Reversible frequency converters in the composition of multimotor electric drives

R Ganiev
Kazan National Research Technological University, Institute of chemical technology
Nizhnekamsk, Avenue of Builders, 47, Republic of Tatarstan, Russian Federation

* E-mail: N7007@mail.ru

Abstract. The article deals with the modeling of multi-motor electric drives based on reversible frequency converters (RFC) based on Autonomous voltage inverters and current inverters in the program Matlab 13. The possibilities of energy recovery using keys with two-way conductivity are shown. The interaction of reversible converters with the supply network, as well as the influence of recovery processes on the capacitor of the DC link is presented. A comparative analysis of three schemes using RFC based on autonomous current inverters (ACI) and voltage inverters (AVI). Technical solutions are proposed to direct the braking energy into the supply network and reduce the voltage level on the capacitor plates without loss of energy efficiency.

1. Introduction
Multi-motor electric drives of modern production lines, in particular lines of production of a cord for tires, work in the modes providing change of size and the sign of speeds and the torques of working shafts at loading and unloading of material, and also in brake modes. Since the loaded line has a significant inertia, the change of modes creates conditions for the reverse conversion of mechanical energy into electrical energy – recovery of energy into supply network.

In such lines, a scheme with a common DC bus and individual inverters for motors is used to power the motors. In this case, it is advisable to use reversible frequency converters (RFC). Reversibility provides for instantaneous readiness of the frequency converter to change the direction of active power flows between the motor and the supply network. In the case of a multi-motor electric drive with a common DC link, this property allows for the danger of exceeding the capacitor voltage in the DC link. This phenomenon can lead to violations of the technological regime in the production lines.. Below are the variants of the multi-motor drive with RFC based on the analysis of the state of the DC link, as the central element of the energy exchange between the network and the motor.

2. The electric drive on the basis of RFC with constant sign DC-link (LCCD)

2.1. General information on the operation of RFC with ACI
The initial idea of the conditions of the rectifier and inverter modes in the thyristor converter is shown in Figure 1 computer model of a single-motor drive made on the basis of an Autonomous current inverter [1]. The main purpose of the unit R/I in such systems is to set the current and torque of induction motor (IM) and the speed control of the motor is carried out by changing the switching frequency of the valves in the ACI circuit. The condition of the frequency-current electric drives is to
set the value and phase of the current at the output of the ACI. ACI is performed on lockable valves with one-way current conductivity, which pair work as part of the bridge circuit occurs with the duration of the conducting state of each valve on the period $\lambda=2\pi/3$. Under these conditions, the absence of reverse diodes and a capacitor filter leads to significant overvoltages at the moment of locking the valves. The overvoltage protection device discharges excess switching energy into the polar capacitor of the $C_f$ filter, shunted by the discharge resistor. $C_f$ connection (Figure 1) is carried out by means of an auxiliary diode bridge parallel to the stator windings of the IM. Thanks to the keys with unilateral conductivity is achieved by the constancy of the sign of the current $i_{df}(t)$ at the inputs of ACI. It allows you to perform the rectification unit/(inverting) $R/(I)$ in the form of a single converter [2,3]. According to this [4], the element base of this converter can be single-operation thyristors. Indicated by brackets, the link $I$ is present in the structure of the converter in an implicit form, since its functions are provided by setting the thyristor control angle in the range $\alpha\geq\pi/2$ and the functions of the link $R$ require setting the control angle of the same thyristors in the range $\alpha\leq\pi/2$.

Figure 1. A computer model of a single-motor drive with a current inverter (a) and the rectifier diagrams obtained with it at $t\leq0.12$ c., $\alpha\leq\pi/2$ and inverter at $t\geq0.12$ c., $\alpha\geq\pi/2$ modes (b).

