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CRITICAL FREQUENCY OF AUTONOMOUS CURRENT INVERTER WHEN OPERATING ON ACTIVE-INDUCTIVE LOAD

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Abstract. The article presents the results of a study of a circuit of an autonomous current inverter with shut-off valves when operating on an active-inductive load in terms of identifying its properties, energy characteristics and comparing the circuit with a traditional parallel current inverter with capacitive switching without additional valves.
Key words: automatic current inverter; cut-off diodes; active-inductive load; intermediate transformer; switching capacitor

Introduction

The range of operating frequencies of automatic current inverters (ACI) is limited by the switching capabilities of the valves, i.e. their unlocking and locking with the help of the reverse current flowing through them due to the discharge of energy accumulated in the switching capacitors [1, 2]. However, this energy may be insufficient to close the operating valves or sufficient, but not conserved during the working period due to its discharge through other circuits. In both cases, switching breaks down, respectively, the frequency of the ACI is limited by this frequency. This frequency is called the critical frequency and is determined by the charge and discharge time constant of the switching capacitor circuit.

To reduce the operating frequency, there are a number of methods based on cutting off the charging circuit after switching the valves in order to save the capacitor energy from its further discharge. The main cutoff element in the discharge circuit are valves (diodes), which are called cutoff diodes [3, 4]. In fig. 1, 2 show the diagrams of single-phase ACI without cut-off diodes and with them (ACI COD).

The aim of the work is to study the dependence of the critical frequency on the parameters of the discharge circuit, including an active-inductive load, an intermediate transformer and a switching capacitor, using the example of a single-phase circuit (ACI COD).

1 Determination of the critical frequency and period when the ACI is operating on an active-inductive load

Single-phase thyristor ACI are widely used in electromechanical systems for frequency, pulse, amplitude regulation of motors [4, 5, 6]. So, from single-phase circuits, it is possible to supply single-phase asynchronous motors (AM), single-phase capacitor AM, single-phase collector motors, single-phase synchronized capacitor motor, etc. In all these cases, the inverter load is some kind of AM with its equivalent equivalent circuit. As a rule, these equivalent circuits are reduced to some form (parallel or series connected) active - inductive LR load. Therefore, generalizing the inverter load with a certain value $Z_H = R_H + jX_C$, we obtain the equivalent circuit shown in (Fig. 1) Further, presenting the transformer as an ideal apparatus (without active losses), we obtain the equivalent circuit shown in (Fig. 2).

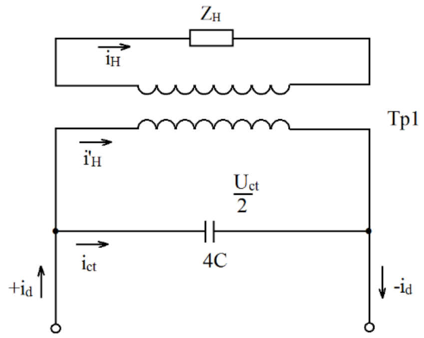

Fig. 1. Equivalent circuit ACI with COD

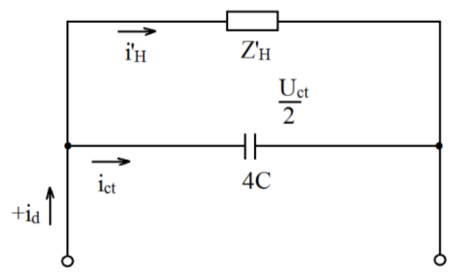

Fig. 2. Equivalent circuit ACI with an COD with an ideal transformer.

Let us consider in this diagram the influence of electromagnetic processes associated with Zn load on the critical frequencies and periods of operation of the inverter. For this, we will accept the following generally accepted assumptions [7, 8]:

1) switching occurs instantly, therefore, at each moment one thyristor operates in the circuit;

2) the smoothing coefficient of the inductor in the DC circuit is taken to be infinity, i.e. direct current i0 = const.

The actual process of operation of the inverter in the time interval 0 <t <τ1 is obtained by superimposing on Fig. 2.3, and currents and voltages on currents and voltages at time t = 0. For the cases t> τ1, this reasoning is meaningless.

The following equations correspond to this scheme:

$$i_{C_t} = 2Cpu_{C_t},$$

$$\frac{1}{2}u_{C_t} + i'_{\text{н}}Z'_{\text{н}}(p), \tag{1}$$

$$i_0 = i_{C_t} + i'_{\text{н}}, \tag{2}$$

where $\frac{d}{dt} = p$ – is an operator and $Z'_{\text{н}}(p)$– is an operator resistance (impedance).

