Qualitative Analysis of Increasing the Dynamic Stability of autonomous inverters by connecting cut-off valves

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Abstract. The article presents the results of a qualitative analysis of circuits of autonomous current and voltage inverters with cut-off valves; the influence of the charge value of the switching capacitor in parallel and series equivalent circuits on the restoration of the switching properties of the thyristors of the inverter power circuit is studied. It is shown that due to the energy periodically accumulated in the inductive elements of the load, the voltage on the switching capacitor in the cut-off state is greater than in a conventional parallel autonomous current inverter. This circumstance ensures an increase in the switching stability of the inverter and therefore the circuit of an autonomous current inverter with cut-off valves is operational in valve converters for variable-frequency electric drives and remains operational during sudden load surges and short circuits, since the voltage value on the switching capacitor does not depend on the load voltage value those. the charge on the switching capacitor is maintained even when the load voltage sharply decreases between switching the thyristors of the power circuit.

INTRODUCTION

In the world, special attention is paid to solving the problems of developing power semiconductor converter technology based on current converters that are widely used in various industrial fields, their rational use with high accuracy of maintaining energy parameters, increasing operational reliability and increasing service life. Currently, in developed countries, "... more than 60% of the electricity generated passes through semiconductor converters. When using power electronics systems to a world-class level, it will be possible to save 12-15% of the electricity generated". In this regard, issues related to improving the energy efficiency of valve converters based on current converters for various purposes designed to provide the required power supply regime for energy facilities with increased requirements for the quality of energy consumed and reliability of energy resources are relevant [1-6].

The description of the modes of operation of the ACI implies the need to have a load with a resulting capacitive impedance, which facilitates instantaneous switching of the current in the load. For this purpose, a compensating capacitor is connected in parallel to the L, R load. This combination in the ACI is considered as its load. The corresponding algorithms for switching the thyristors of the automatic control system with a given frequency facilitate the conversion of the continuous current of the power source into the alternating current of the load and the voltage of the compensating capacitor [7-11].

It should be noted that the presence of parallel capacitance in the case of operation on the engine [2] leads to the occurrence, in certain modes, of capacitor self-excitation of the engine, causing the phenomenon of self-swinging. As a result, oscillations of the angle of recovery of the commutating properties of the thyristors - δ appear and the switching failure occurs.

The prospects for solving this issue led to the need to reduce the value of switching capacitances when regulating the output frequency over wide limits, by creating an automatic heat sink with cut-off valves (CV) [12-16].

The introduction of cut-off valves into the circuit results in the fact that in each time interval between the transmission of unlocking pulses to the control electrodes of the valves, the capacitors are disconnected from the load and the power source for some time. This circumstance allows to maintain the highest voltage appearing on it between commutations on C_k, making $U_c(t)$ independent of $U_H(t)$. As a result, the ACI with CD and CT have the ability to maintain the dynamic stability of the inverter with increasing load current.

The development and practical implementation of each next generation of power semiconductor devices, in turn, led to the qualitative development of converter devices with a corresponding increase in their power and expansion of their fields of application, as well as significant development of their research and design methods.

METHOD

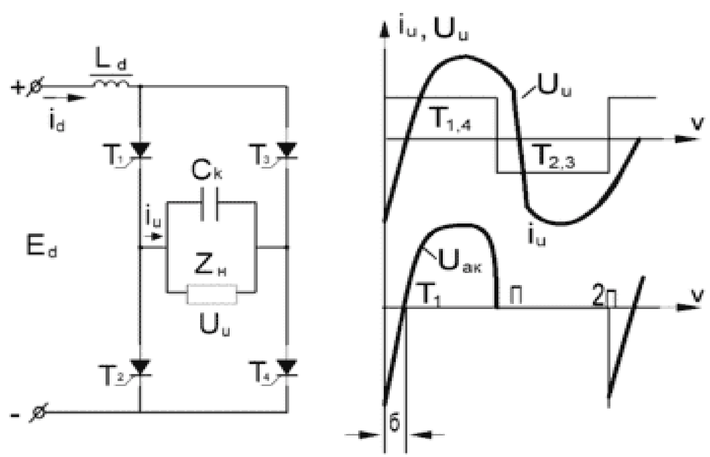
As is known, in quasi-steady-state mode, capacitors of the power circuit of an autonomous current inverter (ACI) are the only energy sources to compensate for the reactive power of the load and restore the locking properties of thyristors, i.e. there is a balance of reactive energy [18-22].

