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THE MONOSPIRAL MOTORISED CABLE REEL IN CRANE APPLICATIONS

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Abstract. *The main consideration of any reeling system is the effect it has on cable tensions and hence cable life. This paper explains the relationship of reel torque to cable tensions and the reasons why this relationship is so important. Such system is characterized by variable parameters, primarily a variable moment of inertia and a variable diameter of the coiled cable. For these reasons, in order to ensure proper dimensioning of the drive, it is necessary to know the motor torques that need to be developed as a function of the coiled cable. The motor should be able to develop the required torques in a very wide speed range. It is shown that for properly sizing the motor it is necessary take into account the dynamics of the cable reel drive. In this paper monospiral motorized cable reel for winding power cable in crane applications with frequency converter fed induction motor is analyzed. Also, the equipment selection procedure for the real crane with concrete data is shown. Experimental results are recorded during the crane commissioning in real condition.*

Key Words: *Induction Motor Drive, Cable Reel, Frequency Converter, Tension Control*

1. INTRODUCTION

Overhead and gantry cranes are typically used for moving containers, loading trucks or material storage. This type of crane usually consists of three separate motions for transporting material. The first motion is the hoist, which raises and lowers the material. The second is a trolley (cross travel), which allows the hoist to be positioned directly above the material for placement. The third is a gantry or bridge motion (long travel), which allows the entire crane to be moved along the working area. Very often, in industrial applications additional drives as auxiliary hoist, power cable reel and conveyer belt are needed. Therefore, generally, a crane is complex machinery. That is why the cranes are often the subject of

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analysis in terms of performance improvement and drive modernization. Electrical technology for the crane control has undergone a significant change during the last few decades. Old solutions with Ward-Leonard drive systems and induction motors with wound rotor are replaced with more contemporary technology that uses frequency converters and standard squirrel-cage induction motors for all types of motion [1, 2, 3]. General classification divides induction motor control schemes into scalar and vector-based methods. Opposite to the scalar control, which allows control of only output voltage magnitude and frequency, the vector-based control methods enable control of instantaneous voltage, current and flux vectors. For electric motor drives on cranes, the vector control methods have to be used, rotor field oriented control (RFOC) or direct torque and flux control (DTFC) [4, 5].

Energy saving has become an important aspect of the design and operation of new building machinery. Currently, energy-saving research has mainly focused on container ports with the focus mostly on only one aspect of electrical or mechanical energy-saving [6]. Some experts have only considered electrical energy saving methods. For example, [7, 8] an energy-saving method based on energy recovery by active front end rectifier (AFE) at the input of frequency converter is proposed. The AFE provides four quadrant operation of drive, which means in motoring and regenerative operation mode. In [9, 10] to achieve energy savings through frequency control and load sharing between the motors in multi-motor drives are proposed. The improvement of electrical drives efficiency can be obtained with the use of storage devices. In recent years new electrochemical storage technologies have been developed and, among these, supercapacitors are becoming more and more interesting. Their high power density makes them very attractive for application where high powers for short time are required [11]. On the other hand, some experts only consider mechanical energy-saving methods. For example, in [12] the use of flywheel in the operation process of the crane is proposed to perform energy recovery.

In the papers [13, 14] dynamic behavior of the carrying structure of the portal cranes excited by the crane motion is analyzed, but it does not include the influence of electric motor driven subsystem and control algorithm on crane performance. Dynamic behavior of the drive mechanisms that take into account the impact of variable frequency control of the electric motor on executive parts of mechanisms is presented in [15].

One of the most critical issues in overhead cranes is the swing of a suspended load while the crane starts to move and accelerates, changes the movement direction, breaks or stops. In papers [16, 17, 18] continuous anti-swing tracking schemes for crane systems are presented. Methods are based on information about the swing angle. Sensorless anti-swing control for overhead cranes is described in [19]. This method is based on measuring the voltage and current of trolley drive motor. Using the features of rotor field oriented control algorithm, electrical torque, electrical speed, driving force and swing angle are estimated.

Movable cranes, as container bridges, other outdoor cranes or indoor cranes, realize the current transfer and data transfer by means of flexible energy cables and control cables. Maintaining the transmission requires a permanently available system for storing and releasing the cables which moves as synchronously as possible with the movable cranes. The basic patterns of the movement (distance, direction, acceleration, speed, mass) are being defined only by the use of the movable crane. Systems which meet such requirements are the motor driven cable reels.