After intermediate transformations, we get:

$$u_{C_t}(p) = \frac{2i_0}{\frac{1}{Z'_{\text{н}}(p)}+4Cp}\ , \tag{3}$$

$$i_{C_t}(p) = 4Ct_0\frac{p}{\frac{1}{Z'_{\text{н}}(p)}+4Cp}. \tag{4}$$

Hence it can be seen that the work of the ACI with COD depends significantly on $Z'_{\text{н}}(p)$, i.e., on the kind of receiver.

We analyze expressions (3) and (4) for special cases.

The load is purely active, then

$$\frac{1}{Z'_{\text{н}}(p)} = \frac{1}{R'_{\text{н}}}. \tag{5}$$

Omitting intermediate transformations, we obtain expressions for the capacitance current:

$$i_{C_t} = i_0 \cdot e^{-2\alpha_C}. \tag{6}$$

The receiver consists of a parallel connection of inductance and active resistance, then

$$\frac{1}{Z'_{\text{н}}(p)} = \frac{1}{R'_{\text{н}}} + \frac{1}{L'_{\text{н}}p}. \tag{7}$$

In this case, equation (4) will take the following form:

$$i_{C_t}(p) = i_0\frac{p^2}{p^2+\frac{1}{4R'_{\text{н}}C}p+\frac{1}{4L'_{\text{н}}C}}. \tag{8}$$

By designating

$$\frac{1}{4R'_{\text{н}}C} = 2\alpha_C \quad \text{и} \quad \frac{1}{4L'_{\text{н}}C} = \text{v}^2,$$

get

$$i_{C_t}(p) = i_0\frac{p^2}{p^2+2\alpha_C p+\text{v}^2}. \tag{9}$$

Depending on the ratio of α_C and v, we have three solutions to the operational equation (9):

а) at $\text{v} > \alpha_C,\ i_{C_t} = -i_0\frac{\text{v}}{\text{v}'}\cdot e^{\alpha_C t}\cdot\sin(\text{v}'t-\theta)$,

Where $v' = \sqrt{\text{v}^2-\alpha_C^2};\ \theta = arc\ tg\frac{\text{v}'}{\alpha_C}$;

б) at $\text{v} = \alpha_C,\ i_{C_t} = i_0\cdot e^{-\alpha_C t}(1-\alpha_C t)$;

в) at $\text{v} < \alpha_C,\ i_{C_t} = i_0\frac{1}{n-m}(ne^{-nt}-me^{-mt})$,

where (-n) and (-m) are the roots of the characteristic equation

$$p + \text{v}^2 = 0, \tag{10}$$

$$-n = -\alpha_C + \sqrt{\alpha_C^2 - \text{v}^2}, \tag{11}$$

$$-m = -\alpha_C - \sqrt{\alpha_C^2 - \text{v}^2}. \tag{12}$$

It should be noted that expression (6) can be obtained from equation (12) by setting $L_н = \infty$.

Accordingly, when the ACI operates with an COD to an active-inductive receiver at $f < f_{\text{к}}$, we have three equations for determining the time τ_1 and the critical period $T_к$, for which i_{C_t} vanishes:

а) at $\text{v} > \alpha_C$ or $R'_{\text{н}} > \frac{1}{4}\sqrt{\frac{L'_{\text{н}}}{C}}$,

$$\tau_1 = \frac{\theta}{\text{v}'}\frac{arc\ tg\frac{\text{v}'}{\alpha_C}}{\text{v}'} = \frac{1}{2}T_{\text{к}}\frac{1}{2f_{\text{к}}}; \tag{13}$$

б) at $\text{v} = \alpha_C$ or $R'_{\text{н}} = \frac{1}{4}\sqrt{\frac{L'_{\text{н}}}{C}}$,

$$\tau_1 = \frac{1}{\alpha_C} = 8R'_{\text{н}}C = 2\sqrt{L'_{\text{н}}C} = \frac{1}{2}T_{\text{к}}; \tag{14}$$

в) at $\text{v} < \alpha_C$ or $R'_{\text{н}} < \frac{1}{4}\sqrt{\frac{L'_{\text{н}}}{C}}$,

$$\tau_1 = \frac{ln\frac{p}{m}}{n-m} = \frac{1}{2}T_{\text{к}} = \frac{1}{2f_{\text{к}}} \tag{15}$$

2 Investigation of a single-phase ACI with COD when working on an active-inductive receiver

The objective of the study was to clarify the qualitative and quantitative indicators of the circuit (the shape of the curves $u_{\text{н},}\ t_{\text{н}}$ and external characteristics $U_{\text{н}} = \varphi(I_{\text{н}})$ at various values: voltage of the direct current source E_0, load $I_{\text{н}}$, frequency f, capacity C and $\cos\varphi_{\text{н}\infty}$ and comparing them with the characteristics of the inverter additional valves.