2.2. Results of computer simulation of RFC with constant sign DC-link
The transition of the circuit from the rectifying mode to the inverter mode [5] is shown in Figure 1,b at time $t=0.12$ c. It can be seen that the change in the sign of the rectified voltage $e_{df}(t)$ contributes to the beginning of regenerative braking. This is indicated by a decrease in the speed of the shaft, accompanied by the transfer of the accumulated energy of the motor through the $C_f$ capacitor, through the link $I$ into the supply network. The process is accompanied by a decrease in the voltage of the capacitor $u_C(t)$ (curve 2) and the current consumption at the network phase input $i_{df}(t)$.

2.3. Interaction of electric drive with RFC and supply network
On the Figure 1,a a model of a twin-motor drive is shown, the modes of which are determined by the ratio of the mains voltage $E_1$ and the DC-voltage $E_d$ as a function of the thyristor control angle $\alpha$ of the $R/(I)$ unit on the one hand and the reduced RFC of the motor rotation $E_{12}$ on the other hand. The consideration is carried out taking into account the equivalent resistances of the network $r_1, L_1$ and stator windings IM ($r_2, L_2$). Mathematically, the three-phase sinusoidal voltage in the complex form:
\[ e(t) = E_{\text{m}} \sin(\omega_1 t) \], \[ a(t) = \exp(j\omega_1 t) \] (1)

A similar representation of the remaining voltages and currents in the equivalent circuit Figure 2, turns blocks R/I and ACI into a single-phase valve circuit with equivalent parameters of network input \(r_1, x_1, E_1, E_{12}\) and load \(r_2, L_2, E_2\) [1,4,6].

The balance equation of steady-state voltages in the network input circuits of the obtained model (Figure 1,b):

\[ E_1 = E_{12} + I_1 r + j I_1 x, \]

(2)

where \( E_{12} = \mu E_{12a} \cdot \exp(j\varphi_\mu) \) - the vector given to the network input of the main harmonic of back-EMF of rotation of the motor; \( I_1 = I_{1a} \exp(j\varphi_1) \) - the vector of the main harmonic of network current; \( r = r_1 + r_2; \ x = x_1 + x_2 \) is equivalent to that given to the network input, active and inductive resistance of the equivalent circuit. The reduction is carried out on the basis of the balance of the active power of the network input and the DC link [6] \( E_d I_1 3/2 = E_d I_d \) [6]. On the plane of rotating with a network frequency \( \omega_1 \) orthogonal coordinates \([x ; y]\) equation (2) can be displayed as a fixed vector diagram (Figure 3,a,b).

Compatible unchanged modulo \( E_m = \text{const} \) and the phase \( \varphi = 0 \) the vector of the mains voltage with the real axis 0x of this chart. The energy regime depends on the magnitude and mutual arrangement of two vectors: the network voltage [7] and the DC-link led to the network input of the EMF.

It is known that the phase control of the voltage at the output of the thyristor rectifier at \( \alpha = \varphi_i \geq 0 \) turns the unit R/I, and hence the entire electric drive, into a consumer of “reactive shear power” from the supply network. In this case, the upper quadrant illustrates the operation of the block R/I in the rectifying mode with the consumption of both power components \( P1 \geq 0, Q1 \geq 0 \) [8], the lower quadrant indicates the conditions for the occurrence of the inverter mode occurring at \( P1 \leq 0, Q1 \geq 0 \) (Figure 3).
Thus, the energy regime in the RFC circuit is determined by the sign of active power in the DC-link. The execution of ACI on unidirectional keys turns the specified part of the circuit into a link of a sign-constant current (LCCD).