For the rail mounted cranes with a long crane path, power supply is usually implemented through the cable reel that is used for winding/unwinding the power cable. Based on the available literature, the authors of this paper have noted that problems associated with the cable reel are not sufficiently represented, although they are very important for the operation of the crane. There are published papers related to the tension control in manufacturing industries such as rolling mills and cable industry. Due to the similar requirements for tension control, variable winding diameter and moment of inertia, individual experiences can be used to control cable reel drives [20].

In this paper the monospiral motorized cable reel for winding power cable in crane applications is considered. The cable reel, from the perspective of electric drives, can be realized in several ways by using: torque motor, wound rotor induction motor, frequency converter fed induction motor. Regardless of the way of realization, basic requirement for cable reel drive is maintaining a constant tensile force in the cable, which enables winding/ unwinding cable uniformly. Related to this, there are two contradictory demands which are related to tensile force in the cable: large enough value of tensile force sufficient for cable winding as the first and lower value of tensile force in comparison with maximum permitted cable tensile stress as the second.

This paper is organized as follows. In the second section theoretical basis for torque, speed and power calculation of monospiral cable reel is exposed. Induction motor selection method is described in the next section. In the fourth section selection of induction motor and frequency converter for concrete example (derrick crane installed at the open mine pit in MB Kolubara) is illustrated. In the fifth section experimental results of monospiral motorized cable reel for winding power cable with frequency converter fed induction motor in the derrick crane are presented. At the end, some conclusions and recommendations are drawn regarding the monospiral cable reel drive design.

2. Theoretical Basis

Induction motor, which drives cable reel, at its shaft must develop torque T_m, which should provide cable set-point tensile force, $F_{c,z}$. Therefore, the motor torque must correspond to torque of cable reel, T_w, taking into account the losses in the drive and dynamics of the drive.

Cable reel torque, based on Fig. 1, is equal to:

$$T_w = F_{c,z} \frac{D}{2} \tag{1}$$

where D is the outer diameter of the coiled cable.

The outer diameter of the coiled cable, based on Fig. 1, can be determined as follows:

$$D = D_{core} + 2k D_c \tag{2}$$

where D_{core} is diameter of the core that the cable is wound around, k is number of cable windings on the cable reel, and D_c is outer diameter of the cable.

Number of winding of the cable on cable reel, k, can be determined based on the length of coiled cable, L_c, which is based on Fig.1:

$$L_c = \pi(kD_{core} + k(k+1)D_c) \tag{3}$$

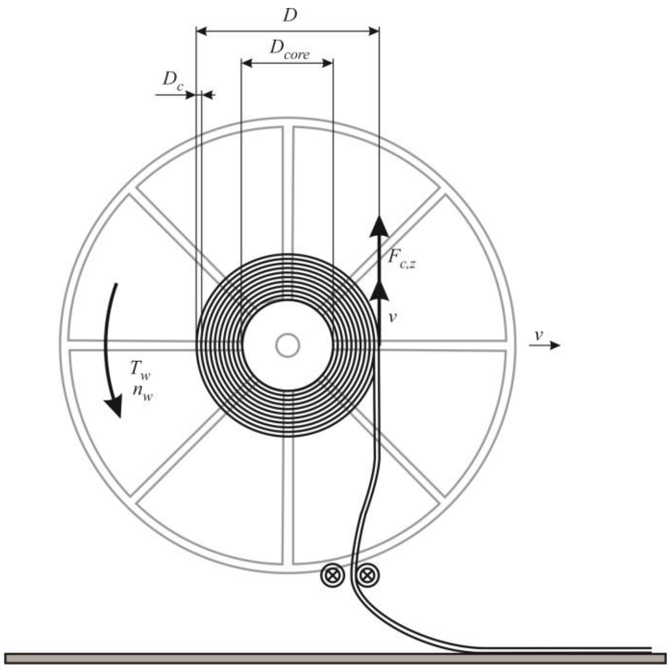

Fig. 1 Schematic view of the cable reel

The number of the cable windings on the cable reel must be a positive real number, and can be determined from the following expression:

$$k = \frac{-(D_{core} + D_c) + \sqrt{(D_{core} + D_c)^2 + 4D_c \frac{L_c}{\pi}}}{2D_c} \tag{4}$$

Taking into account that the length of the coiled cable must be equal to the distance relative to a reference point in which the coiled cable length is zero, the following applies:

$$L_c = \int v\,dt \tag{5}$$

where v is the line speed of the winding/unwinding cable which is equal to the speed of the crane.

If motor speed of cable reel, n_m, is measured, cable winding/unwinding line speed, v, can be determined as follows:

$$v = \omega_w \frac{D}{2} = n_w \frac{2\pi}{60}\frac{D}{2} = n_m \frac{1}{I_t}\frac{2\pi}{60}\frac{D}{2} \tag{6}$$

where ω_w is rotational speed of cable reel in rad/s, n_w is rotational speed of cable reel in rpm, and I_t is total gear ratio from the motor to the cable reel.

