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ELECTRIC ENERGY LOSS AT ENERGY EXCHANGE BETWEEN CAPACITORS AS FUNCTION OF THEIR INITIAL VOLTAGES AND CAPACITANCES RATIO

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The processes of electrical energy exchange between two connected capacitors of different capacity charged to different voltages are studied. The features of influence of the ratio of capacitor capacities, as well as their initial voltages on a loss of electric energy during its redistribution between the capacitors are determined. The conditions of decrease of such losses and increase of coefficient of energy transfer from one capacitor to another one are defined.
References 10, figures 2, table 1.
Keywords: Power processes, capacitors, electric power losses, energy-transfer coefficient.

Capacitors are widely applied as electro-energy storage systems in the electro-discharge installations, which are currently used for high-performance electro-hydraulic [10], shock electric ark [3], magneto-impulse [9], dimensional and volume electro-erosion [1, 2, 3, 5, 8] and other kinds of processing of materials, media and products. In many circuit designs of electro-discharge installations the several capacitors with various capacitances are applied [4, 6, 10]. They discharge on load with a time delay for shape control of pulse currents in load.

In the systems with semiconductor direct voltage shapers, which contain the filtering high-capacitance capacitors it is applied the additional dosing capacitors for more exact control of energy in load [1, 3–5, 7]. Thus, the parallel connection of capacitors of different capacity is one of the most common methods for regulating the dynamic parameters of electro-discharge installations.

Besides it is usually assumed that the exchange of electric energy between connected capacitors takes place without energy losses. However, our research has shown that in some cases, such losses may be unacceptably high, and their value depends on the capacitance of capacitors and their voltages.

Therefore, the ***aim of the work*** was to determine the regularities of influence of the capacitances ratio, as well as the initial capacitor voltages on the losses of electric energy during its redistribution between two connected capacitors.

Fig. 1 shows the electrical equivalent circuit of electric pulse installation with two capacitors $C1$ and $C2$ connected in parallel, between which after switching on commutator (thyristor) VT2 at time point $t = 0$ can take place a redistribution of electrical energy if capacitors were pre-charged from shaper of direct voltage (SDV) to different voltages (i.e. if $U_{C1}(0-) \neq U_{C2}(0-)$). Here $U_{C1}(0-)$ and $U_{C2}(0-)$ – voltages on capacitors $C1$ and $C2$ before moment of commutation, respectively.

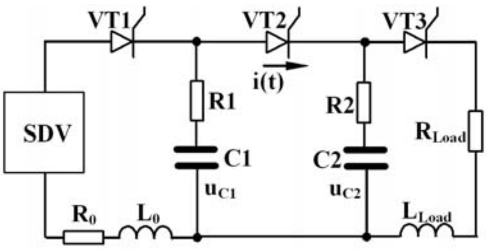

Fig. 1

In analyzing the following assumptions have been accepted: inductance capacitors and wires is negligible; internal pure resistances of capacitors and their capacitances are not equal ($R_1 \neq R_2$ и $C_1 \neq C_2$); before turning on the switch VT2 at time point $t = 0$ the inequality $|U_{C1}(0-)| > |U_{C2}(0-)|$ holds for initial voltages on capacitors; after turning on the switch VT2 the commutators (thyristors) VT1 and VT3 remain switched out until the time point $t = t_n$, at which the voltages on capacitors become equal $U_{C1}(t_n) = U_{C2}(t_n)$ with the accuracy required for the operation of the circuit.

Analysis of voltage variation on capacitors. On the basis of the law on changeless of a total charge of capacitors before and after their connection, and taking into account that charges of capacitors $q_1 = C_1U_{C1}$ and $q_2 = C_2U_{C2}$, we can write the following expression for the voltages on the capacitors $C1$ and $C2$ after the completion of transient of charging of capacitor $C1$ from capacitor $C2$ (for $t \geq t_n$)

$$U_{C1}(t_n) = U_{C2}(t_n) = [C_1\, U_{C1}(0-) + C_2 U_{C2}(0-)]\cdot/\,(C_1 + C_2). \quad (1)$$

It is noteworthy that if $C1 = C2$, then the final voltages on the capacitors would not depend on their capacitance values, and according to (1) are defined as

$$U_{C1}(t_n) = U_{C2}(t_n) = [U_{C1}(0-) + U_{C2}(0-)]\cdot/2. \quad (2)$$

As can be seen from (2) if voltages $U_{C1}(0-)$ and $U_{C2}(0-)$ would be equal on value, but different on sign, then after transient completion both capacitors would be discharged to zero.

Analysis of energy distribution between capacitors $C1$ and $C2$. The following expressions have been found in [7] for:

– Relative energy loss in pure resistances of circuit under consideration:

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$$W_R^* = W_R / W_{C1}(0-) = k\left(U_{C2}^*(0-) - 1\right)^2 / (1+k). \quad (3)$$

Here $k = C_2/C_1$, and $U_{C2}^*(0-) = U_{C2}(0-)/U_{C1}(0-)$ – relative initial voltage of capacitor $C2$.