The study of a single-phase ACI with an COD when operating on an active-inductive receiver was carried out according to the schematic diagram in (Fig. 2) and an inverter without additional valves according to the diagram in (Fig. 1). According to these schemes, the external characteristics of the ACI were taken at different values of the switching capacitance C, the voltage of the DC source E_0, the frequency f, the load power factor $\cos\varphi_{\text{н}\infty}$ (Fig. 3, 4 and 5). active load with almost all capacitances, the external characteristics of the inverter without a additional valves are somewhat higher than the external characteristics of the ACI with an COD. This circumstance is explained by the fact that with a purely active load, the operating conditions of the switching capacitors in both circuits are the same, that is, the reactive power of the switching The capacitor is mainly consumed for switching the current. At the same time, the voltage drop across the additional uncontrolled valves is a factor affecting the decrease in the external characteristics of the automatic power supply with an optical fiber at $\cos\varphi_{\text{н}\infty} = 1$.

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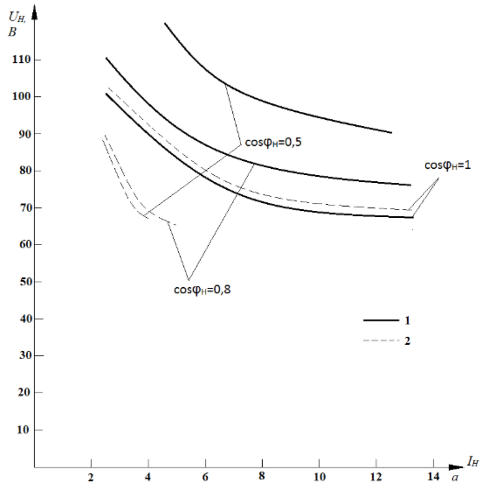
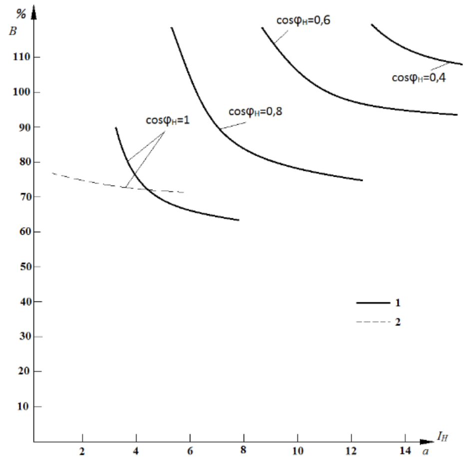


C=6 μF, $E_0 = 150\, V$, f=50 *Hz*.
Fig. 3. External characteristics of ACI: 1 - ACI with COD; 2 - ACI without additional valves.

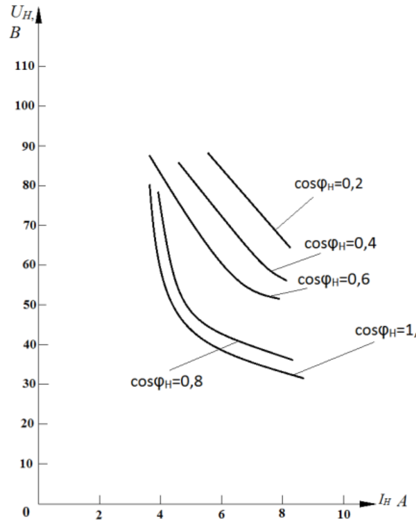
As seen from (Fig. 3) with a load power factor $\cos \varphi_{\text{H}\infty} < 1$ and any values of the switching capacity, as well as the same load of the ACI receiver with an optical fiber, the inverted voltage at the terminals of the receiver Uн is 60 - 70% higher than the inverter without a additional valves. On the other hand, all other things being equal, in particular, with very low load power factors, an ACI with an COD can give a significantly higher load current than an inverter without a additional valves.



f=30 *Hz*, C = 9 μF, E_0 =150 *V*. Inverter without d.c. when $\cos \varphi_{\text{H}\infty} < 1$ it overturns.
Fig. 4. External characteristics of ACI: 1 - ACI with COD; 2 - inverter without additional valves.