In order to adapt the speed and torque according to the load it is necessary to incorporate gear units between the motor and the cable reel (e.g., worm gear, spur gear reduction, chain gear). With gear ratio I_t, the all gears between the motor and the cable reel are taken into account.

Set-point cable tension force is determined experimentally during commissioning of the drive, based on the desired cable length in the air between the cable reel and the pad. Its value may be estimated based on the desired cable length in the air assuming that there are no losses in the cable movement between the cable reel and pads:

$$F_{c,z} = M_{c,l} \, L_{c,v} \, g \tag{7}$$

where $M_{c,l}$ is mass per unit cable length, $L_{c,v}$ is desired cable length in the air, and g=9.81 m/s^2 acceleration of gravity.

During winding/unwinding the total mass of cable reel is changed, and thus the total moment of inertia. The total moment of inertia for cable reel, J_t, is:

$$J_t = J_w + J_c \tag{8}$$

where J_w is moment of inertia for cable reel, and J_c is moment of inertia of cable on the cable reel.

Moment of inertia for the cable reel, assuming that it can be regarded as a hollow cylinder, is:

$$J_w = \frac{1}{8} M_w (D_w^2 + d_w^2) \tag{9}$$

where M_w is mass of cable reel, D_w and d_w are outer and inner diameter of the cable reel, respectively.

Moment of inertia of the cable on the cable reel, assuming that it can be considered as a hollow cylinder, is:

$$J_c = \frac{1}{8} M_c (D^2 + D_{core}^2) \tag{10}$$

where M_c is the mass of coiled cable.

The mass of coiled cable is:

$$M_c = M_{c,l} \, L_c \tag{11}$$

Losses for all elements of the drive are usually provided in the form of efficiency.

The dynamics of the drive is taken into account by time derivative in the Newton equation. Moments of inertia of the motor and gears are constant. The moment of inertia of the cable reel is a variable quantity. Newton's equations for the drive cable reel, reduced to the motor shaft, which takes into account losses in the drive, and the dynamics of the drive, wherein the losses are "covered" by the motor, can be written as:

$$I_t (J_m + J_g) \frac{d\omega_w}{dt} + \frac{1}{I_t} \frac{1}{\eta_t} \left[\omega_w \frac{dJ_t}{dt} + J_t \frac{d\omega_w}{dt} \right] = T_m - \frac{1}{I_t} \frac{1}{\eta_t} T_w \tag{12}$$

where J_m is moment of inertia of the motor, and J_g is total moment of inertia of all gears, reduced to the motor shaft.

Because the moment of inertia is a slow rate variable, it is clear:

$$J_t \frac{d\omega_w}{dt} >> \omega_w \frac{dJ_t}{dt} \tag{13}$$

Based on the analysis the conclusion is that the drive with sufficient accuracy can be modeled by:

$$I_t(J_m + J_g)\frac{d\omega_w}{dt} + \frac{1}{I_t}\frac{1}{\eta_t} \quad J_t\frac{d\omega_w}{dt} = T_m - \frac{1}{I_t}\frac{1}{\eta_t}T_w \tag{14}$$

Based on the Eq. (14), and taking into account Eq. (1), the motor torque is:

$$T_m = I_t(J_m + J_g)\frac{d\omega_w}{dt} + \left(J_t\frac{d\omega_w}{dt} + F_{c,z}\frac{D}{2}\right)\frac{1}{I_t}\frac{1}{\eta_t} \tag{15}$$

If the angular speed is expressed through the line speed, and taking into account the time derivative, the expression for the motor torque can be written as follows:

$$T_m = I_t(J_m + J_g)\frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + \left\{J_t\frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2}\right\}\frac{1}{I_t}\frac{1}{\eta_t} \tag{16}$$

In Eq. (16), at a constant tension force of the cable, the time dependent variables are outer diameter of coiled cable, D, and total moment of inertia of cable reel, J_t. Also, in acceleration and braking of the drive line speed of winding/unwinding cable is time dependent.

Equations (12) and (14-16) correspond to the case where motor torque, T_m, is opposed by cable reel torque T_w which happens during the cable winding, Fig. 2. It is accepted that, in the motor mode during the cable winding, the motor torque and the motor speed have positive values. Also, during the cable winding, the cable reel speed and the cable line speed of winding/unwinding are assumed to be positive. Since the direction of the cable force tension does not change, the cable reel torque always has a positive value.

