Determination Of Quality Parameters Of Hoisting Electric Drive Systems With 3-Phase Induction Motors

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***Abstract* - This paper illustrates a mathematical analysis of AC hoisting electric drive systems (incorporating three-phase reversible voltage controlled – slip-ring induction motors) for determining the main quality parameters of the transient processes. The effect of the quality parameters on the shape of the system transients is shown using the derived mathematical model. A new closed-loop control system to enhance the character of transients is suggested.**

***Index Terms* - Quality parameters, cranes, hoisting mechanism, transients, AC electric drive, thyristor dual converter.**

I. INTRODUCTION

It is known that a 3-phase induction motor is a complicated interconnected electromagnetic system, the response of which is oscillatory in most transients. In the case of crane drive applications these motor torque oscillations are accompanied by elastic torque oscillations in the ropes, long shafts, etc. which, in turn, generate more complicated transients in the overall hoisting mechanism [1]. Here the shape of the transient depends on both the electrical and mechanical parameters. Furthermore, both the electrical and mechanical parameters are interconnected and affect the system transients in differing manner. This paper identifies the relationship between the electrical and mechanical parameters of the above mentioned hoisting electric drive system in order to attain the optimum transient response. Notably it is desired to minimize the torque oscillations in the minimum possible transient time.

For most crane hoisting mechanisms, it is rational to use a relatively simple and reliable AC electric drive systems, [3,4,5,6] with the 'three-phase reversible voltage controlled – slip-ring induction motor', most common and widespread. The latter motor drive system permits a practical range of speed regulation and exhibits smooth starting or stopping. Operation of these motors, at low sped is effected using motor speed feedback. During low speed operation series resistances are connected to the rotor circuit to reduce the heat created in the rotor windings.

II. MATHEMATICAL ANALYSIS

Typically hoisting mechanisms can be physically modelled as double (two) – mass electromechanical systems. Here the first mass (inertia) J_1 represents the equivalent inertia of the motor rotor and all elements rotating on the motor shaft including the brake drum, coupling, etc.. On the other hand the second inertia J_2 represents the equivalent inertia of the suspended cargo and all elements moving with and at common speed to the cargo. The motion is transferred from J_1 to J_2 via ropes with an elastic coefficient C_{12}. It is obvious, for analysis, that both J_2 and C_{12} are referred to the motor shaft.

Therefore, the electro-mechanical system for the hoisting mechanism driven by a 'three-phase reversible voltage-controlled slip-ring induction motor' can be presented using the block-diagram depicted in fig. 1.

Where, in reference to fig. 1,
V_{in}- Input system voltage;
$H_1(s)$ – the equivalent transfer function of the following proportional elements:

a) Voltage regulator with a gain of $K_{\text{reg.}}$;
b) Three-phase thyristor reversible voltage controller (converter) with a gain of K_{TC};
c) Equivalent electrical part of the three-phase induction motor K_{M}, presenting the ratio of the motor torque change to the motor voltage change $K_{\text{M}}=\Delta T/\Delta V$.

$H_2(s)=\dfrac{1/\beta}{T_{\text{M1}}s+1}$ - Motor mechanical component transfer function:
β - Motor speed-torque characteristic rigidity.
$T_{\text{M1}}=J_1/\beta$ - Motor electromechanical time-constant.
$H_{\text{FB}}(s)=K_{\text{FB}}$ - Motor speed feedback transfer function.
$H_{\text{C}}(s)=C_{12}/s$, with C_{12} defined previously.
$H\text{j}(s)=1/J_2 s$;
T_{L}- Load torque;
$T_{\text{el.}}$- Elasticity torque.

The block diagram depicted in fig. 1, after effecting some mathematical rearrangements, yields the following equivalent transfer function:

$$H(s)=\frac{\omega_2(s)}{V_{\text{in}}(s)}=\frac{K_1}{T_{\text{M1}}T_2^2s^3+(1+K)T_2^2s^2+T_{\text{M}}s+1+K} \qquad (1)$$

Where,
$K_1=K_{\text{reg.}}\cdot K_{\text{TC}}\cdot K_{\text{M}}\cdot 1/\beta$,
$K=K_1\cdot K_{\text{FB.}}$

