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Energy-Efficient Drive System for Lift-and-Carry Tranfer Mechanisms

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***Abstract*—The results of study and development of the energy-efficient drive system for mechanisms working in the regeneration braking mode for a long time (lift-and-carry transfer mechanisms, hoists, cranes) are shown in this paper. The energy consumption and system efficiency of a converter with and without regenerative block for the mentioned mechanisms have been described. The results of experiments with MATLAB/Simulink are shown.**

***Keywords*—Mine Winder; lift-and-carry transfer mechanisms; two level frequency converter; the energy regeneration link.**

I. INTRODUCTION

Nowadays, the efficient use issue of energy resources has become important in the modern world economy system. In all developed countries, energy efficiency has become a major and actual technical field. In accordance with the energy strategy of Russia until 2030 reduction of energy intensity, more efficient use of energy and energy efficiency in the industry are the most important strategic directions.

Most of the produced electricity (about 60 %) in the industry is consumed by electric drives. At the same time, part of electric drives, working as a part of mining machines and systems such as lift-and-carry transfer mechanisms, conveyors, excavators, etc., a significant part of the cycle working with the regeneration of electricity [1]. If we consider that the power of electric drives is significant, in this case the part of electricity would be the same.

The current practice of using electric drives of lift-and-carry transfer mechanisms is based on the fact that the electricity generated by a motor during the load descent or braking of an inertial mechanism, is not transferred to the supply network, and is dissipated as heat in the brake resistor blocks. This practice is not acceptable currently. So, according to CJSC "ERASIB" the total annual unproductive electric losses of the existing electric drive of Mine Winder 2Ц-5*2.3 of Mine "Osinnikovskaya" constitute 2875250 kW · hours [2].

Mentioned losses have been eliminated by the utilization of an electric Mine Winder control system and the frequency converter. At the same time, there are not sufficient substantiations of complex use of frequency converters with control systems. Currently, research, development and study of energy-efficient electric drives are conducting by global corporations in the field of microprocessor technology, as well as in a number of universities around the world. Proposed various circuit solutions of AC and DC electric drives systems. The most advanced project is the project of Siemens (Germany), dedicated to designing and building energy-efficient electric drives for lift-and-carry transfer mechanisms equipped with a two level frequency converter and regenerative module «Active Infeed» [3].

Thereby, the tasks of research and development of energy-efficient electric drives for mechanisms working in the regenerative braking mode for a long time, with the ability to return the electricity to the main supply (lift-and-carry transfer mechanisms) seems relevant.

II. SYSTEM DESCPITION

In this section, fundamentals of energy saving in Mine Winder mechanisms reviewed. A motor of a hoist decelerates by applying negative electromagnetic torque to the shaft (descent of the load). In this case the regeneration of the electric power occurs.

The physical principle of all lift-and-carry transfer mechanisms (hoists, elevators, lifts) is converting electrical energy into potential energy of the load and vice versa. Since the range of travel of lift-and-carry transfer mechanisms is limited, therefore half the time the cabin of hoist is travelling up, and half the time it is travelling down. There are two ways to obtain electrical energy from potential energy in hoists. In a case when the car of the hoist is traveling down with the load and when it travelling up without the load. Fig.1. demonstrates regeneration cases in Mine Winder mechanisms. Fig.1,a corresponds to the case when the hoist is travelling down, and the counterweight is less than the car (load) weight. During braking mode (Fig.1), the electromagnetic torque would be in opposite direction to the speed. Fig.1,b corresponds to the case when the hoist is travelling up without the load.

This structure allows saving energy during the hoist moving as well, if the motor is controlled by regenerative frequency converter with an efficient control system. In the most cases electric power generated during motor braking, when the car of the hoist is travelling down with the load or up empty is dissipated as heat in resistance blocks. This drawback

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limits the range of hoist drive system functions during regeneration. Traditional, hoist drive control system consists of two level back-to-back frequency converters with diode rectifier. This structure does not allow returning the braking energy to the main supply. This task can be solved by using of frequency converter with regenerative blocks.

