Studies of Current Modulation in the DC Voltage Link of the Frequency Converter during its Operation with Asynchronous Load

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Abstract. The paper discusses current issues on the inverters peculiarities in the frequency converter. Theoretical studies have been carried out to determine the influence of the induction motor mode on the current modulation in the DC link. The authors suggest a calculation technique to determine the form of transient current characteristics when exposed to a single pulse of the inverter. Model studies of the system, calculation and construction of current characteristics proved the correspondence of theoretical and practical results. The research results determined the relationship between the current modulation in the DC link and the induction motor mode of operation.

1. Introduction

Mechatronic systems are the basis of modern production. They allow implementing a whole range of interrelated actions, movements and transitions united into a single technological process. The primary link of such a system is a controlled electric drive (ED), which moves the executive bodies of the working machines. At the same time, the electric drive configuration, the degree of semiconductor converting devices (SCD) application, and the degree of numerical control determine the possibility of regulating the process and controlling ED [1-3]. Thus, there is dependence between the technological process, the method of organizing a controlled electric power supply and the possibility of its integration into the general production automation system.

A common way to construct a controlled electric drive system is to implement the electric control method, when the magnitude and mechanical movements are carried out by regulating the parameters of the CD eclectic energy, with its subsequent supply to the electromechanical converter - electric motor (EM) [2-6]. The basis of modern controllers is a semiconductor converter, which must correspond to the external power supply system, an electric motor type, the possibilities to organize additional control by introducing feedback signals characterizing the output coordinates of the electric power and process parameters [6-9].

At present, the controlled electronic drive is mainly implemented in production by frequency controllers with asynchronous EM (FC-AD). Such a system is universal and allows organizing different ways of controlling separate, group and interconnected mechanical movements. The use of an asynchronous EM with a squirrel-cage rotor increases the reliability of the electromechanical system [8-12]. The study of the operation of the systems allows expanding their functionality; formulate recommendations for their use in electronic information technology.
2. Theoretical studies of current modulations in the FC-AD system

The basic schema of the frequency CD is a two-link system, with an autonomous voltage inverter. Studies have shown that there is an undoubted connection between the current modulation in the DC link with the operation mode of the asynchronous EM [11], the ratio of the active and reactive power of the consumer. To identify the basic laws of the process, it is necessary to consider the process of the inverter when implementing a three-phase voltage system.

Let us consider the process of a single pulse working out of the inverter key. Non-stationary phenomena in circuits with lumped parameters make the theoretical basis of the study. Figure 1 shows the design scheme that determines the inverter key influence on the active-inductive load (figure 1a) and the characteristics of the transient process (figure 1b), whose analysis allows determining the main patterns occurring in the DC link in the FC-AD system.

![Diagram](image)

Figure 1. Calculation scheme for the inverter key in the switching mode (a) and a general view of the transient characteristics (b).

The following elements and quantities are present in the circuit:

- $E$ – emf corresponding to the voltage in the DC link;
- $C_i$ is a capacitive filter to smoothen ripple in the DC voltage circuit;
- $K$ is a switch simulating the operation of an inverter key;
- $D$ is a reverse diode forming a circuit with the key turned off;
- $r_l$, $L_l$ are the resistances determining the asynchronous EM mode of operation.

Characteristics determine the transient process when $K$ is turned on. In general, the current flowing through a load simulating an EM equals:

$$i = i_{f0} + i_{fr},$$

where: $i_{f0}$ is the forced current component corresponding to the steady state;

- $i_{fr}$ is the free component of the current, maximum at the moment of switching on $K$ ($t=0$) and tends to 0 as $t\to\infty$, is directed opposite to the forced component of the current $i_{f0}$;

$$-L_d\frac{di}{dt}$$

emf of inductance, at the moment of switching on $K$ is equal to the voltage in the DC link $E$, and tends to 0 as $t\to\infty$.

The current rise rate at the moment of switching on $K$ ($t=0$) is determined by

$$\left(\frac{di}{dt}\right)_{t=0} = \frac{E}{L_l}.$$

Graphically, it is determined by the tangent tilt to the characteristic $i_{fr}(t)$, its intersection with the line $i_{f0}$ (point A). It is evident that the tangent tilt does not depend on the active load $r_l$.

Based on the equation (1), the current via the transient load can be determined by the expression

$$i = \frac{E}{r_l} - \frac{E}{r_l} e^{-\frac{r_l}{L_l} t},$$

where $L_l$ and $r_l$ are the inductance and resistance of the load.