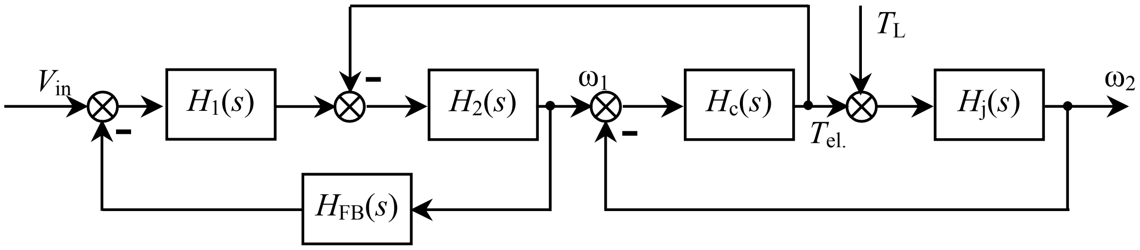

Fig. 1. Block-diagram of the hoisting electric drive mechanism driven by 'three-phase reversible power controller –slip-ring induction motor'.

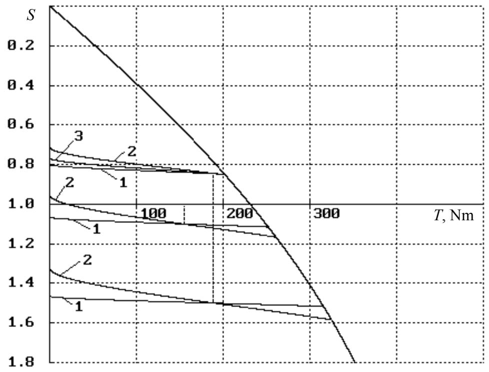

Fig. 2. Speed-torque characteristics during lifting and lowering the rated cargo for different $K_{reg.}$ values:
1- $K_{reg.}$=3.8; 2- $K_{reg.\,(opt.)}$= (1.3; 0.9; 0.75); 3- $K_{reg.}$=2.2.

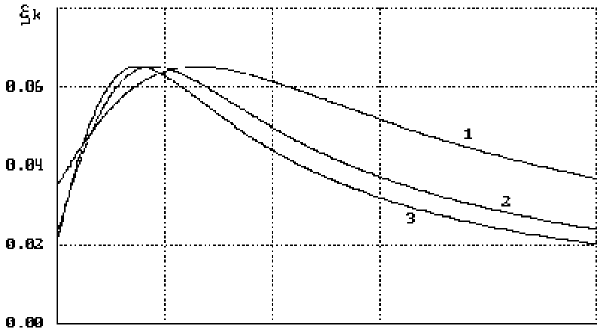

Fig. 3. ξ_k versus $K_{reg.}$ for various slip (S) values:
1- S=0.85; 2- S=1.1; 3- S=1.5.

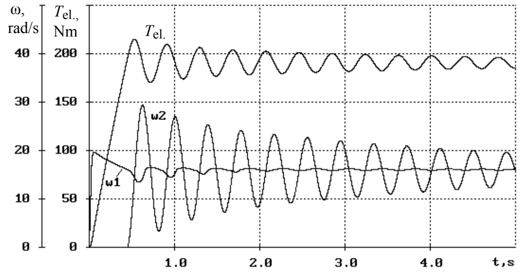

Fig. 4(a). Starting transients with $K_{reg.}$=3.8

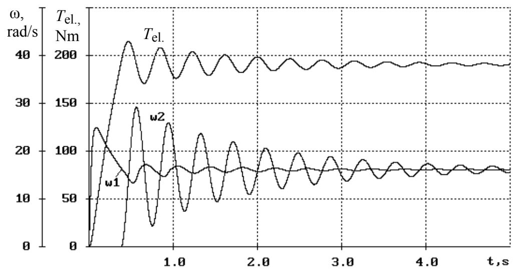

Fig. 4(b). Starting transients with $K_{reg.}$= $K_{reg.(opt.)}$=1.3

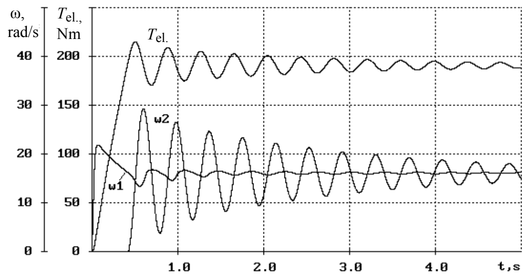

Fig. 4(c). Starting transients with $K_{reg.}$=2.2

$$T_2 = \sqrt{\frac{J_2}{C_{12}}}\ , \ T_{\text{м}} = \frac{J_1 + J_2}{\beta}\ .$$

It's obvious that $\gamma = \dfrac{J_1 + J_2}{J_1} > 1$

The characteristic equation for the system transfer function (equation (1)) is:

$$\frac{T_{\text{м}1} T_2^2}{1+K} s^3 + T_2^2 s^2 + \frac{T_{\text{м}}}{1+K} s + 1 = 0\ . \tag{2}$$