Equations (12) and (14-16) are valid during rolling up of the cable, in the quasi-stationary state, at a constant speed of the crane which is equal to the line speed of the winding. In this case, the change in line speed is zero and the change in diameter over time is a positive slow rate variable close to zero. For this reasons it is:

$$J_t\frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2} > 0 \tag{17}$$

Also, this relationship holds true at the crane acceleration i.e. drives of the cable reel, when the variation of line speed is positive and the change of diameter is a positive slow rate variable.

In these cases, there is the motor mode, the energy flow is from the motor to the cable reel, and the losses in the drive are "covered" by the motor, which is taking account with $1/\eta_t$ in equations.

During the crane braking, the speed variation is negative and the change in diameter is a positive and slow rate quantity and it can happen that the drive from the motor mode goes into the regenerative mode and the energy flow from cable reel to the motor. Then there is:

$$J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2} < 0 \tag{18}$$

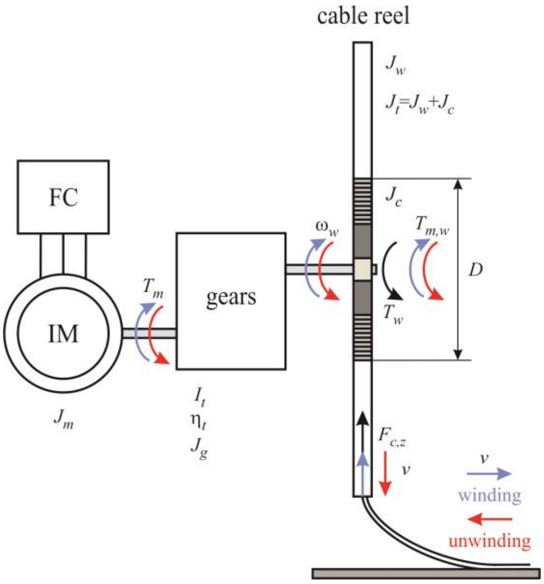

Fig. 2 Schematic view of the cable reel drive - winding/unwinding operation

In that case, the losses in drive are "covered" by the cable reel, and in Eqs. (12) and (14-16) term $1/\eta_t$ should be replaced with η_t.

The case when motor torque T_m, and cable reel torque T_w, operating in the same direction happen during the cable unwinding is shown in Fig. 2. It is accepted that, in the motor mode during the cable unwinding, the motor torque and the motor speed have negative values. Also, during the cable unwinding, the cable reel speed and the cable line speed of winding/unwinding are assumed to be negative.

During unwinding of the cable, in the quasi-stationary state, at a constant speed of the crane which is equal to the line speed of unwinding the change in line speed is zero and the change in diameter over time is a negative slow rate variable close to zero. For this reason it is:

$$J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2} > 0 \tag{19}$$

Also, this relationship holds true during the crane and cable reel braking, when the line speed changes are positive and the variation of diameter is a negative slow rate variable.

In these cases, there is a generator mode, the energy flow from the cable reel to the motor and the losses in the drive are "covered" by the cable reel. In Eqs. (12) and (14-16) term $1/\eta_t$ needs to be replaced with term η_t.

During the crane or cable reel acceleration, the line speed variation is negative and the change in diameter is a negative and slow rate quantity and it can happen that the drive from the generator mode goes into the motor mode operation and the energy flow from the motor to the cable reel. In that case it is:

$$J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2} < 0 \tag{20}$$

In that case, the losses in the drive are "covered" by the motor and Eqs. (12) and (14-16) are valid.

In order to implement Eqs. (12) and (14-16) all operation modes of cable winding and unwinding, term $1/\eta_t$ should be replaced with $1/\eta_t^{rw}$, where *rw* is operation mode of the cable reel drive, which can be determined as follows:

$$rw = sign\left\{\left[J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2}\right]v\right\} \tag{21}$$

In accordance with Eq. (21), the operating mode of cable reel drives during winding/unwinding of the cable can take one of the following values:

$$rw = \begin{cases} 1 & \text{, for } \left[J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2}\right]v > 0 \\ 0 & \text{, for } \left[J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2}\right]v = 0 \\ -1 & \text{, for } \left[J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2}\right]v < 0 \end{cases} \tag{22}$$

For example, Eq. (16) can be written in the following form:

$$T_m = I_t(J_m + J_g)\frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + \left\{J_t \frac{2}{D^2}\left[D\frac{dv}{dt} - v\frac{dD}{dt}\right] + F_{c,z}\frac{D}{2}\right\}\frac{1}{I_t}\frac{1}{\eta_t^{rw}} \tag{23}$$

Induction motor, which drives cable reel, on its shaft must develop speed, n_m, which should correspond to cable reel speed n_w, i.e. winding/unwinding line speed of the cable that is equal to crane speed *v*:

$$n_m = n_w I_t = \omega_w \frac{60}{2\pi} I_t = v\frac{2}{D}\frac{60}{2\pi} I_t \tag{24}$$

In Eq. (24), when the crane is working at constant speed which is equal to the cable line speed of winding/unwinding, the outer diameter of coiled cable, *D*, is always a time depending quantity. However, during the acceleration and deceleration of the drive, cable winding/unwinding speed, *v*, is also a time depending quantity.

