Supercapacitors application possibilities for lifting equipment induction electric drives

O A Lysenko¹, A V Simakov²
¹Omsk State Technical University, Mira Ave, 11, Omsk, 644050, Russia
²Omsk State Transport University, Marx Ave, 35, Omsk, 644046, Russia

Abstract. In the article, the supercapacitors (ionistors) application for lifting equipment induction electric drives is considered. Electric lifting equipment is widely used in industry, construction, municipal services. The lifting equipment efficiency is insufficient, therefore the research topic is relevant. At the moment, an induction electric motor with a frequency converter with a DC link is used to regulate the mode of lifting and lowering loads. To smooth out the ripple and use the braking energy of the moving masses when lowering the load, it is proposed to use a supercapacitor as a DC bus storage. A supercapacitor has three to four degrees more capacity than an electrolytic capacitor and can store more electricity. The paper provides simulation modeling of the electric drive of the lifting equipment. Stern's equation is used as a supercapacitor mathematical model. According to the simulation results, the power consumption of an electric drive with a supercapacitor is 41.02% less than that of an electric drive with an electrolytic capacitor.

1. Introduction
The lifting equipment electric drive has a significant part among the electrotechnical complexes. Electric drives for lifting equipment include electric hoists, various types of cranes, elevators, etc. The main part of such an electric drive consists of a frequency converter with a DC-link and a squirrel-cage rotor induction motor. A frequency converter usually consists of an uncontrolled rectifier, a voltage inverter, a capacitor-based DC link filter and a braking chopper.

The lifting equipment electric drive feature is the gravity force acting on the load. Therefore, there is an active load torque, the sign of which does not depend on the movement direction. Due to the active load torque, the lifting equipment goes into braking mode when lowering the load. In variable frequency drive braking mode, a braking resistor is used to convert kinetic energy into heat.

In this article, it is proposed to use supercapacitors to improve the electric drive effectiveness in terms of energy consumption [1, 2].

Study object is a variable frequency electric drive of lifting equipment with a supercapacitor in the DC link of the frequency converter.

Research subject is operating modes of a lifting equipment electric drive with a supercapacitor in the DC link of the frequency converter.

2. Supercapacitors applying
A supercapacitor is an electrochemical device with a double-layer dielectric, which is formed by placing a porous membrane between the electrodes. The membrane active area is greatly increased because many small pores are used [3, 4]. Thus, the supercapacitors stored energy is much greater than that of electrolytic capacitors, with the same dimensions. At the same time, the battery pack capacity is
higher than that of supercapacitors, but the charging and discharging currents do not allow direct use of these devices in an electric drive with high dynamic loads.

The supercapacitor model can be represented as a current-controlled voltage source according to the Stern equation (1) [5, 6]:

$$U_{SC} = \frac{N_S Q_T d}{N_S N_e \varepsilon \varepsilon_0 A_i} + 2N_eN_S RT \sinh^{-1} \left( \frac{Q_T}{N_p N_e^2 A_i \sqrt{8RT \varepsilon \varepsilon_0 \varepsilon}} \right) - R_{SC} i_{SC}$$

Where:

- $A_i$ – is the interfacial area between electrodes and electrolyte ($m^2$);
- $c$ – is the molar concentration ($mol/m^3$);
- $r$ – is the molecular radius ($m$);
- $F$ – is the Faraday constant;
- $i_{SC}$ – is the supercapacitor current ($A$);
- $U_{SC}$ – is the supercapacitor voltage ($V$);
- $R_{SC}$ – is the total resistance (ohms);
- $N_e$ – is the number of electrodes layers;
- $N_p$ – is the number of parallel supercapacitors;
- $N_S$ – is the number of series supercapacitors;
- $Q_T$ – is the electric charge ($C$);
- $R$ – is the ideal gas constant;
- $d$ – is the molecular radius ($m$);
- $T$ – is the operating temperature (K);
- $\varepsilon$ – is the material permittivity;
- $\varepsilon_0$ – is the free space permittivity.

The supercapacitor electric charge is determined by the equation (2)

$$Q_T = \int i_{SC} dt$$

In the self-discharge mode, the electric charge is defined as (3)

$$Q_T = \int i_{\text{self dis}} dt$$

Where the self-discharge current $i_{\text{self dis}}$ is determined from the equations (4)

$$i_{\text{self dis}} = \begin{cases} 
C_T \alpha_1 & \text{if } t \leq t_1 \\
\frac{C_T \alpha_2}{1 + sR_{SC} C_T} & \text{if } t_1 < t \leq t_2 \\
\frac{C_T \alpha_3}{1 + sR_{SC} C_T} & \text{if } t_2 < t \leq t_3 
\end{cases}$$

where $C_T$ is the total capacitance (F);
$R_{SC}$ is the total resistance (ohms);
$\alpha_1$, $\alpha_2$, and $\alpha_3$ are the constant rates of the supercapacitor voltage change during time intervals $(0, t_1)$, $(t_1, t_2)$, and $(t_2, t_3)$. 
The frequency converter circuit (Figure 1) contains a three-phase bridge uncontrolled inverter. Supercapacitor series (SC) are connected in parallel with the DC link. The DC link also includes a transistor breaker (VTBR) with rheostat (RBR) to limit the overvoltage level. A three-phase bridge inverter connected to the DC link works as a DC-AC converter. The bridge inverter has the two-way power transmission function for braking modes in the case of lowering the load [7, 8].

