APPLICATION OF SUPERCAPACITOR ENERGY STORAGE DEVICES IN INDUCTION DRIVES

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Abstract. The article discusses an actual theme about improving of energetic efficiency of industrial induction drives. New AC motor control schemes with supercapacitor energy storage devices for motor stator parametric control in continuous and pulse modes are developed. The starting device allows decreasing of motor torque jerks at the beginning of the transient process thus providing elimination of the consumed energy and drive system mechanical wear. There is given the storage system efficiency factor calculation in the capacitor charging mode with constant current. The new device has a higher efficiency factor.

Keywords: induction motor, supercapacitor energy storage system, efficiency factor.

Introduction

The modern variable speed AC motors are the most frequently drives encountered in industry and transport due to the variable speed drive high efficiency and low exploitation costs of simple and rugged construction motor. The induction drive could be easily and quickly reversed and switched to regenerative braking mode without additional power circuit switch equipment. The regenerative braking is efficient almost full stop. Due to this reason, AC drives become very popular in most variable speed drive systems and their prices significantly dropped to the level of PWM controlled DC drive. However, due to the lack of regenerative breaking equipment in modern commercial frequency converter systems the braking energy is wasted, moreover the braking resistor often is included in the scheme as option.

Energy storage systems in AC drive

The AC drive performance benefits are not completely used in a typical industrial AC drive system. The real energy saving strongly depends on its efficient consuming by giving to other consumer connected to the same power supply or sending back to the power grid. If multiple drives such as electric vehicles and elevators are connected to a single frequency converter DC bus, a part of the regenerative braking energy could be used by other motors when they are operated in drive mode, but in the case of multiple motor simultaneous braking the energy could not be utilized and is wasted in braking resistor. The most widespread AC drive voltage source inverter input DC voltage polarity remains unchanged in induction motor regenerative braking mode, which requests either to connect inverter parallel to rectifier or utilizing the contactors for converter DC bus polarity switching. Although the power system possibility of instant regeneration energy consuming is large enough due to the relatively small amount of the latter, the introduction of second rectifier-inverter block operating in inverter mode worsens the converter power factor, increases the converter block size and doubles the rectifier unit cost. The four quadrant AC/DC converter maintains the same DC voltage polarity in all operation modes and provides high power factor but has complex control algorithms. The energy transfer from the source drive to the power grid when the consumer locates in a significant distance from the power supply is coupled with great energy losses, which decreases the power saving effect even for 10 %. The industrial bench and elevator drives often have only single motor connection to the power supply, when no consumer is available on DC bus, which do not allow the regeneration mode and all braking energy is lost.

Electric vehicles, elevators and cranes have typical load cycles with high power demand during acceleration and high power regeneration during braking. This increases the energy cost expenses due to overpriced tariffication for high peak power consumption. On the one hand, the strongly modulated power demand represents a problem of availability of enough power feeding network, on the other hand, the typical solution of industrial variable speed drive frequency converters with breaking resistors causes high amount of wasted energy [1]. The high power peaks also cause voltage variations – voltage drop at drive starting and overvoltages during deceleration, which could not be eliminated in drive systems with brake resistors and net inverters.

The reducing of starting and braking power peaks could be achieved by using the energy storage system (ESS) instead of rheostats. To obtain the useful utilization of regenerative energy, it should be saved in a special energy accumulator until the corresponding power consumer is connected to the DC line. One of the most perspective energy storage devices is a large capacity supercapacitor battery. In comparison with chemical accumulator batteries and rotating fly-wheels the supercapacitors have better charge and discharge dynamic characteristics despite the smaller total energy capacity. The supercapacitor advantages are also independence on the environment temperature, smaller weight, lower cost and dimensions than other types of the energy storage system type.

The energy storage device with DC bus connection reduces the amount of the transferred energy between the power network and drive cannot affect the drive mechanical transient processes and is preferred to optimal use with variable voltage variable frequency converters. The obtaining of constant motor torque without oscillations is very important in transport and elevator drives to prevent damaging and obtain jerk free load mechanism operation. The control of induction motor transient processes demands the motor side connected energy storage system. The efficiency of inexpensive parametric control systems still used in simplest induction drives could be improved by installing the energy storage device in the power circuit AC side.