$$Q_c = Q_н + Q_\delta \tag{1}$$

where: Q_δ - is the reactive power to restore the valve;

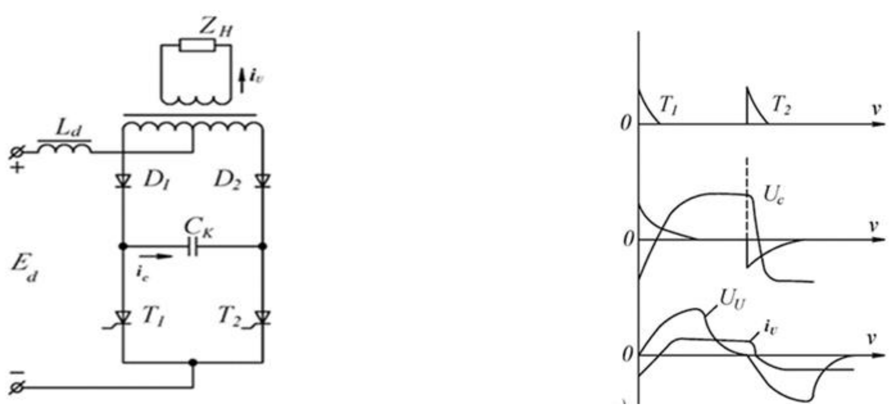
$Q_н$- is the reactive power of the load.

As can be seen from Fig. 1. and 2, the voltage on the capacitors in the circuit of an autonomous current inverter (ACI) without cut-off valves has a shape close to a sine wave, and in circuits with CV – close to a trapezoid. The smaller the trapezoid front, the smaller the capacitance of the capacitors, i.e., with a decrease in the capacitance value, the load voltage is enriched with higher harmonics. The formation of additional higher harmonics in the output voltage curve of the CV circuits affects the redistribution of energy Q_c between $Q_н$ and Q_δ in such a way that $Q_н$ increases and the power Q_c decreases [23-25].



a) b)

FIGURE 1. Scheme (a) and time diagrams (b) of a single-phase ACI



a) b)

FIGURE 2. Scheme (a) and time diagrams (b) of a single-phase ACI with CV

Let us consider in more detail the operation of ACI with CV in quasi-steady-state mode using the example of a single-phase bridge circuit (Fig. 1) [25-27].

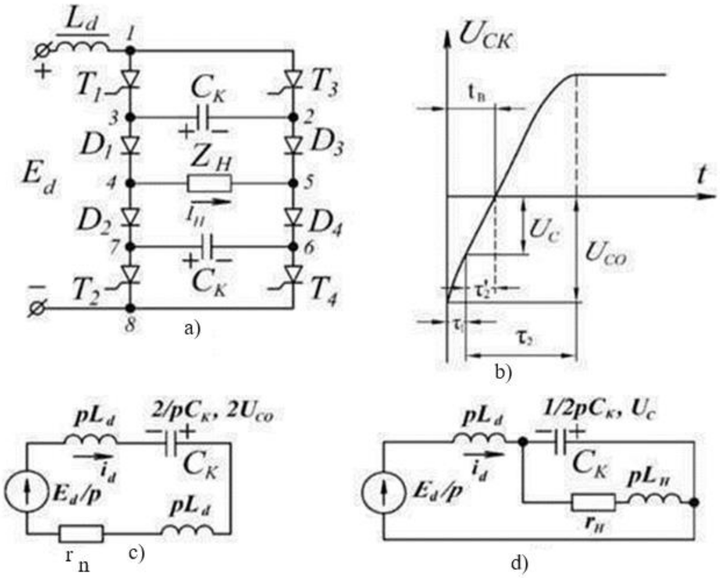


FIGURE 3. ACI with CV: circuit (a); time diagram of the capacitor voltage (b); replacement circuits (c, d).