– Energy transfer coefficient K, which is defined as the ratio of the total energy of the capacitors $C1$ and $C2$ after the energy exchange between them to their total energy before commutation:

$$K = \left(1 + kU_{C2}^*(0-)\right)^2 \Big/ (1+k)\left(1 + kU_{C2}^{*2}(0-)\right), \quad (4)$$

– The efficiency η, which is determined as the relation of energy that went in capacitor $C2$ to the energy, which was taken from capacitor $C1$ after power exchange between them:

$$\eta = \left(1 + (1+2k)U_{C2}^*(0-)\right) \Big/ \left(2 + k + kU_{C2}^*(0-)\right). \quad (5)$$

Let's note that according to (5) there are conditions, at which $\eta \le 0$:

$$U_{C2}^*(0-) \le -1/(1+2k). \quad (6)$$

Analysis shows that the efficiency $\eta \le 0$ when the following three conditions are satisfied: 1) initial voltages on $C1$ and $C2$ have different polarity (it follows from (6)); 2) after the energy exchange the final voltage on $C1$ remains the same polarity, whereas the voltage on $C2$ changes its polarity (follows from condition 1 and from equalization of final voltages on $C1$ and $C2$); 3) when $|U_{C2}(t_n)| \le |U_{C2}(0-)|$ (follows from definition of η).

Table represents the results of calculations W^*_R, K and η using (3) – (5) when $U^*_{C2}(0–)$ changes from – 1 to 1 and for $k = C_2/C_1$ = 0,1; 1; 10.

$k = C_2/C_1$	$U^*_{C2}(0–)$	1	0.8	0.6	0.4	0.2	0	– 0.2	– 0.4	– 0.6	– 0.8	– 1
0,1	W^*_R	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.18	0.23	0.29	0.36
	K	1.00	1.00	0.99	0.97	0.94	0.91	0.87	0.82	0.78	0.72	0.67
	η	1.00	0.90	0.80	0.69	0.58	0.48	0.37	0.25	0.14	0.02	0.00
1	W^*_R	0.00	0.02	0.08	0.18	0.32	0.50	0.72	0.98	1.28	1.62	2.00
	K	1.00	0.99	0.94	0.84	0.69	0.50	0.31	0.16	0.06	0.01	0.00
	η	1.00	0.89	0.78	0.65	0.50	0.33	0.14	0.00	0.00	0.00	0.00
10	W^*_R	0.00	0.04	0.15	0.33	0.58	0.91	1.31	1.78	2.33	2.95	3.64
	K	1.00	1.00	0.97	0.87	0.58	0.09	0.06	0.31	0.49	0.60	0.67
	η	1.00	0.89	0.76	0.59	0.37	0.08	0.00	0.00	0.00	0.00	0.00

In Fig. 2 the following dependences are given: *a* – relative energy loss W^*_R, *b* – energy transfer coefficient K, *c* – efficiency η as functions of relative voltage $U^*_{C2}(0 –)$ (which is changed in interval from +1 to –1 for $k = C_2/C_1$ = 0,1; 1; 10).