In accordance with the foregoing, it can be concluded that the speed of induction motor varies in all operation modes of the cable reel drive.

Induction motor for the cable reel drive on its shaft must develop power, P_m, which corresponds to motor torque, T_m, and motor speed, n_m:

$$P_m = T_m n_m \frac{2\pi}{60} \tag{25}$$

By replacing Eqs. (23, 24) in Eq. (25) for the motor power is obtained:

$$P_m = \left\{ I_t^2 (J_m + J_g) \frac{2}{D^2} \left[D\frac{dv}{dt} - v\frac{dD}{dt} \right] + \left\{ J_t \frac{2}{D^2} \left[D\frac{dv}{dt} - v\frac{dD}{dt} \right] + F_{c,z} \frac{D}{2} \right\} \frac{1}{\eta_t^{rw}} \right\} \frac{2}{D} v \tag{26}$$

Finally, based on Eq. (26), the motor power is equal to:

$$P_m = \frac{4}{D^3} \left[I_t^2 (J_m + J_g) + J_t \frac{1}{\eta_t^{rw}} \right] \cdot \left[D\frac{dv}{dt} - v\frac{dD}{dt} \right] \ v + P_w \frac{1}{\eta_t^{rw}} \tag{27}$$

On the basis of the Eq. (27) it can be concluded that motor power, P_m, should correspond to power of cable reel, P_w, taking into account the losses and dynamics of the drive.

In accordance with the foregoing, the conclusion is that the motor power is changed in all modes of cable reel operation during winding/unwinding the cable. Also, power can have both positive and negative values i.e. the motor can operate in motoring and in generating mode.

3. Induction Motor Selection

The selection of the induction motor, which drives the cable reel, is performed based on the maximum required values of the motor torque and the motor speed.

Maximum required motor torque, $T_{m,\max}$, is the maximum value of the motor torque, which should provide set-point cable tensile force in all operation modes for winding and unwinding, and taking into account the losses in the drive and drive dynamics. Required maximum motor torque can be determined based on Eq. (23). It is expected to occur for the crane position near the connection point (CP) i.e. in the middle of the crane runway (Fig. 3), during the winding of the cable in the acceleration regime, when rw=1. For the above mentioned case, in order to simplify the motor selection, the following may be adopted:

$$D\frac{dv}{dt} >> v\frac{dD}{dt} \tag{28}$$

Also, at the position of the crane near the connection point i.e. in the middle of crane runway, the total moment of inertia has a maximum value, and in Eq. (23) the corresponding addend is dominant.

Having in mind the above, in order to select the motor, the expression for the torque given by Eq. (23), can be written as follows:

$$T_m = \left\{ J_t \frac{2}{D} \frac{dv}{dt} + F_{c,z} \frac{D}{2} \right\} \ \frac{1}{I_t} \frac{1}{\eta_t^{rw}} \tag{29}$$

Maximum motor speed, $n_{m,\max}$, occurs in the extreme left and right position of the crane in relation to the connection point, or at the ends of the crane runway (Fig. 3), and at maximum crane speed, $v_{\max}$, it can be determined using Eq. (24).

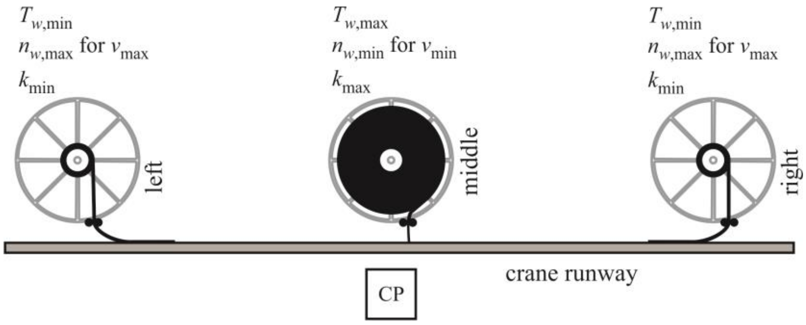

Fig. 3 Typical crane positions

Having in mind the required maximum torque and motor speed, minimum motor power, $P_{m,\min}$, can be determined using the following expression:

$$P_{m,\min} = T_{m,\max}\, n_{m,\max} \frac{2\pi}{60} \tag{30}$$

Minimum required motor speed, $n_{m,\min}$, is expected in a crane position near the connection point, i.e. in the middle of crane runway, at a minimum speed of the crane, $v_{\min}$, and can be determined using the Eq. (24). Minimum required motor speed is the minimum value of the motor speed in the quasi-stationary state in which the motor must develop maximum required torque.