Suppose at the moment *t = 0* the current passed through $L_d - T_1 - D_1 - Z_{(\text{p})} - D_4 - T_4$ and the capacitors had a voltage U_{co}. At the moment *t = 0* the thyristors *T₃, T₂* are switched on from the control system. Under the action of a reverse voltage of U_{co}, T_1, T_4 are instantly locked, but diodes D_2, D_3 are not switched on. This happens because we always have $|U_{co}| > |U_{\text{н}}(0)||$ in circuits with CV, and the next pair of cut-off diodes can open only after eliminating this inequality as a result of capacitor discharge.

The discharge occurs along the contour (in numbers): 1-2-3-4-5-6-7-8 and corresponds to the replacement circuit (Fig. 3, c) in the form of a sequential *L, C* circuit. At the moment $t = \tau_1$ we have

$$U_c(\tau_1) = U_{\text{н}}(\tau_1). \tag{1}$$

In this case, diodes D_2, D_3 are opened and in the interval τ_2 , the current in the load and the voltage on the capacitors change sign. At the moment$t_{\text{B}} = \tau_1 + \tau_2'$ when the voltage $U_c(t) = 0$, the interval for restoring the locking properties T_1, T_4 ends.

Let us consider the effect of the charge of the Sc in parallel and serial substitution circuits on the interval t_B and the establishment of the voltage U_{co}. To do this, instead of diodes $D_1 \div D_4$, cut-off thyristors (CT) $T_1' \div T_4'$, are installed, and the possibility is used to delay the supply of control pulses to T_2' , T_3' relative to the moment *t = 0* and set the interval of existence of the first substitution circuit (τ_{11}) within the required value, for example:

$$\tau_1 < \tau_{11} < (\tau_1 + \tau_2). \tag{2}$$

For the case of replacing cut-off diodes with thyristors, under the simplifying assumption $i_d(\text{t}) = I_d = const$, the following system of calculation expressions can be obtained for a single-phase ACI with cut-off thyristors:

$$U_{11}' = r_{\text{н}} I_d$$

$$\tau_2 = \frac{\left[\pi - arctg\left(\frac{\Omega_1}{6_1}\right)\right]}{\Omega_1}$$

$$U_{11} = r_{\text{н}} I_d + \frac{[2\Omega_1 L_H I_d \cdot \exp(-6_1\tau_2)]}{\sin \Omega_1 \tau_2} \tau_1 = C\left(\frac{U_{11}}{I_d - r_{\text{н}}}\right)$$

where: (3)

$$6_1 = \frac{r_{\text{н}}}{2L_H}; \quad \Omega_1 = \left[\frac{1}{(2L_H C) - 6_1^2}\right]^{\frac{1}{2}}.$$

$$U_{11} = |U_{C0}| = |u_C(\tau_1 + \tau_2)|$$

$$U_{11}' = u_C(\tau_1) = u_{\text{н}}(\tau_1) = u_{\text{н}}(0)$$

Here, τ_1 is characterized as the moment of transition from a serial to a parallel recharge circuit of a switching capacitor C_k.

Suppose the switching on of the cut-off thyristors is delayed relative to the moment t=0 until $u_C(\tau_{11}) = 0$. is obtained. Then, in the interval τ_{11}, a sequential replacement circuit of the charge C_k operates. If you enter the interval τ_{21} for a parallel circuit, then you can write the inequality:

$$\tau_{11} + \tau_{21} \neq \tau_1 + \tau_2$$

Under the above assumptions, the system of calculation ratios for ACI with cut-off thyristors has the form:

$$U_{11}^1 = 0\,,$$
$$\tau_{21} = \frac{\pi}{2\Omega_1}\,,$$
$$U_{11} = r_H\ I_d + 2\Omega_1 L_H I_d * exp\,(\text{-}б_1\ \tau_{21})\,, \tag{4}$$
$$\tau_{11} = C * U_{11}/\,I_d\,.$$