Asynchronous drive with stator side energy storage systems

The new scheme (Fig. 1) with a supercapacitor energy storage system is proposed for the induction motor mechanical transient process control during transient processes [2].

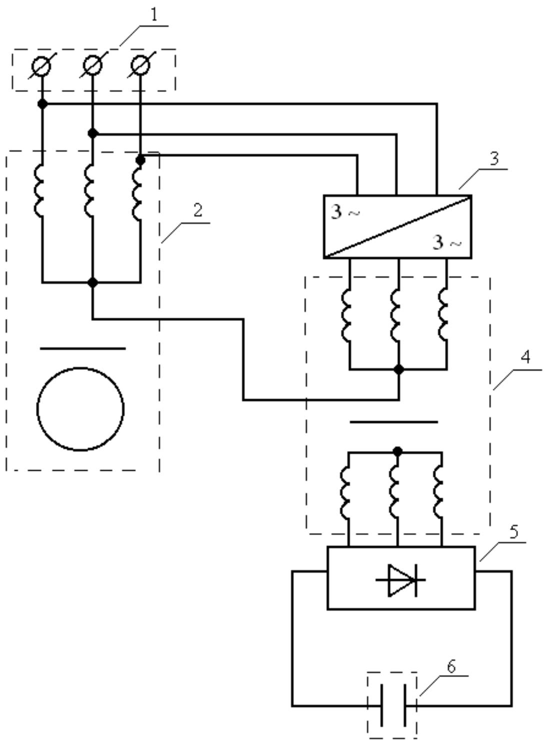

Fig.1. **Induction drive with stator side energy storage system**

In this circuit the induction motor 2 stator windings and three phase regulator 3 with series connected three phase transformer 4, which primary winding zero point is connected to the induction motor zero point, are connected to the power supply 1. The three phase transformer 4 Y-connected secondary winding output is connected to the three phase rectifier 5, which output is connected to the electrical energy storage system capacitor 6. During the mechanical transient processes when asynchronous motor torque is changing, the three phase transformer 4 primary windings are connected parallel to the induction motor 2 stator windings through three phase regulator 3 in accordance with the given control law. This allows to change the induction motor mechanical time constant and transient process characteristics.

Induction motor pulse control system with energy storage equipment

The induction motor parametric pulse control scheme restricts current and torque during the starting process by varying the stator voltage. The drawbacks of this simple solution is the high stator circuit switching frequency which causes current and torque ripple and energy losses if the switch is bypassed by the resistor. For providing continuous current mode and improving induction drive performance the supercapacitor energy storage system and net inverter are connected parallel to the DC pulse converter switch [3].

The power supply network 1 is connected to the induction motor stator windings 1, 2, 3 connected in series with controlled bridge rectifier 4, which output is connected to the supercapacitor 5 (Fig. 2). The choke 6 and controllable switch 7, which has parallel connected three phase net inverter 9, are connected parallel to the supercapacitor 5. By setting the supercapacitor 5 charging current, it flows through the three phase induction motor stator windings 1, 2, 3 and determines the cage rotor asynchronous motor electromagnetic torque. The three phase net inverter 9 is switched on at the determined supercapacitor 5 voltage level and periodically bypassed by controllable switch for estimating the stable commutation processes in net inverter. In the case of static load or network frequency changing the supercapacitor charging current must be changed, which keeps the constant electromagnetic torque.