The selection of the frequency converter, which fed induction motor, is performed taking into account rated values of selected motor. Based on the Section 2 analysis, it may be noted that during the operation of the cable reel drive, the motor can operate in a motor mode but also in a regenerative mode. For this reason, it is necessary to select the frequency converter that can operate in four quadrants. Also, the possible operation area is in constant torque region (T = const.) and constant power region (P = const.).

4. Case Study

The selection of an induction motor will be illustrated in a concrete example for derrick crane installed at the open mine pit in MB Kolubara (Ref. num. DK004). The crane is designed for mounting of the mining equipment. In the Fig. 4a the crane with indicated drives is shown. In the Fig. 4b the cable reel drive components are shown, and in the Fig. 4c the terminal box with all elements, for the crane position left in relation to the connection point, are shown.

Derrick crane has the following drives:

- main hoist: load capacity 60 t; lifting height 46 m, maximum lifting speed 6.27 m/min,
- auxiliary hoist: load capacity 12.5 t, lifting height 49.2 m, the maximum lifting speed 6.27 m/min,
- jib-boom motion: angle of inclination in the range of 82.5 ° ÷ 31.5 °,
- travel motion: maximum speed 14.27 m/min,
- cable reel: the length of the crane path 500 m, middle connection point.

Fig. 4 Derrick crane DK 004 with: a) indicated drives, b) cable reel drive components, c) terminal box of cable reel

Installed power of the crane is 318 kW. The crane power supply is with 4x95 mm^2 cable cross section. All drives are equipped with appropriate frequency converters. For crane control the Programmable Logic Controller (PLC) with adequate performances was used.

In the paper [7] all the hoist drives are described in detail. In this paper, the cable reel drive from the point of motor selection is described.

The cable reel drive consists of three-phase induction motor (IM), worm, spur and chain gear. Principal block diagram of the cable reel drive is shown in Fig. 5. The induction motor is powered by a frequency converter (FC).

Taking into account the values in Fig. 5, the total gear ratio from the induction motor to the cable reel is:

$$I_t = I_{wg}\, I_{sg}\, I_{cg} = 318.2667 \tag{31}$$

The total efficiency from the induction motor up to the cable reel is:

$$\eta_t = \eta_{wg}\eta_{sg}\eta_{cg}\eta_w = 0.5841 \tag{32}$$

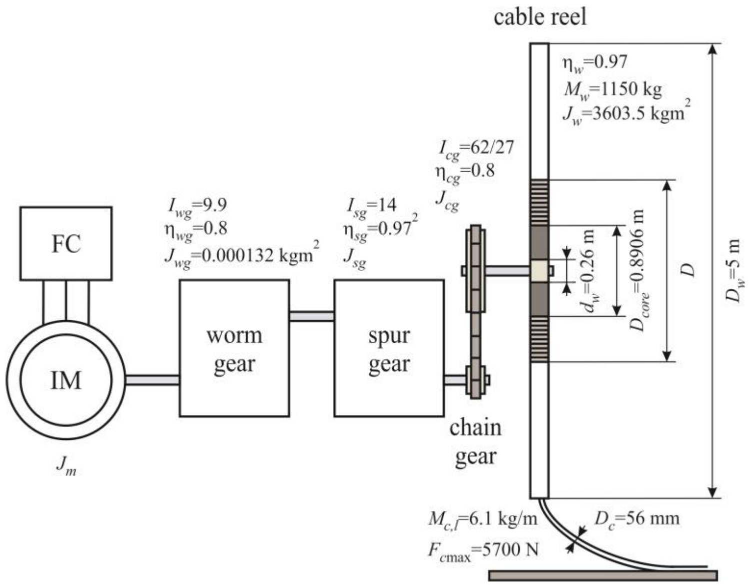

Fig. 5 Principal block diagram of the cable reel drive on derrick crane DK 004

Set-point cable tension force, in accordance with Eq. (7), and for desired length of the cable in the air $L_{c,v}$=5 m is $F_{c,z}$=299.2050 N < $F_{c,\max}$.