2
When the current changes, magnetic energy is accumulated in the reactance of the circuit \( L_c \), i.e. reactive power consumption occurs according to the change in the transient component \( i_{fr} \). Based on this, we can write an expression for determining the energy consumed by the inductance

\[
A = \frac{L_c}{2} i_{fr}^2,
\]

or with the account of (2)

\[
A = \frac{L_c}{2} \left( -\frac{E}{r_i} \theta \right)^2.
\]

As the current in the switching circuit changes, the potential energy of the magnetic field increases. It depends on the parameters of the circuit and the time of the transient.

Instantaneous AC Power in inductive coil is

\[
q = ui_{fr}.
\]

For the case under consideration, this equation can be written as

\[
q = \frac{E}{r_i} \theta l_{fr}.
\]

From this equation, we can conclude that the reactive power generation during the FC-AD system operation occurs as a result of the current modulation in the DC link. In this case, the nature of the inductance charge process corresponds to the curve of change \(-L \frac{di}{dt}\) (figure 1b).

3. Experimental studies of current modulations in the FC-AD system

The empirical research was carried out with the numerical experiment method, applying the MatLab program. The FC-AD system was simulated with a block of parameters included for the study of current modulations in the DC link of an autonomous inverter [2, 11]. As a load, an asynchronous EM with a power of 125 kW and a synchronous rotation speed of 1500 rpm was used.

Figure 2 shows the operation of the inverter when generating the output voltage. The state diagram of the inverter switches (figure 1a) corresponds to the output three-phase voltage (figure 1b) obtained as a result of the simulation of the FC-AD system [11].

![Diagram](image)

(a) Figure 2. The inverter works when generating the output voltage: a) a state diagram of the inverter keys, b) an output three-phase voltage system.

The main studies were carried out at a standard frequency of 50 Hz and a rated supply voltage of 0.4 kV. The oscillation period was \( \frac{2 \pi}{\omega_{el}} = 0.02 \) s, the time shift in the operation of the inverter keys, \( \Delta t = 0.0033 \) s correspondingly. The above diagram and a graph of three-phase voltage correspond to the results received [1...6, 11] and are the basis for further research.
To determine the main dependences of the current modulation in the DC link on the load nature, model studies of the FC-AD system were carried out. Figure 3 shows the current characteristics for the load mode $P = 81$ kW, $Q = 60$ kW, which corresponds to $\cos \phi = 0.8$, with a probable load of 80%.

Analysis of current curves shows that the time shift between them is $0.0033$ s, which fully corresponds to the time diagram of the inverter keys ($\Delta t$ value, figure 2a).

The steady-state current value (maximum value) is 185 A and is confirmed by the calculation data received for this mode according to the above procedure. This value, with an error of 10%, corresponds to the forced component of the current $I_{fo}$ for the considered mode, 169 A.

According to (2), the calculated equation is

$$i = 169 - 169e^{-479t},$$

where $E = 400$ V, $r_1 = 2.37$ Ohm, $L_i = 4.6 \times 10^{-3}$ GN.

Figure 4 shows the results of the calculation for the current modulation curve $i_{fr}(t)$ in the DC link for the considered mode of the FC-AD system.

The obtained characteristic shows that the current change period, when the inverter key is turned on is $0.0108$ s, which is comparable with the pulse duration of the public key $0.01$ s. The tangent to the initial phase of the characteristic shows the minimum time $i_{fr}$ changes to reach the steady-state value.
\( i_{fr} \) The physical meaning of this process is theoretically determined as (\( \cdot \) A, figure 1b), \( t_{min} = 2.6 \cdot 10^{-3} \) s. The characteristic of the free current component in the DC link is dying out, varies within -169 \( i_{fr} > 0 \). In general, the calculated current change curve reflects the physical processes in the DC link of the inverter.

Its differences from the experimentally determined current modulation (figure 3) are due to three simultaneous pulses. They are shown by the diagram of the inverter keys. This overlapping distorts the final pattern of the pulses distribution and does not allow determining the effect of a single key switch.

4. Conclusion
Theoretical studies have made it possible to predict the current modulation when powered by a constant voltage. It has been determined that the parameters of the switching circuit - the active and reactive resistances of the asynchronous load, the voltage value in the DC link have a key influence on the current transient process. In this case, the current modulations have a forced \( i_{fr} \) and a free component \( i_{fr} \). The nature of the change in reactive power at the inductive-active load of the inverter has been determined. The model studies confirmed the main theoretical results with an error of no more than 10%.

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