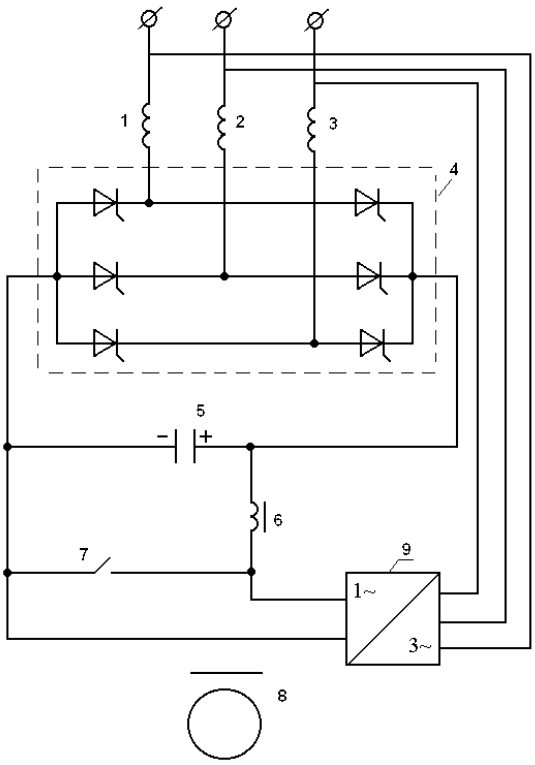

Fig. 2. **Induction drive with parametric pulse converter and energy storage system**

Energy storage equipment efficiency factor

The efficiency factor of the energy storage system converter depends on the charging mode characteristics, which could be obtained from converter equivalent circuit [4]. For normal operation of the pulse converter the supercapacitor voltage must be

$$U_C = U_{C0} + \frac{1}{C}\int_0^{t_{ch}} i_c(t)dt\,, \tag{1}$$

where U_C – energy storage system voltage at the end of charging;

U_{C0} – energy storage system voltage at the begining of charging;

C – supercapacitor capacity;

t_{ch} – charging time.

The influence of charging circuit internal parametres is taken into account by introduction of three linear resistances (Fig. 3): input circuit resistance R_{in}, converter output capacitor charging circuit resistance R_{out} and capacitor shunting resistances R_s. The efficiency factor obtained from equivalent circuit has the maximum possible value for the charging converter, the real value is lower due to the influence of transformer magnetic losses and energy dosator circuits.

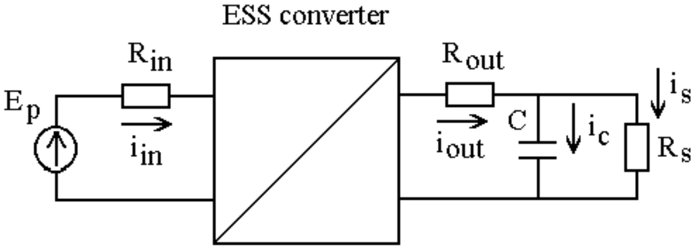

Fig. 3. **Induction drive with ESS equivalent circuit**

The main task solved by equivalent circuit is determining the optimal charging mode which provides the optimal efficiency factor when power losses in all resistances are minimal:

$$W_l = W_{lin} + W_{lout} + W_{ls} = i_{lin}^2 R_{in} + i_{lout}^2 R_{out} + i_{ls}^2 R_s, \quad (2)$$

where W_{lin}, W_{lout}, W_{ls} – power losses in corespoding equivalent circuit resistances.

If $R_s \to \infty$, then the total efficiency factor is

$$\eta = \eta_{in} \eta_{out}, \quad (3)$$

where η – equvalent circuit total efficiency factor;

η_{in} – converter input circuit efficiency factor;

η_{out} – charging output efficiency factor.

The charging efficiency factor is obtained form expression

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$$\eta_{out} = \frac{W_C}{W_C + W_{lout}} = \frac{1}{1 + W_{lout} / W_C}, \quad (4)$$

where W_C – energy stored in ESS.

In the case of constant charging current the relative energy losses in charging resistance are

$$\frac{W_{lout}}{W_C} = \frac{I_{cRMS}^2 R_c t_c 2C}{I_c^2 t_c^2} = 2 \frac{R_c C}{t_c} k_{fc}^2, \quad (5)$$

where I_{cRMS} – charging current RMS value;

I_c – charging current medium value;

k_{fc} – charging current shape factor.