In case of derrick crane DK004, maximum required torque occurs at $k_{\max}$=34 and $a=dv/dt$=0.25 ms^{-1}/5 s, and in accordance with Eq. (29) is $T_{m,\max}$=4.8015 Nm.

Maximum required motor speed occurs at $k_{\min}$=3 and $v_{\max}$=0.25 m/s and in accordance with Eq. (24) is $n_{m,\max}$=1238.9 rpm.

Minimum motor power, according to Eq. (30), has a value $P_{m,\min}$=622.9296 W.

Minimum required motor speed occurs at $k_{\max}$=34 at $v_{\min}$=0.06 m/s, and in accordance with Eq. (24) is $n_{m,\min}$=77.6203 rpm.

Having in mind the values required for maximum motor torque, maximum and minimum motor speed and minimum motor power to run the cable reel drive, with a minimum safety factor 2, one can choose a three-phase induction motor with cage rotor 1LE1001-0EB4, the manufacturer Siemens. The catalog data for this motor are given in Table 1.

Torque-speed dependence $T_m=f(n_m)$, obtained on the basis of Eq. (24) and Eq. (29) shown with a possible working area for motor 1LE1001-0EB4 and for S1 operation mode (continuous duty cycle), is given in Fig. 6.

The analysis of Fig. 6 can lead us to conclude that minimum motor overload factor, $\upsilon_{m,\min}$, for S1 operation mode is in the fields of constant torque, and crane position near the connection point, i.e. in the middle of the crane runway where $k_{\max}$=34, in the winding of the cable during acceleration. The minimum motor overload factor is: $\upsilon_{m,\min}$=10 Nm/4.8015 Nm=2.0827. Given that applies $\upsilon_{m,\min} \geq 2$, the desired minimum safety factor is ensured.

Table 1 Catalog motor data 1LE1001-0EB4, Siemens

motor: 1LE1001-0EB4 (Siemens)		
Voltage	U_n	400 V
Frequency	f_n	50 Hz
Rated power	$P_{m,n}$	1.5 kW
Rated speed	$n_{m,n}$	1435 rpm
Rated torque	$T_{m,n}$	10 Nm
Rated efficiency	η_n	0.828
Power factor	$\cos\varphi_n$	0.79
Rated current	I_n	3.3 A
Locked rotor/rated torque	$T_{LR}/T_{m,n}$	2.6
Locked rotor/rated current	I_{LR}/I_n	6.4
Break down/rated torque	$T_B/T_{m,n}$	3.4
Moment of inertia	J_m	0.0036 kgm^2
Maximal speed	$n_{m,\max}$	4200 rpm

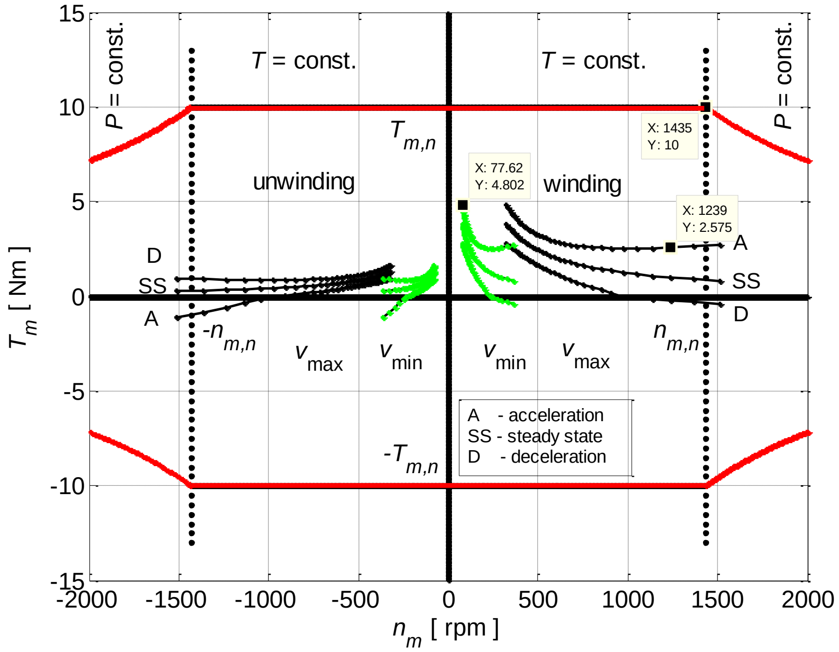

Fig. 6 Torque-speed characteristics for $v_{\max}$ (black) and $v_{\min}$ (green) with possible working area for motor (red)

Having in mind the above, it can be concluded that the three-phase induction motor with cage rotor 1LE1001-0EB4, manufacturer Siemens, can be used to run the cable reel drive, and with a safety factor 2.0827.

