-t^*)^2. \qquad (7)$$

Therefore, the parameter t^*_{MP} can be determined by solving such a quadratic equation

$$t^{*2}(r^*-1) + 2t^* - 1 = 0. \qquad (8)$$

This equation has two roots

$$t^*_1 = \frac{\sqrt{r^*}-1}{r^*-1}; \quad t^*_2 = \frac{1+\sqrt{r^*}}{1-r^*}. \qquad (9)$$

Taking into account the physical meaning of the parameter t^* we come to the conclusion that only the root t^*_1 will be valid, i.e.

$$t^*_{MP} = \frac{\sqrt{r^*}-1}{r^*-1}. \qquad (10)$$

Table 1 shows the calculated numerical values of the parameter t^*_{MP} for different values of relative resistance r^*. The numerical value for the case $r^* = 1$ is obtained by revealing the uncertainty of the form 0/0.

The results presented in Table 1 are confirmed by the graphs in Fig. 3. Thus, at the PR input (Fig. 1) a storage capacity C_0 of sufficient value is installed, this regulator, in contrast to the up or down PR [6], provides the ability to extract from the power supply maximum power, theoretically, at any value of the load resistance of the regulator R_{LD}.

Table 1

Dependence of the parameter t^*_{MP} on the resistance r*

r^*	0,05	0,1	0,25	0,5	0,8	1
t^*_{MP}	0,84	0,77	0,67	0,58	0,53	0,5
r^*	1,25	2	4	10	20	
t^*_{MP}	0,48	0,41	0,33	0,24	0,19	

In [6] it is shown that the electric circuits that form the up and down PRs are dual. This, in particular, explains the similarity of their parameters and characteristics. If we apply the principles of construction of dual electrical circuits to the circuit of the considered PR (Fig. 1), we obtain the circuit of the PR shown in Fig. 4, which is well known as the Ćuk circuit [9, 11, 12].

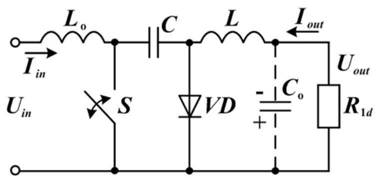


Fig. 4. Step-up/step-down regulator according to Ćuk circuit

Taking into account the principle of duality, the following relations are valid for it

$$U^*_{out} = U^*_{in} \cdot \frac{1-t^*}{t^*}, \quad I^*_{out} = I^*_{in} \cdot \frac{t^*}{1-t^*}, \qquad (11)$$

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

Similar to the previous circuits, it can be shown that its regulatory characteristic for the output voltage will look like

$$U^*_{out} = U^*_{in} \cdot \frac{t^*(1-t^*)}{r^*(1-t^*)+t^{*2}}. \qquad (12)$$

Taking into account that for dual circuits the parameter r^* is analogous to the parameter $R^*_{LD} = R_{LD}/r = 1/r^*$, it can be argued that this circuit will take the maximum power from the source, provided that

$$t^* = t^*_{MP} = \frac{\sqrt{R^*_{LD}}-1}{R^*_{LD}-1}. \qquad (13)$$

Table 2 shows the calculated numerical values of the parameter t^*_{MP} for different values of relative resistance $r^* = 1/R^*_{LD}$.

Table 2

Dependence of the parameter t^*_{MP} on the resistance r*

for Ćuk circuit

r^*	0,05	0,1	0,25	0,5	0,8	1
t^*_{MP}	0,19	0,24	0,33	0,41	0,48	0,5
r^*	1,25	2	4	10	20	
t^*_{MP}	0,53	0,58	0,67	0,77	0,84	

Figure 5 shows graphs of the dependence $t^*_{MP} = f(r^*)$ for the PRs the circuit of which is shown in Fig. 1, 4.

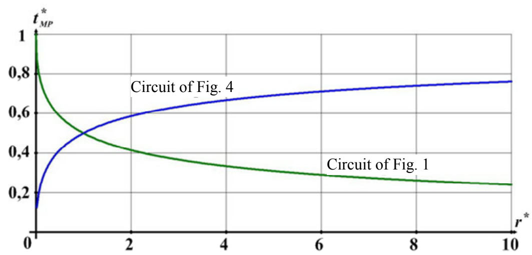


Fig. 5. Dependence of the parameter t^*_{MP} on the resistance r*

These graphs are a mirror image of each other relative to the corresponding lines which corresponds to $t^*_{MP} = 0.5$. Figure 6 presents graphs of the regulatory characteristics of the regulator (Fig. 4) for different values of the parameter r^* which confirm the results presented in Table 2.

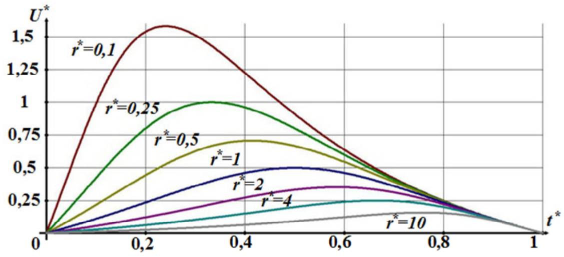


Fig. 6. Regulatory characteristics of Ćuk circuit

Thus, both of these circuits provide the ability to take the maximum power from the power supply, theoretically, at any value of load resistance R_{LD}.