3. The electric drive based on RFC with constant sign voltage link (LCVD)

3.1. Modeling of the electric drive based on RFC with LCVD

In contrast to the scheme Figure 2,a, the implementation of the AVI on the keys with two-way conductivity [9] makes the DC-link (LCVD), Figure 2,b. We consider the conditions of the energy interaction of the RFC in the assumption of the sinusoidal network voltage. The total power supply $\mathcal{R}/I$ allows us to consider the magnitude and shape of the voltage at the input of all inverters is the same. In this regard, the main reason for the energy interaction of drives in the multi-motor structure should be considered the equalizing current $i_{yp} = id_1 - id_2$. From the LCVD-scheme in Fig.2,b it can be seen that in the schemes based on the AVI, the appearance of an equalizing current is possible in the cases of operation of neighboring drives in different energy modes, and its closure occurs along the circuits passing the $C_F$ capacitor. The positive side of this phenomenon should be considered the current discharge of the capacitor and, accordingly, the reduction of voltage fluctuations in the LCVD-link.

3.2. Modeling of the electric drive based on RFC with LCVD

Confirmation of the capacitor discharge is obtained using the computer model of the twin-motor drive in Figure 4 inverter AVI1 and AVI2. Provided that the regulation of voltage and frequency at the outputs of the AVI is pulse-width method to eliminate between the R and I the currents of the interphase short circuit failure – fully controlled (lockable) valves are used [10]. The presence of the LCVD-link schematic condenser filter $C_F$ not only provides the traditional function of smoothing the voltage and circuit reactive current, but also of locking the diode block In hindering the development
of current phase-to-phase short-circuit. At intervals of simultaneous operation of the valves blocks And and V.

Figure 4. Computer model of a twin-motor electric drive made by the system R-I-IVI-IM+Cf (option 3): IVI (Independent (autonomous voltage inverter), IM (Induction motor), R(I) (Rectifier - Invertor), Cf (Capacity of filter).

Figure 5. The results of modeling the electric drive system R-I-IVI-IM+Cf (option 3): a – phase voltage and current of the network input; b – rectified voltage and current in the link LCVD at the common input of inverters; c – voltage on one of the keys of the block B/I; f,g,h – currents of the stator windings AD1; i,j – curves of the moment and speed of motor.
The test program of the model included the start of the electric drive at idle, followed by a sequential transfer of IM1 and IM2 at moments $t=0.05$ c. and $t=0.1$ c. in regenerative braking mode by applying a torque to the shaft. For comparison, the braking is carried out at the off and on States of the network inverter and. As can be seen from the curve Fig.5,b, the transfer of AD2 at the time $t=0.1$ c to the generator mode, along with an increase in the capacitor voltage level, led to a noticeable decrease in the resulting current at the input of the inverter $AVI1 \ id1= id2 - i_{yp}$ (see Figure 5,l) [11]. Repetition of this experiment with the inverter $I$ allowed to stabilize the capacitor voltage at a lower level (see Figure 5,C).

4. Motor at ACI with return power buses
According to 1-st variant [12], the block diagram of a multi-motor electric drive with separate power flows, in addition to power consumption buses, can be equipped with additional return power buses. The polarity of the voltage on the reverse power buses, thanks to the rectifier diodes, remains unchanged, corresponding to the conductive state of the thyristors of the recuperating inverter. Verification of this solution is carried out using the Figure 6 computer models of twin-motor drive with independent inverters and ACI1, ACI2 [13]. As before, the test program included simultaneous start of electric motors IM1 and IM2 at idle speed with their subsequent transfer to the regenerative braking mode. This translation was carried out by successive application to the motors at $t=0.1$, $t=0.15$ s. negative load torque [13].

**Figure 6.** Computer model of a twin-motor electric drive on the system R-I-ICI-IM-Cf (Controlled Rectifier/ Invertor - Independent (autonomous) current inverter – Induction motor – Capacity of filter), (option 3) with separate buses of direct and reverse power flows.