The next step in the selection of equipment is the selection of the frequency converter for induction motor feeding. A possible area of motor operation supplied from the frequency converter is shown in Fig. 6 and it is indicated with a red line. It may be noted that during the operation of cable reel drive at certain section motor operate in a regenerative mode. For this reason, it is necessary to select the converter that can operate in four quadrants. One option is to select the drive which contains the braking chopper with an appropriate resistor. The other option is to select the drive with regenerative capability [7].

Having in mind the rated values of the selected induction motor, one can choose single motor module 6SL3120-1TE21-8AA4 (vector control), the manufacturer Siemens, series SINAMICS S120. This inverter module uses common DC bus for power supply (regenerative capability). The inverter is in a torque control mode with encoder speed feedback. Minimum required motor speed, $n_{m,\min}$=77.6203 rpm, is 5.4091 % of rated motor speed, which provides high control performance.

5. Experimental Results

The experimental results are recorded during the crane commissioning in real conditions using the Siemens software Starter for Sinamics inverter series.

In this paper the experimental results of the monospiral motorized cable reel during the winding of the cable in the acceleration regime for crane position near the connection point, i.e. in the middle of the crane runway, are presented (Fig. 7). The induction motor, powered by a frequency converter, is in the torque mode, with about 4.8 Nm torque reference, in accordance with the previous analysis. After cable tensile, about 2.5 s from beginning, starts cable winding in the acceleration regime (speed increases).

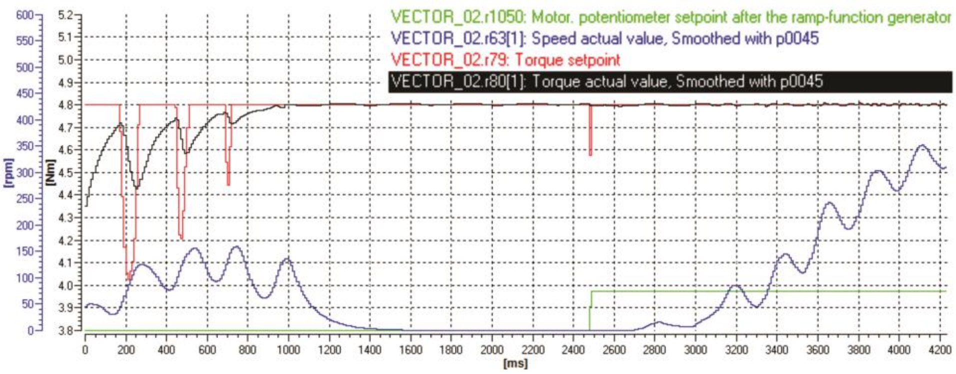

Fig. 7 Experimental results – cable winding, acceleration regime

In case of different losses and/or dynamics of the drive in comparison with their adopted values, the cable tensile force will be different from set-point, which essentially does not affect the functionality.

6. CONCLUSION

The cable reel is present in a large number of applications with cranes. Its design and dimensioning are not easy and depend on many factors. Depending on the application site, the crane speed and thus the speed of the cable winding/unwinding has a very significant impact both on the motor selection and converters as well as the implementation of adequate control algorithm.

This paper presents the dynamic equations of the mechanical part for the cable reel drive, which can be applied for all operating modes (acceleration, steady state and braking regime). In these equations variation of the moment of inertia and the outer diameter of the coiled cable are taken into account. Also, the expression for motor power which corresponds to the cable reel power and which takes into account losses and dynamics of the drive is obtained. The conclusion is that the motor power is changed in all modes of the cable reel operation during winding/unwinding the cable. Also, power can have both positive and negative values i.e. the motor can operate in motoring and in generating mode. Based on these equations, with appropriate simplifications, the expression of required motor torque, speed and power are obtained.

As proof of the validity of the obtained relations a real case of cable reel drive in derrick crane is considered. Based on actual data, mechanical characteristics of the induction motor that respects power supply conditions and the presence of frequency converter are shown. It may be noted that during the operation of cable reel drive at certain section motor operate in a regenerative mode. For this reason, it is necessary to select the converter that can operate in four quadrants. In order to demonstrate the validity of the proposed procedure for the selection of equipment the experimental results are recorded during the crane commissioning in real conditions. In this paper, the control algorithm is not considered. Based on the results, a very good agreement with the results of the calculations can be observed.

The proposed method for the induction motor selection is applicable in all the cases of monospiral motorized cable reel drives with the total moment of inertia as dominant value.

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