Therefore the charging circuit efficiency factor is

$$\eta_{out} = \frac{1}{1 + 2R_{out} C k_{fc} / t_c}. \quad (6)$$

The converter input circuit power factor is derived from expression

$$\eta_{in} = \frac{W_p - W_{lin}}{W_p} = 1 - \frac{W_{lin}}{W_p}. \quad (7)$$

The relation $\frac{W_{lin}}{W_p}$ could be presented as

$$\frac{W_{lin}}{W_p} = \frac{R_{in}\int_0^{t_c} i_{in}^2 dt}{E_p \int_0^{t_c} i_{in} dt} = \frac{I_{inRMS}^2}{I_{in} I_{shc}} = k_{fin}\frac{I_{in}}{I_{shc}}, \tag{8}$$

where I_{inRMS} – input current RMS value;

I_{in} – input current medium value;

k_{fin} – input current shape factor;

I_{shc} – input circuit short circuit current.

The input current medium value is derived from energetical balance expression

$$W_p - W_{lin} = W_C + W_{lout} = \frac{W_C}{\eta_{out}}, \tag{9}$$

or

$$E_p I_{in} t_c - I_{in}^2 k_{fin}^2 R_{in} t_c = \frac{W_C}{\eta_{out}}. \tag{10}$$

At the minimal input losses the input current value is obtained from the smallest root of expression (10):

$$I_{in} = \frac{E_p}{2R_{in}k_{fin}^2} - \sqrt{\frac{E_p}{4k_{fin}^2 R_{in}^2} - \frac{W_C}{n_{out}k_{fin}^2 R_{in}^2 t_c}}. \tag{11}$$

The input efficiency factor is obtained by solving the equations (7), (8) and (11) together

$$\eta_{in} = \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{P_C k_{fin}^2}{2P_{pm}\eta_{out}}} \tag{12}$$

where $P_C = {U_C^2 C}/{2t_{out}}$ – charging medium power;

P_{pm} – input power maximum value.

Total efficiency factor is

$$\eta = \frac{\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{P_C k_{fin}^2}{2P_{pm}}\left(1 + \frac{2R_{out}C}{t_c}k_{fc}^2\right)}}{1 + \frac{2R_{out}C}{i_{out}}k_{fc}^2}. \tag{13}$$

The highest efficiency factor is provided at k_{fin}=k_{fc}=1, when input and charging currents are equal. The charging circuit energetic diagram for substitution scheme is shown on Fig. 4, where line 1 – energy consumed from power supply, 2 – output energy. The diference between them in ordinate axis is power losses in input resistance R_{in}. The line 3 represents the charging circuit energy changing rule at minimal losses at R_{out}. The converter must store the energy diference between the output energy 3 and converte the consumed energy 2, which demands large intermediate energy storage systems.

Additional storage devices are increasing the converter weight and dimensions, therefore must be provided the checkout of the efficiency factor improoving from them.

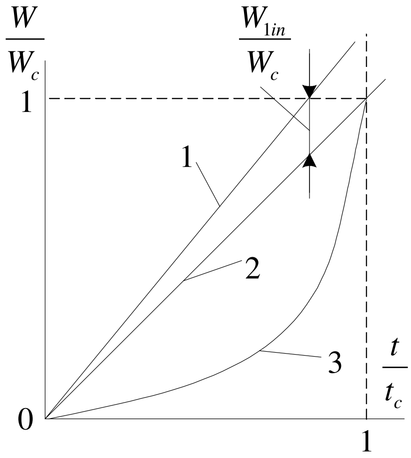

Fig. 4. **Induction drive with ESS energetic diagramm**

Conclusions

1. The supercapacitor storage device improves the AC motor electromechanical transient process, eliminates motor torque ripple and power losses in braking ballast resistance.
2. This device can save the excessive transient process energy. The amount of the stored energy and efficiency factor could be calculated from the substitution scheme.
3. The transient process forwarding is possible by equivalent resistance values varying in the induction drive parametric control scheme, which affects the mechanical time constantes.
4. The energy storage device with the net inverter allows to stabilize the asynchronous motor torque with minimal stator losses because they are returned to the power supply network.

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