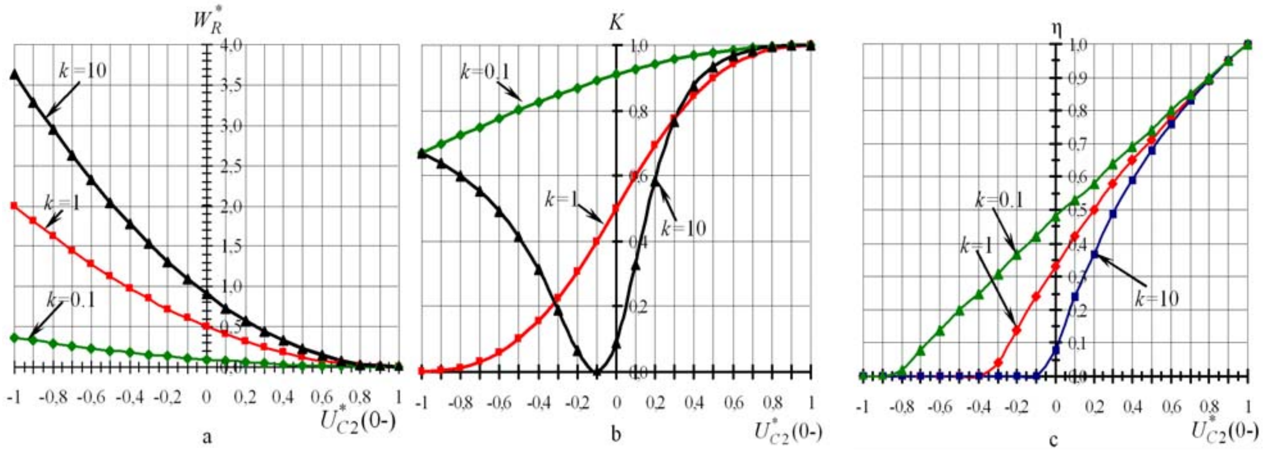

Fig. 2

As can be seen from Fig. 2, *a* the relative energy loss W^*_R increases from zero to maximal value when relative initial voltage $U^*_{C2}(0 –)$ changes from +1 to –1 for all k considered. Moreover, the larger is k (capacitance C_2 with respect to C_1), the value of W^*_R is greater. For example, when k increases 10 times from 0.1 to 1 the maximal energy loss increases 5.6 times, whereas at changing k from 1 to 10 the W^*_R rises 1.8 times.

From (4) follows that energy transfer coefficient $K = 0$ at $U^*_{C2}(0 –) = –1/k$. It can be seen in Fig. 2, *b* at $k = 10$ and $U^*_{C2}(0 –) = – 0,1$, as well as at $k = 1$ and $U^*_{C2}(0 –) = – 1$.

In these cases, the final voltages $U_{C1}(t_n) = U_{C2}(t_n) = 0$, and thus the total final energy in the capacitors is zero. It is noteworthy that when $k = 10$, and voltage $U^*_{C2}(0 –)$ continues to decrease below the value – 0,1 then coefficient K

begins to increase again. This is explained by the fact that at $U^*_{C2}(0-) < -0{,}1$ the final voltage on $C2$ changes its polarity, and, hence, final voltage on capacitors and their total final energy will not be equal to null any more. From (6) follows that for $k = 0{,}1$; $k = 1$; $k = 10$, efficiency $\eta = 0$ at $U^*_{C2}(0-) \le -0{,}83$; $\le -0{,}33$; $\le -0{,}05$ respectively (Fig. 2, *c*).

Conclusions. It was found that decrease in a difference between initial voltages on two connected capacitors, as well as decrease in the ratio capacitance of charged capacitor to capacitance of discharged one cause a decrease in electric energy loss and increase in efficiency of energy redistribution between capacitors. Additionally the energy loss and efficiency do not depend on the resistances of the analyzed circuit. In particular at initial voltages on charged capacitor and discharged one $U_{C2}(0-) = 0$; $U_{C1}(0-) > 0$ respectively, as well as at variation of coefficient $k = C_2/C_1$ from 10 to 0,1 (i.e. 100 times) the value of efficiency increases from 0,08 to 0,48 (see the table for $U^*_{C2}(0-) = 0$). At the same time, for $U^*_{C2}(0-) = 0{,}5$ and the same changes in the coefficient k the efficiency increases from 0,68 to 0,74, while for $U^*_{C2}(0-) = 0{,}9$ efficiency is almost constant and equals to 0,95.

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ЗАЛЕЖНІСТЬ ВТРАТ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ ПРИ ЕНЕРГООБМІНІ КОНДЕНСАТОРІВ ВІД ЇХНІХ ПОЧАТКОВИХ НАПРУГ ТА СПІВВІДНОШЕННЯ ЄМНОСТЕЙ

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Досліджено процеси обміну електричною енергією між двома з'єднаними конденсаторами різної ємності, зарядженими до різних напруг. Встановлено особливості впливу співвідношення ємностей конденсаторів, а також їхніх початкових напруг на виникаючі втрати електроенергії при її перерозподілі між конденсаторами. Визначено умови зменшення таких втрат і збільшення коефіцієнта передачі електричної енергії від одного конденсатора до іншого. Бібл. 10, рис. 2., табл. 1.

Ключові слова: енергетичні процеси, конденсатори, втрати електроенергії, коефіцієнт передачі енергії.

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ЗАВИСИМОСТЬ ПОТЕРЬ ЭЛЕКТРИЧЕСКОЙ ЭНЕРГИИ ПРИ ЭНЕРГООБМЕНЕ КОНДЕНСАТОРОВ ОТ ИХ НАЧАЛЬНЫХ НАПРЯЖЕНИЙ И СООТНОШЕНИЯ ЕМКОСТЕЙ

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Исследованы процессы обмена электрической энергией между двумя соединенными конденсаторами различной емкости, заряженными до разных напряжений. Установлены особенности влияния соотношения емкостей конденсаторов, а также их начальных напряжений на возникающие потери электроэнергии при ее перераспределении между конденсаторами. Определены условия уменьшения таких потерь и увеличения коэффициента передачи электрической энергии от одного конденсатора к другому. Библ. 10, рис. 2, табл. 1.

Ключевые слова: энергетические процессы, конденсаторы, потери электроэнергии, коэффициент передачи энергии.

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