As shown in Figure 7,m, the resulting twisting of the motors is accompanied by an additional increase in the speed and EMF of rotation, but, depending on the state of the recuperating inverter $I$, it can differently affect the voltage level of the capacitor filter $C_F$ (Figure 7.g) [14]. According to option 3, the plates of this capacitor are connected in a conductive direction to the input terminals of the inverter $I$ forming a return power bus. The operation of this inverter was considered closed at $\alpha \to \pi$ and open at $\alpha \to \pi/2$ states [15]. As you can see from Figure 7,V, closing the inverter leads to a significant increase in the capacitor voltage, causing an unacceptable increase in overvoltage. Under these conditions, the growth of overvoltage can be limited only by dissipating excess energy in the discharge resistor [16]. At open thyristors of the inverter, on the contrary, (voltage and current...
curves of the capacitor $C_F$ in Figure 7,d there is a reverse power flow. It is seen that the emerging opportunity to direct the braking energy into the supply network leads to a decrease in the voltage level on the capacitor plates.

**Figure 7.** The results of modeling the electric drive system CR-I-ICI-IM-Cf (Controlled Rectifier/Inverter - Independent current inverter – Induction motor – Capacity of filter) (option 2): a – phase voltage and current of the network input; b – rectified voltage and current in the link LCCD at the common input of inverters; c,d - voltage and current filter CF in the closed (b) and open (d) states of the network inverter (I); e,f,g – currents of the stator windings IM; h,i – curves of torque and motor speed.

5. Conclusions

Thus, consideration of three versions of the multi-motor drive with RFC, indicates the advantage of the 3rd option – the ability to change the level of the steady-state voltage of the capacitor by adjusting the control angle of the thyristors of the link and in the range $\alpha=\pi/2 \div \pi$-um, where the um is the maximum switching angle, excluding the possibility of emergency mode “tipping” of the inverter. The results verify the efficacy of this decision is confirmed by the reduction of the overvoltage, the lack of energy of interaction of the drives with separate power flows [17].

References

[1] Sidorov S N 2004 Electrical Motorering 4 37-41
[2] Nagy I , Hamar J , Buti B 2007 European Power Electronics and Drives Journal 17(3) 5-15
[3] Valdez-Resendiz J E , Mayo-Maldonado J C , Llamas-Terres A , Rosas-Caro J C 2018 IET Power Electronics 11 8
[4] Sidorov S N 2010 Electricity 7 26-33
[5] Anish T , Gopinath A , Shiny G , Baiju M R 2014 European Power Electronics and Drives 24(2) 12-20
[6] Sidorov S N 2001 Electrical Motorering 5 6-11
[7] Rehaouilia A , Rehaouilia H , Fnaiech F 2018 Archiv für Elektrotechnik) 100(2) 733-9
[8] Dendouga A , Abdessemed R , Bendaas M L 2009 European Power Electronics and Drives Journal 19(1) 50-6
[9] Zambou S, Nussl R, Azeutsap F M, Zekeng S S, Ndjaka J M, Magunje B, Walton S D, Jonah E O, Harting M, Britton D T 2018 IET Power Electronics 11(1) 168-74
[10] Airabella A M, Oggier G G, Piris-Botalla L E, Garcia G O, Falco C A 2016 IET Power Electronics 9(6) 1103-10
[11] Ramos C, Martins A, Carvalho A 2011 European Power Electronics and Drives Journal 21(1) 43-54
[12] Al-Sheakh Ameen N, Naassani A A, Kennel R M 2010 European Power Electronics and Drives Journal 20(4) 37-44
[13] drives Cacciato M, Consoli A, Scarcella G, Scelba G 2008 European Power Electronics and Drives Journal 18(4) 34-41
[14] Mathematical model of a five-phase voltage-source pwm-controlled inverter Záskalický Electrical Motorering (Archiv für Elektrotechnik) 2017 99(4) 1179-1184
[15] Bernacki K, Rymarski Z 2017 Elektronika ir Elektrotechnika 23(3) 55-63
[16] Joksimovic G, Binder A 2004 Electrical Motorering (Archiv für Elektrotechnik) 86(2) 105-16
[17] Prabaharan N, Palanisamy K 2017 IET Power Electronics 10(9) 1023-33