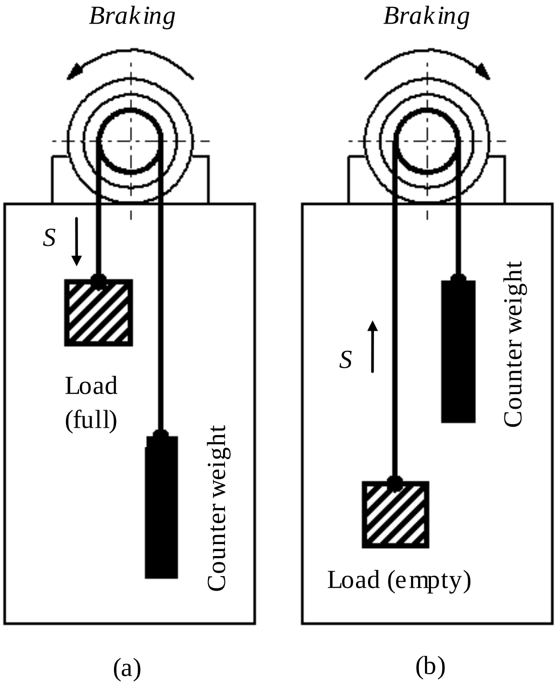

Fig. 1. Regeneration cases in Mine Winder mechanism.

Regeneration has been widely used in the industry. This process (regeneration) is considered one of the most effective ways to save energy in the electric drive system of the lift-and-carry transfer mechanisms. Regeneration occurs whenever the load on the motor's shaft tries to turn the motor shaft faster than the inverter's output frequency is trying to drive it. This is referred to as "overhauling". An example of the latter would be a load being lowered on the hoist; a downward inclined conveyor carrying a heavy load; or a fully loaded passenger elevator moving downward. In these situations, the inverter is acting to restrain the motion of the load, and this causes regeneration [4].

The frequency converters with regenerative blocks are effective solution that can be used instead of drive systems which consist braking resistor blocks. The using of frequency converters with regenerative blocks in applications working for a long time in regenerative braking mode (hoists, conveyors, elevators, cranes) allow to save electrical energy.

III. FREQUENCY CONVERTERS TOPOLOGY

A. *Frequency converter system using an active rectifier*

A schematic diagram of the two level frequency converter with the active rectifier is shown in Fig. 2. The converter consists the active rectifier (also well-known as an active front end) and an inverter unit connected with a common dc-link [5]. An electromagnetic interference input filter (EMI) is one of the important elements of the two level frequency converter, which using to eliminate the current harmonics on the main supply side [6]. The active rectifier and the inverter units are formed using IGBT – modules. Similar formation of the units allows electrical current to flow in both directions, from main supply to the load side and vice versa. During regeneration operating mode the inverter unit operates as the rectifier and the active rectifier operates as the inverter.

One of the advantages of the two level frequency converters with the active rectifier in certain applications is that energy generated during motor braking can be return to the main supply instead of wasting in braking resistor blocks [7].

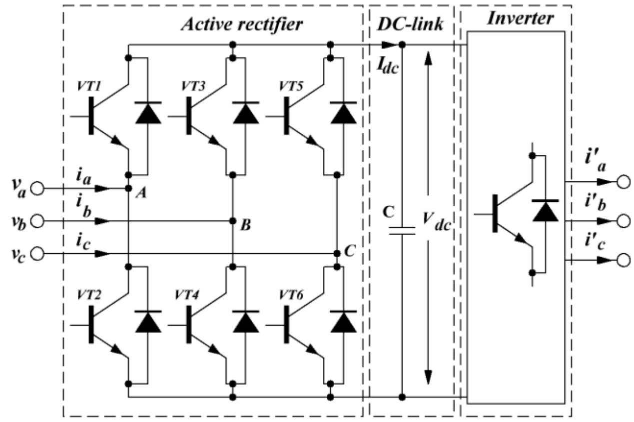

Fig. 2. Two level frequency converter with the active rectifier.

Despite of mentioned advantage the two level frequency converter possesses a disadvantage in regeneration operating mode. This disadvantage depends on the active rectifier construction. When the motor decelerates the regenerative energy begins to charge dc-link capacitor (Fig.2). In a case when the voltage of dc-link exceeds the line to line voltage of the main supply, the energy of regeneration returns to the main supply. This disadvantage imposes certain restrictions for the energy flow during breaking the motor.