In the circuit with cut-off thyristors $t_{B1} = \tau_{11}$, and in the circuit with cut-off diodes $t_B = \tau_1 + \tau_2'$ Obviously, in the latter case, it is necessary to have the expression U_c (t) on the recharge interval in a parallel circuit, and then the value of τ_2' ' is found from the solution of the equation:

$$U_c(\tau_2') = 0. \tag{5}$$

Thus, the following features can be noted in the ACI schemes:

a) due to the energy periodically accumulated in the inductive elements of the load andL_d, the voltage on the $C_к$ in the cut-off state is greater than in a conventional parallel ACI at the time of commutation;

b) the form of voltage at C and at load is not the same, $U_c\ (t) \neq\ U_H\ (t)$. In particular, U_{CO} does not depend on the frequency of ACI operation when it decreases, and therefore the ACI circuit with CV is operable for a frequency electric drive [25-27];

c) since U_c (t) does not depend on $U_H\,(t)$, the charge on $C_к$ is preserved even with a sharp decrease in $U_H\ (t)$ between switching thyristors, that is, with sudden load surges and short circuit. This property can be used to provide switching during overloads and short circuit;

d) the introduction of cut-off thyristors makes it possible to change the ratio of recharge durations $C_к$ in serial and parallel circuits with load and the value U_{co}. Regulation τ_{11} makes little difference to the time allowed for power thyristors to recover.

ACI circuits with CT on the switching interval consist, as it were, of two independent circuits: connecting $C_к$ and connecting the load. However, the complete independence of the $C_к$ and load connection circuits is achieved only in the ACI circuit with DC, in which only a pulse of the C_k recharge current flows through the switching circuit (C_k plus thyristor). The single-phase version of ACI with CT in Fig. 4 has the same half-cycle substitution schemes as ACI with CD in Fig. 3 and the same lifetime of these substitution circuits as ACI with CT, provided that τ_{11} is the delay in switching on the next power thyristor relative to the time of switching on the previous switching thyristor.

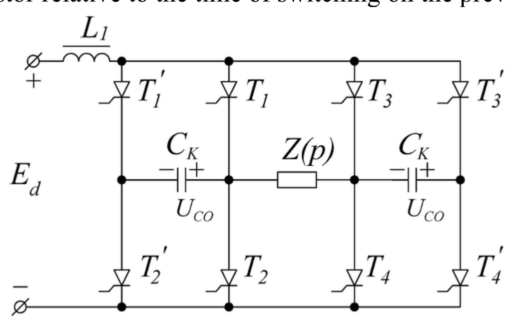


FIGURE 4. Single-phase ACI circuit with CT

Compensation of the reactivity of the load in the ACI is carried out due to the reactive current valves and the capacitance of the filter connected to the power source E_d or due to inter-phase interactions. It will be shown below that the separation of the $L_к$. From the $C_к$ circuit is possible in a single-phase ACI only in the presence of CV.

Let's consider the operation of a single-phase bridge circuit of an ACI with an CV (Fig. 5).