![Figure 1. Frequency converter circuit with supercapacitor](image)

Increasing the DC link capacity can store more energy. This energy can be used in the electric drive lifting modes to reduce the braking resistor using [9].

3. Numerical modelling
A simulation model (Figure 2) was developed to analyze dynamic modes and estimate energy consumption of a lifting equipment electric drive.

![Figure 2. Lifting equipment electric drive model](image)

The model includes a three-phase sinusoidal voltage source (Three-Phase Source), a three-phase bridge rectifier, a DC link energy storage (Supercapacitor), a braking resistor switch (DC-Chopper), an inverter, an induction motor (Induction Machine), a vector control subsystem (Control), mechanical load (TI), speed controller (N_t), and measuring system. The work cycle includes lifting a load weighing 630 kg for 7.5 seconds, pause for 1 second, lowering the load for 7.5 seconds, pause for 1 second, lifting for 7.5 seconds (Figure 3, Figure 4). Acceleration at start and stop is limited to 1750
rpm per second. The electric drive control system is vector with field orientation. The supercapacitor capacity is 1 F, for the electrolytic capacitor is 7500 μF.

![Figure 3. Timing diagrams of preset (NT) and rotor (NSC) angular velocity](image)

In numerical experiments, there is no load torque during pauses. This is due to the motor shaft breaking (Figure 4).

![Figure 4. Timing diagrams of the motor electromagnetic (Te) and load torque (Tl).](image)

A braking resistor with a transistor chopper is used to limit overvoltages. The breaker opening voltage is 750 V, the closing voltage is 660 V. Figure 5 shows the DC link voltage when using a series of supercapacitors and electrolytic capacitors.
Figure 5. Timing diagrams of the DC link voltage in a circuit with a supercapacitor ($U_{dcSC}$) and an electrolytic capacitor ($U_{dcC}$).

The supercapacitor charge level is determined by the equation (5):

$$SOC = \frac{Q_{init} - \int_{0}^{t} i_{SC} dt}{Q_T}$$  \(5\)

Figure 6 shows the supercapacitor charge / discharge dynamics.

Figure 6. Supercapacitor charge level timing diagrams.

To compare the power consumption of the electric drive with electrolytic capacitor and a supercapacitor in a lifting and lowering cycle, Figures 7 and 8 show the power consumption and current curves.
Figure 7. Timing diagrams of power consumption for circuits with supercapacitor \((E_{1SC})\) and electrolytic capacitor \((E_{1C})\).

Figure 8. Timing diagrams of current for circuits with supercapacitor \((E_{1SC})\) and electrolytic capacitor \((E_{1C})\).

4. Conclusion
Dynamic dependencies (Figure 3-8) of the lifting equipment electric drive with a frequency-controlled induction motor are obtained by modeling. These characteristics show the performance and compatibility of a system with supercapacitor, inverter, motor and DC brake chopper. There are practically no differences between the rotor speed dynamic characteristics when using a supercapacitor. The supercapacitor charging and discharging time is much longer than that of an electrolytic capacitor. The supercapacitor is charged during the load lowering due to the braking
energy of the electric drive moving parts. The supercapacitor is discharged during the load lifting (Figure 5). There is no electric power consumption from the network during the supercapacitor discharge and charge (Fig. 7, 8). Thus, the supercapacitors using as a DC link storage device makes it possible to increase the lifting equipment effectiveness and reduce energy consumption by 41.02%.

5. References

[1] Vukajlović N, Miličević D., Dumnić B., Popadić B. Comparative analysis of the supercapacitor influence on lithium battery cycle life in electric vehicle energy storage. *Journal of Energy Storage*. 2020. 31: 101603.

[2] Soumeur M. A, Gasbaoui B, Abdelkhalek O, Ghouili J, Toumi T, Chakar A. Comparative study of energy management strategies for hybrid proton exchange membrane fuel cell four wheel drive electric vehicle. *Journal of Power Sources*. 2020. 462: 228167.

[3] Liu S, Wei L, Wang H. Review on reliability of supercapacitors in energy storage applications. *Applied Energy*. 2020. 278: 115436.

[4] Fadil H. E, Belhaj F.Z, Rachid A , Giri F, Ahmed-Ali T. Nonlinear Modeling and Observer for Supercapacitors in Electric Vehicle Applications. *IFAC-PapersOnLine*. 2017. 50(1): 1898–1903.

[5] Oldham, K. B. A Gouy-Chapman-Stern model of the double layer at a (metal)/(ionic liquid) interface. *J. Electroanalytical Chem*. 2008. 613(2): 131–38

[6] Xu, N., and J. Riley. Nonlinear analysis of a classical system: The double-layer capacitor. *Electrochemistry Communications*. 2011. 13(10): 1077–81

[7] Sreedhar S, Siegel J. B, Choi S. Topology Comparison for 48V Battery-Supercapacitor Hybrid Energy Storage System. *IFAC-PapersOnLine*. 2017. 50(1): 4733–4738

[8] Jandura P, Černohorský J, Richter A. Electric Drive and Energy Storage System for Industry Modular Mobile Container Platform, Feasibility Study. *IFAC-PapersOnLine*. 2016. 49(25): 448–453

[9] Rahmani M.A, Alamir M, Gualino D, Sanjuan S.L. Experimental Validation of a Novel Control Strategy for an Off-Grid Hybrid Stirling Engine/Supercapacitor Power Generation System. *IFAC Proceedings Volumes*. 2014. 47(3): 9425-9431