When a cabin of the hoist is moving down with the load (or moving up without the load) the motor of the mechanism begins to function as a generator, the energy flows from the inverter side to dc-link. The capacitor of dc-link begins charging. Since dc-link voltage exceeds the line to line voltage of the main supply, the regeneration energy will return to the main supply. This restriction is directly related to the construction of a three-phase active rectifier because of blocking the current flow in the connection points of the active rectifier legs.

B. *Proposed energy regenaration system*

One of the suitable ways to extend the functionality of the electrical drive system in the regenerative braking mode is to change the active rectifier structure by adding appropriate IGBT/Diodes to the active rectifier legs, as shown in Fig.3. Proposed system is called "the energy regeneration link" [8]. The energy regeneration link (rectifier) allows returning the energy during braking without limitations and also allows regenerating the energy of the dc-link capacitor. The added transistors (VT7, VT8, VT9) should be ON during motor mode.

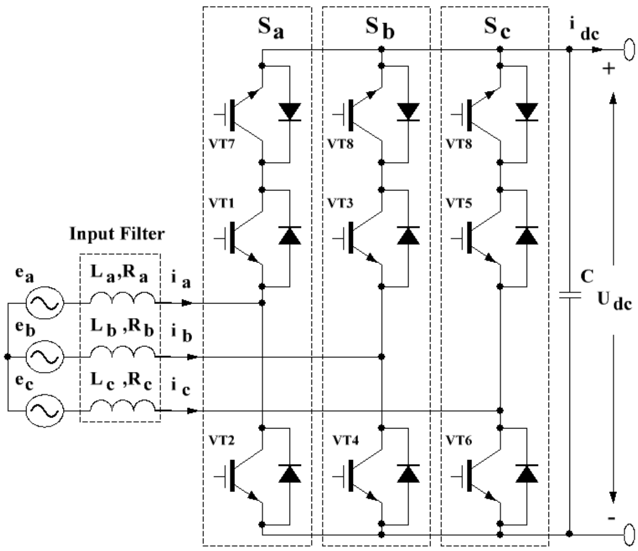

Fig. 3. Energy regeneration link structure.

IV. MODELING OF THE ENERGY REGENERATION LINK

The energy regeneration link can be formulated as:

$$\begin{cases} L_a \frac{di_a}{dt} = e_a - u_{dc} \frac{2S_a-(S_b+S_c)}{3} - R_a i_a; \\ L_b \frac{di_b}{dt} = e_b - u_{dc} \frac{2S_b-(S_a+S_c)}{3} - R_b i_b; \\ L_c \frac{di_c}{dt} = e_c - u_{dc} \frac{2S_c-(S_a+S_b)}{3} - R_c i_c; \\ C \frac{du_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c + i_{dc}, \end{cases} \qquad (1)$$

where e_a, e_b, e_c, i_a, i_b, i_c are respectively line to line voltages and currents of the main supply; R_a, R_b, R_c, L_a, L_b, L_c are respectively active and inductive resistance of an input filter of the energy regeneration link; u_{dc}, i_{dc} are respectively the voltage and the current of the dc-link; $S_a(t)$, $S_b(t)$, $S_c(t)$ are switching functions for each leg of the energy regeneration link. The switching functions can be formulated as:

$$S_x = \begin{cases} 1, upper\ switch\ ON \\ 0, lower\ switch\ ON \end{cases}. \qquad (2)$$

where the subscript x represents the phases a, b, c for the three legs of the energy regeneration link.

Using proposed the energy regeneration link in two level frequency converter structures allows extending the regeneration functionality of the hoist drive system. The functional model of two level frequency converter with the energy regeneration link is shown in Fig. 4. The functional model of the two level frequency converter consists rectifier (the energy regeneration link), dc-link with the capacitor and the inverter.

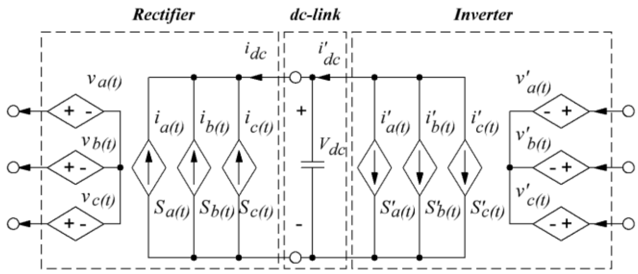

Fig. 4. Overal functional scheme of the converter.