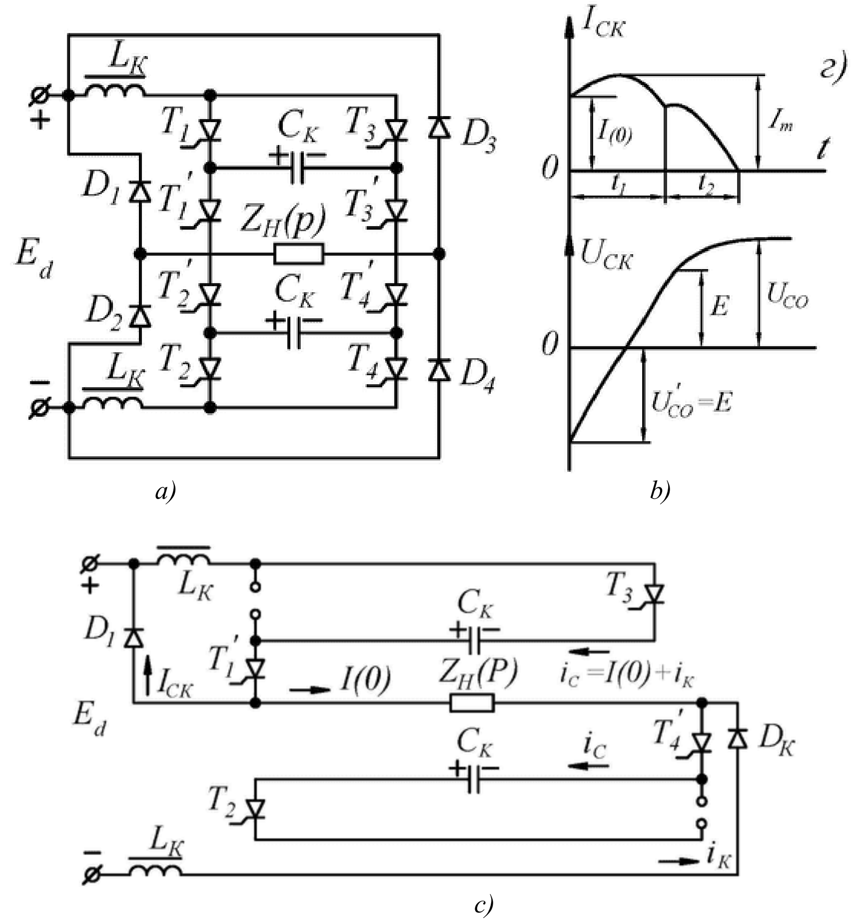


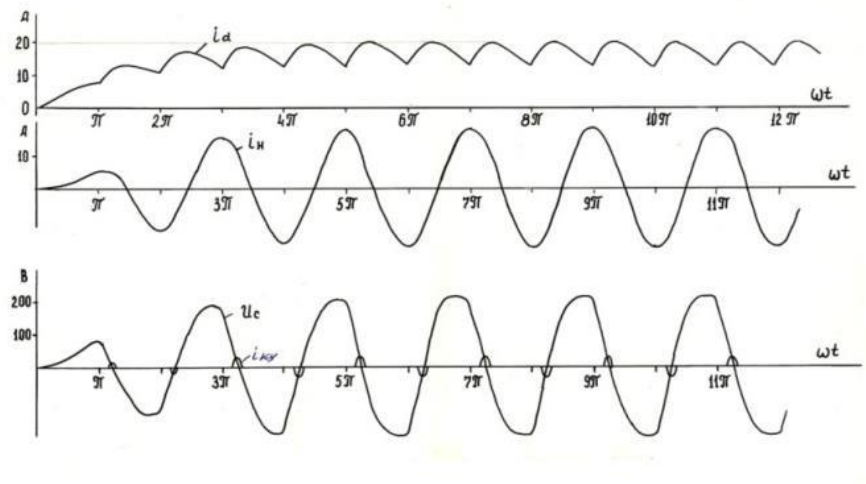
FIGURE 5. The scheme of a single-phase bridge ACI with CV: a) circuit; b) time diagrams; c) switching circuit through D_1, $D_к$