The third order polynomial (equation (2)) can be decomposed into the product of a first and second order polynomial as follows:

$$(T_a s + 1)\cdot(T_k^2 s^2 + 2T_k \xi_k s + 1) = 0\ , \tag{3}$$

Where:

$$T_a = \frac{1}{\alpha}\ ,\ \ T_k = \frac{1}{\sqrt{\alpha_2^2 + \Omega_0^2}}\ ,\ \ \xi_k = \frac{\alpha_2}{\sqrt{\alpha_2^2 + \Omega_0^2}}\ .$$

The roots of characteristic equation (2) have negative real parts:
$s_1 = -\alpha,\ s_2 = -\alpha_2 \pm j\Omega_0$.

Therefore, with knowledge of the damping ratio ξ_k and the time constant T_k, it is possible to evaluate the transient response and system natural frequencies.

III. SIMULATION RESULTS

For a particular hoisting electric drive of a bridge crane, with a 3-phase induction motor type 4MTF160LB6 (P = 15kW), using the specific calculation algorithm for three-phase reversible voltage controllers declared in [2], a mathematical model was developed in order to evaluate the effect of the electrical and mechanical parameters of the hoisting electric drive on the system transient behaviour. Here different speed-torque characteristics were calculated for both the open loop and closed loop systems subject to both lifting and lowering modes.

The effect of changing the voltage regulator gain $K_{\text{reg.}}$ on the damping ratio ξ_k during both lifting and lowering the nominal cargo (T_L=190.7 Nm) is depicted in fig. 3 assuming the speed – torque characteristics depicted in fig. 2.

In fig. 2 three random motor slip (speed) values are selected for analysis: S=0.85 for the lifting mode whereas S=1.1 and S=1.5 are selected for lowering. For S=0.85 three different voltage regulator gain values were used in order to get different speed-torque characteristic curves as follows: $K_{\text{reg.}}$ =3.8 for characteristic 1, $K_{\text{reg.(opt.)}}$ =1.3 for characteristic 2 and $K_{\text{reg.}}$ =2.2 for characteristic 3. For S=1.1 two voltage regulator gain values were used as follows: $K_{\text{reg.}}$ =3.8 for characteristic 1 and $K_{\text{reg.(opt.)}}$=0.9 for characteristic 2. For S =1.5 two voltage regulator gain values were used as follows: $K_{\text{reg.}}$=3.8 for characteristic 1 and $K_{\text{reg.(opt.)}}$=0.75 for characteristic 2.

As an examination of fig. 3 reveals there is an optimum value of $K_{\text{reg.}}=K_{\text{reg.(opt.)}}$ at which the transient mechanical oscillations are minimal. This response occurs at $\xi_k = \xi_{k(\max.)}$. It is also observed that the specific value of $\xi_{k(\max.)}$ is independent of the motor's slip S (speed) or torque. From fig. 3 it is also noted that as the motor's slip increases the maximum ξ_k occurs at decreasing $K_{\text{reg.}}$ ($K_{\text{reg.(opt.)}}$). On the other hand, $K_{\text{reg.}}$ is directly proportional to the rigidity of the speed-torque characteristic, small values of which are undesirable for the above mentioned closed loop control system.

The effect of $K_{\text{reg.}}$, on the transient shape for a starting process to a speed ω =0.15 of the rated speed, is shown in fig. 4 (a, b & c). An examination of figs 4(a), (b) and (c) indicates the optimum transient (i.e. maximum oscillations damping in minimum transient time) occurs at $K_{\text{reg.(opt.)}}$=1.3, which corresponds to the motor slip (S) identified in fig. 3 at S = 0.85.

Further analysis was conducted to observe the effect of varying γ. This analysis, conducted elsewhere but omitted for brevity, revealed that increasing γ does increase ξ_k, therefore minimizing the system transients. However, for typical actual hoisting mechanisms $1.02 \le \gamma \le 1.4$, suggesting it is difficult to reduce the system's oscillations by increasing γ.

IV. CONCLUSION

As this mathematical analysis and simulation has revealed that selection of the optimum value for the supply voltage regulator gain $K_{\text{reg.}}$, to the voltage power controller of a slip-ring induction motor results in reduced transient oscillations. Minimal oscillations are possible by further adjustment of the voltage regulator gain $K_{\text{reg.}}$ and incorporating negative feedback of the elasticity torque into the system [1].

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