Recommended regulatory ranges. In accordance with the regulatory characteristics (Fig. 3, 6), the output voltage of the regulators reaches its maximum value $U^*_{\max}$ provided that $t^* = t^*_{MP}$. The output voltage $U^*_{out} < U^*_{\max}$ can be obtained at two different values of the parameter t^*, one of which is greater than t^*_{MP} and the other less. In such cases, as shown in [6], when choosing the regulatory range, it is advisable to take into account the coefficient of utilization of electrical energy of the power supply η.

If the power supply is a voltage source, taking into account (11), the dependence $\eta = f(t^*)$ for the PR (Fig. 4) will look like

$$\eta = U^* = U^*_{in} = U^*_{out}\frac{t^*}{1-t^*}. \qquad (14)$$

Therefore, with increasing parameter t^*, η will increase. Therefore, in the case of power supply from the voltage source, it is advisable to change the parameter t^* in the range $t^*_{MP}...1$. If the power supply is a current source, the dependence $\eta = f(t^*)$ for the same circuit will look like

$$\eta = I^* = I^*_{in} = I^*_{out}\frac{1-t^*}{t^*}. \qquad (15)$$

Taking into account that $I^*_{out} = U^*_{out} / R^*_{LD} = U^*_{out} r^*$, we obtain that

$$\eta = U^*_{out} r^* \frac{1-t^*}{t^*}.$$

Thus, in the case of power supply from the current source, it is advisable to change the parameter t^* in the range $0....t^*_{MP}$. In addition, the energy efficiency of the source will increase with increasing r^*, i.e. with decreasing load resistance R_{LD}.

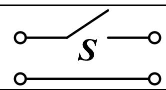
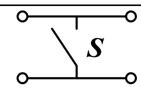
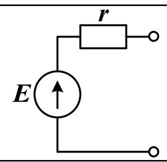
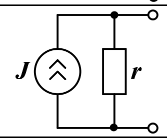
Taking into account the duality of the circuits of the considered regulators, we conclude that for the PR (Fig. 1) the recommendations will be the opposite. The analysis of the obtained results, as well as the results presented in [6], shows that to select the appropriate range of regulation of the parameter t^*, it is necessary to take into account two factors:

1) type of electricity source;
2) method of connecting the controlled key S to the RP, relative to the power supply and load.

Table 3 shows the recommended control ranges of the parameter t^*, depending on the type of power supply and the method of connecting the controlled switch S. In practice, this is not always convenient. Therefore, variants of these circuits have been developed in which the polarity of the output voltage coincides with the polarity of the input voltage.

Table 3

Recommended ranges of parameter t^* regulation

Key / Scheme		
	$0...t^*_{MP}$	$t^*_{MP}...1$
	$t^*_{MP}...1$	$0...t^*_{MP}$

They are known as ZETA converter (Fig. 7) and SEPIC converter (Fig. 8) [13, 14].

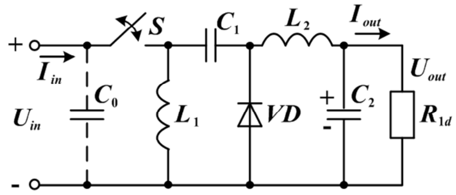


Fig. 7. Regulator type ZETA

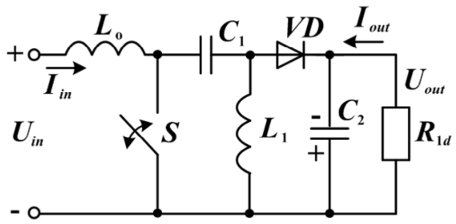


Fig. 8. Regulator type SEPIC

The circuits of these regulators differ from the considered basic circuits (Fig. 1, 4) by the method of construction of the *output* circuit, as well as the presence of additional reactive elements. However, since the most important properties of the regulator are determined by the method of construction of its input circuit, in particular the method of connecting the controlled switch S, the results obtained for the Buck-Boost regulator (Fig. 1) will be valid for the controller type ZETA (Fig. 1) will be valid for the regulator type ZETA (Fig. 7), and the results obtained for the Ćuk regulator (Fig. 4) will be valid for the SEPIC regulator (Fig. 8). In particular, to ensure the possibility of extracting the maximum power from the power supply, capacitor C_0 of sufficient capacity must be installed at the input of the ZETA type regulator (Fig. 7).

Conclusions.

1. Pulse regulators circuits with serial (parallel) connection of the controlled switch S provide the possibility of taking the maximum power from the power supply only if there is a storage capacity C_0 (inductance L_0) at their input.
2. Step-up/step-down pulse regulators provide the ability to take the maximum power from the power supply to the load for almost any value of load resistance R_{LD}.
3. The appropriate range of regulation of the parameter t^* is selected taking into account the type of power supply, as well as the method of connecting the controlled key in the pulse regulator.

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

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