The introduction of additional gates into the inverter circuit causes an improvement (i.e., a slower decay) in external characteristics. This is due solely to their blocking effect, which does not allow the capacitor to discharge through the transformer, which can occur when the operating frequency is less than the critical one.

Therefore, at low $\cos \varphi_{\text{H}\infty}$ and normal frequency, the external characteristics of the ACI with an COD are significantly higher than the characteristics of the inverter without a additional valves. The large discrepancy between the external characteristics of the compared circuits with low load power factors is physically due to the fact that in these cases the "Zigzag" mode is delayed (the transition of the current from one half of the transformer winding to the other in the process of switching is difficult) and, accordingly, the limiting capacitor voltage rises. It remains in the ACI with an COD without significant change until the beginning of the next switching period, while for an inverter without a additional valves. the voltage limit is followed by a voltage drop due to a discharge through the transformer winding.



f=10 *Hz*, C=24 μF, E_0 =80 *V*. The inverter without a additional valves will overturn at the specified values.
Fig. 5. External characteristics of ACI with COD.

Thus, an improvement in the external characteristics of an ACI with an COD at $\cos \varphi_{\text{H}\infty} < 1$, in comparison with the characteristics of an inverter without a additional valves, occurs due to a change in the operating conditions of the switching capacitors. In (Fig. 6) shows the voltage curves of the switching capacitance of the ACI with an COD and an inverter without a additional valves. at $\cos \varphi_{\text{H}\infty} < 1$ as a function of time t. Here $u_C = \varphi_1(t)$ – is the voltage curve of the switching capacitance in the ACI circuit with an COD, $u_C = \varphi_2(t)$ – is the voltage curve of the switching capacitance in the inverter circuit without a DC.

From the given external characteristics of ACI with an COD and an inverter without a additional valves. it can be seen that with a relatively moderate decrease in frequency, the inverter without a d.v. overturns (in our case, at f<30 *Hz*), and at high frequencies it works, but has a relatively low stability factor. Under the same conditions, ACI with an COD works at all frequencies and has a large stability factor. With a decrease in the value of the load power factor and frequency the load current for an ACI with an COD increases, and for an inverter without a additional valves it decreases.

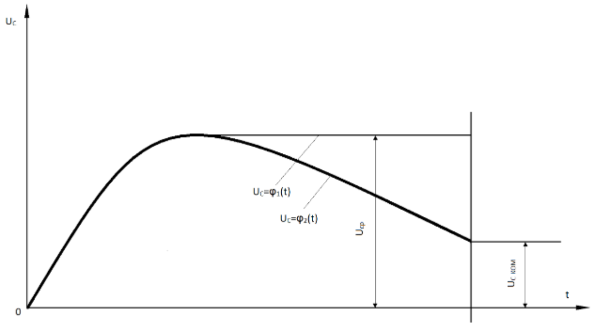


Fig. 6. Curves of voltages of the switching capacitance of ACI with COD and an inverter without a additional valves: $U_C = \varphi_1(t)$ – ACI with an COD; 2 - $U_C = \varphi_2(t)$ ACI without additional valves.

Large stability coefficient, good external characteristics of ACI with an COD and inverter overturning without a additional valves at low frequencies (Figs. 4 and 5) are mainly due to the same physical considerations as when derating the load power factor.

Conclusion

Analyzing the expressions for the capacitance current i_{C_t} and the time interval τ_1 (or critical frequency), we come to the following conclusions:

1. Taking into account the accepted assumptions, the obtained formulas for the current i_{C_t} fully reflect the electromagnetic processes in the ACI circuit with an COD at $f < f_к$.

2. The formulas obtained make it possible to determine the critical period and, accordingly, the critical frequency, depending on the ratio of the parameters, or to solve the inverse problem - for given values of τ_1 or $f_к$, determine the value of the switching capacitance.

3. With a decrease in the capacitance C, the load power factor $\cos\varphi_{н\infty}$ and an increase in the load $I_н$, the time interval τ_2 increases, and τ_1 decreases, i.e., the critical frequency $f_к$ grows.

4. The operation of the ACI with an OF at a frequency exceeding a certain - the critical value does not differ in any way from the operation of an ACI without a additional valves, since in this case additional valves in the ACI circuit with an COD do not play a significant role.

5. At a frequency lower than the critical one, switching failure and inverter overturning occurs in the ACI without additional valves, while due to the presence of additional valves, the ACI with COD remains operational.

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