V. CONTROL TECHNIQUE

Direct torque control (DTC) strategy was proposed by Takahashi and Depenbrock [9,10]. The DTC strategy is characterized by its fast dynamic response and simple implementation [11]. The torque ripple in traditional DTC occurs because of the non-linear nature of torque and flux controllers (relay controllers). Using the vector control strategy for DTC allows minimizing torque ripples. The electric drive system based on the proposed converter (the energy regeneration link) using vector control of DTC system is shown in Fig.5.

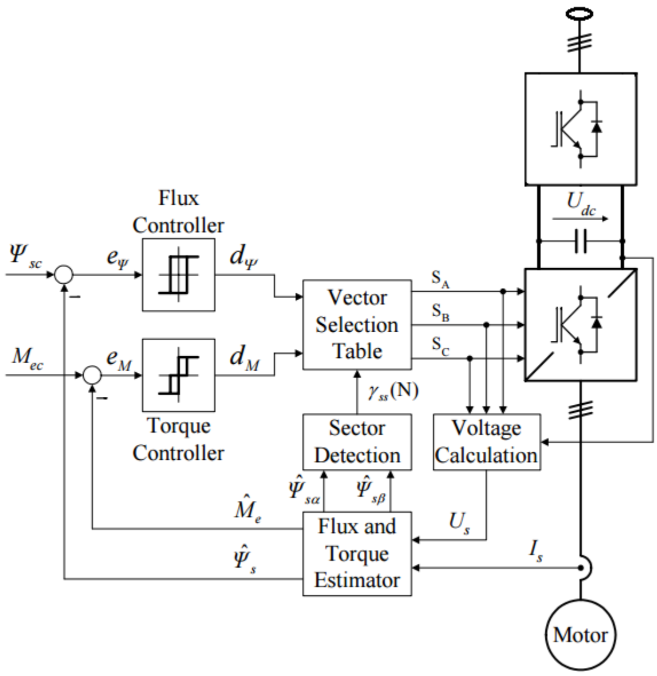

Fig. 5. Block scheme of the DTC of IM.

The amplitude of stator flux Ψ_{sc} and the torque of the IM M_{ec} are the reference signals which are compared with the estimated values from a flux and torque estimator block. The flux e_Ψ and torque e_M errors are delivered to the hysteresis controllers (flux and torque). The output variables d_Ψ , d_M and the stator flux position sector (N) γ_{ss} selects the appropriate voltage vector from the vector selection table. Thus, the selection table generates pulses S_A S_B S_C for control of the inverter [12]. The proposed converter (the energy regeneration link) with a relevant control technique allows effectively controlled the lift-and-carry mechanism. Phase voltages at the output of inverter are step functions (Fig.6).

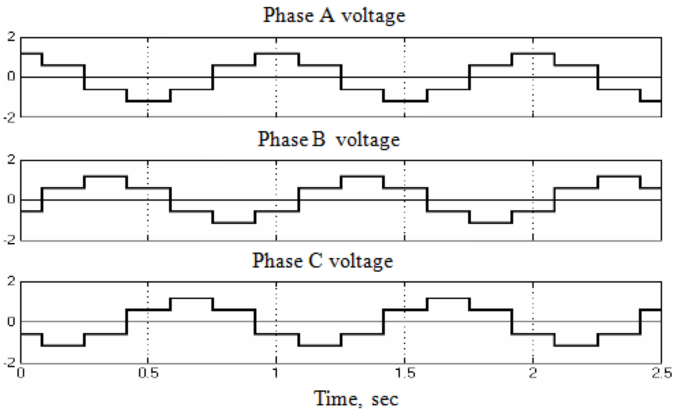

Fig. 6. Phase voltages at the output of inverter.