RESULTS

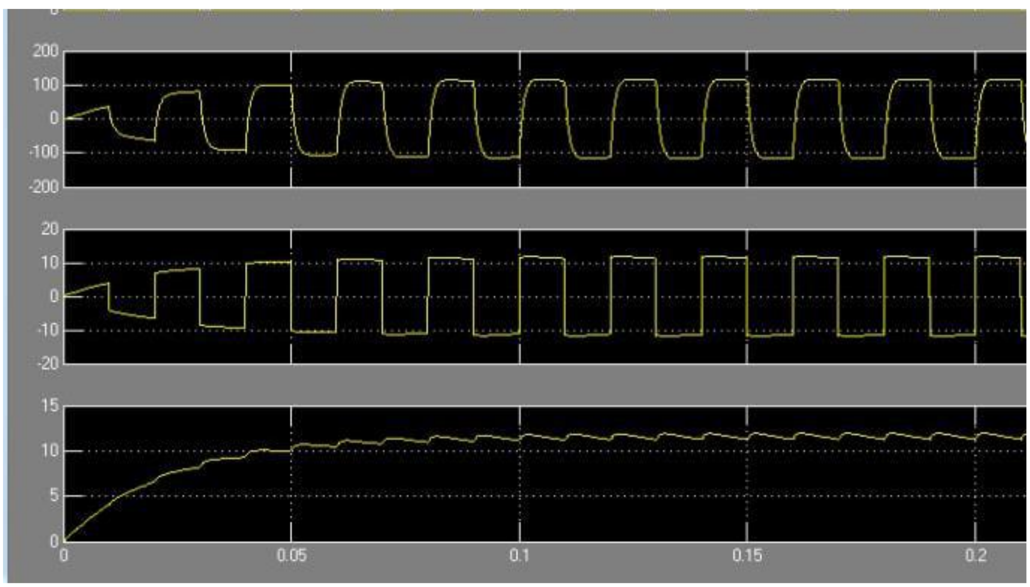
Let all elements be ideal; before the next inclusion of the pair T_3, T_2, there is $U_{co}^1 = E_d$; the load is active – inductive with a large time constant. Then, after switching on T_3, T_2, oscillatory recharge circuits $C_к$ are formed, completely equivalent to the circuits with two-stage switching in the ACI (Fig.5, b). The recharge is oscillatory and therefore on (Fig.5, d) the recharge current $i_{ск}$ has the shape of a dome above the initial value of the load current $i(0)$. From the moment t_1, the current $C_к$ is insufficient to supply the load and the load current tends to close through D_3, D_2 and the source (Fig. 5, c), and the voltage U_H changes the polarity abruptly.

In the replacement circuit (Fig. 5, c) capacitors $C_к$ from $U_c\ (t_1) = E_d$ are recharged in the interval t_2 to $U_{co} = E_d + i(0)\sqrt{L_к}\ /C_к$ due to the energy stored at the moment $t = t_1$in the inductance$L_к$.. Next, you can turn on the thyristorsT_3^1 , T_2^1 at the moment of the i_H current drop to zero or at t > t_1 with a wide pulse, as in conventional ACI. Repeated switching in the scheme under consideration, as can be seen, will lead to an increase in U_{co},, which is limited only by natural or artificially introduced losses into the scheme.

Programming the obtained analytical expressions and making up the algorithm of the process paths, the mathematical model was obtained. The mathematical model was used to calculate the transients and to plot the time diagrams of the currents and voltages to be expected, as shown in Fig. 6, a. Fig. 6, b shows the time diagrams of currents and voltages obtained by simulation. As can be seen from the presented diagrams, the time diagrams of currents and voltages at start-up of the autonomous inverter have a good agreement within 4-6%.



a)



b)

Figure 6. Time diagrams of currents and voltages at start-up:
a) analytical modelling; b) simulation modelling

CONCLUSIONS

Cutting-off diodes allow you to save $U_{co} = E_d$ from the end of any switching to the beginning of the next one and ensure overload operation if it was taken into account when calculating $C_к$with $U_{co} = E_d$. In particular, this approach is successfully applicable in the presence of filters, which have an input resistance not equal to zero at the load efficiency.

The use of cut-off valves in autonomous current (ACI) and voltage inverters (AVI) allows you to save the greatest voltage appearing on it between the switches on $C_к$ making $U_c\,(t)$ independent of $U_H\,(t)$. The resulting useful properties of CD and CT are used equally in both ACI and AVI. They were listed when reviewing the CV in the ACI. However, there is a property of schemes with CD belonging only to ACI. This is the $U_{co} > E_d$ inequality, which increases with increasing load current and is caused by the transfer of energy to $C_к$ from L_H and L_d at the switching interval. As a result, ACI with CD and CT have the ability to maintain switching stability with increasing load current. AVI with CT and AVI with CD schemes have similar properties.

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