VI. SIMULATION

Study of the energy regeneration link dynamics behavior and system efficiencies of the lift-and-carry transfer mechanisms with the proposed converter were conducted using simulation model of the hoist drive system

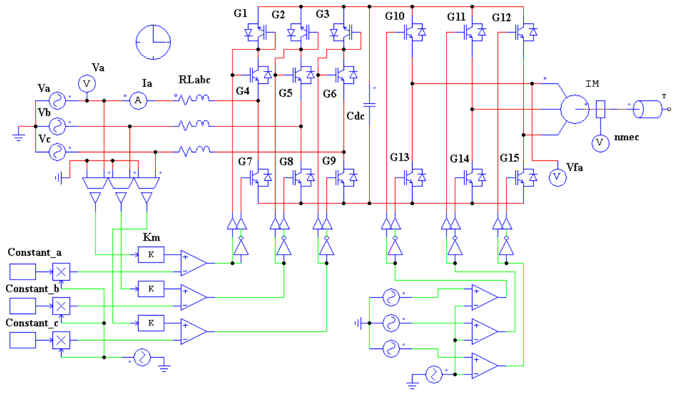

Fig. 7. Powersim model of the energy regeneration link.

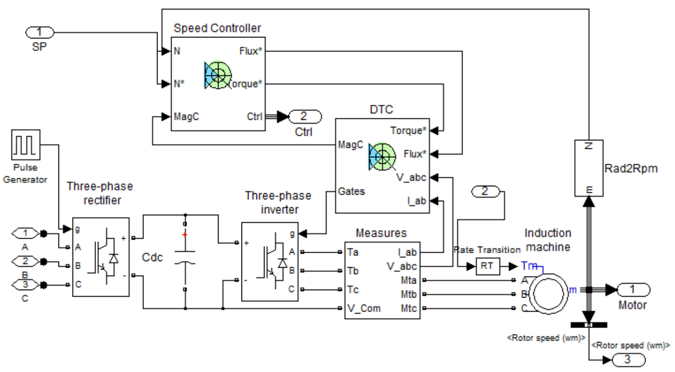

Fig. 8. Matlab model of the DTC Induction motor drive.

Simulation model of the energy regeneration link using Powersim is shown in Fig.7. Simulation model of hoist drive system using Matlab/Simulink is shown in Fig.8. Voltage and current responses of the energy regeneration link are shown in Fig.9. Voltage response at the output of the inverter is shown in Fig.10.

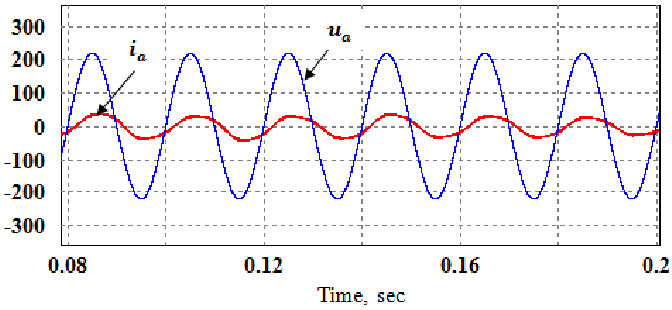

Fig. 9. Voltage and current of the energy regeneration link at the main supply side.

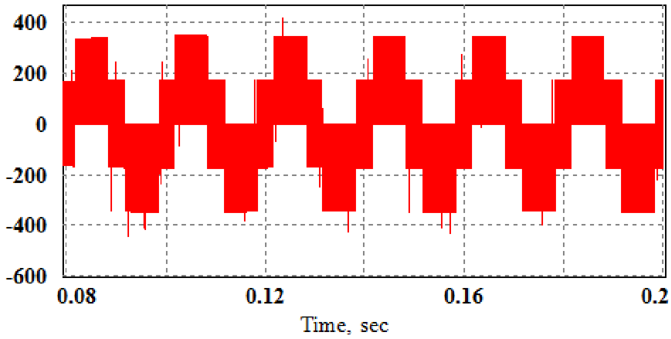

Fig. 10. Voltage response at the output of the inverter.

The main parameters of the induction motor and controllers getting for Matlab simulation are shown in Table I.

TABLE I. THE MAIN PARAMETRES FOR SIMULATION

№	The main simulation parameters			
	Parameter	Value		
1.	Nominal power	kW		120
2.	Phase-to-phase voltage	V		460
3.	DC-link capacitance	μF		7500
	Controllers parameters			
4.	Speed controller	Proportional		30
		Integral		200
5.	DTC controller	Torque	N-m	10
		Flux	Wb	0.02

VII. SIMULATION RESULTS

A step input of 790 *Nm* magnitude electromagnetic torque is applied at 0.5 sec. The load descent torque -790 *Nm* is applied at 1 sec. Results of simulation are shown in Fig.11. Regeneration currents at the main supply side are shown in Fig.12.

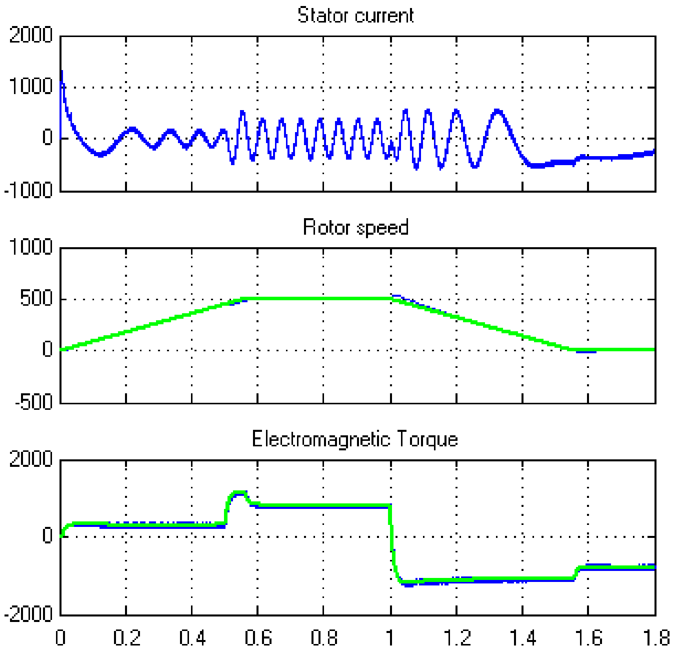

Fig. 11. Stator current, the speed of rotor and electromagnetic torque responses.

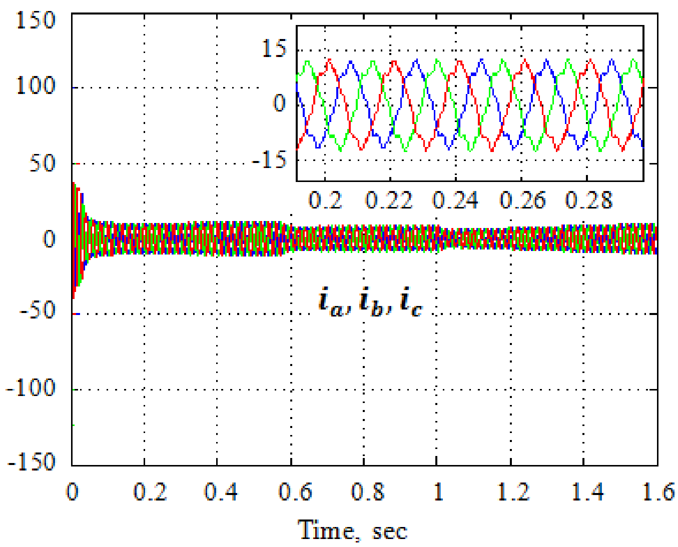

Fig. 12. Regeneration currents at the main supply side.

It can be seen that during descent the load the stator current is increasing. The increasing of voltage in DC-link is related with the overcharging of the capacitor during the motor braking. Regeneration durrents at the main supply side of the hoist drive system show the efficiency of the proposed regeneration link and control system.

VIII. CONCLUSION

Regenerative motors produce energy when the motor is in an overhaul condition. In the hoist, this occurs when the induction motor is used to brake a descending unit. Until recently, the electrical energy generated was sent through a resistor that dissipated the electrical energy as heat. Usage the regenerative drives and the energy regeneration links allow to return the braking energy into the main supply.

Models of the energy regeneration link and hoist have been designed using Powersim and Matlab/Simulink. The proposed energy regeneration link converter structure using DTC strategy has been tested. Simulation results have shown a very high accuracy in stator current, electromagnetic torque and regeneration currents during regeneration operating mode.

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