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Synthesis of Multi-Motor Automatic Electric Drive Systems Linked by Elastic Conveyors

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Key words: Multi-motor drive system, modelling and simulation, elastic conveyors, distributed parameter system, real interpolation method, synthesis of controller

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Abstract: The study presents a new solution of synthesis of multi- motor automatic electric drive systems operating with elastic conveyors. Besides, a structural diagram of the system is proposed with an adjustment algorithm for modeling the transfer functions. The proposed adjustment algorithm is implemented on the simulation environment in order to test quality of the system. The simulation results show that this algorithm can be adapted and applied to many different multi-motor automatic electric drive systems.

INTRODUCTION

In recent years, the multi-motor drive systems have been powerfully studied because of their advantages such as effective power consumption, easy adjustment of total inertia torque and quickly changing speed compared to single motor drivers[1].

Many industrial transport systems use elastic conveyors to generate reasonable flow in the production process. On the one hand, the conveyor reliability needs to be investigated to improve the efficiency of the entire production process.

On the other hand, the conveyor elasticity affects the kinematic parameters such as speed and acceleration. The use of multi-motor drives helps to improve the control quality and the ability to adjust the conveyor's performance[2].

Practical problems of developing control algorithms that meet the technical requirements for elastic conveyors such as in production lines[3], cable coating lines[4], fabrication manufacturing, wires canned lines, automatic robots[5] in automobile and material transportation have required researchers to always find solutions to improve quality.

The automatic transmission system with multi-motor automatic electric drive system in speed is the basic component in most production lines, industrial robots, mechanical processing equipment. However, the quality controlling is a big challenging related to determining the accuracy of the whole line. In order to improve the control quality, it is necessary to take into account the influence of elastic conveyor links connecting the motors in pair.

A number of researchers have investigated in modeling and constructing controllers for multiple-drive drives containing elastic conveyors[6-8]. Besides, the design of multiple tension motor driven controllers based on nonlinear models have been strongly studied[9-11]. They use classical methods of synthesis with a set of modifiers based on the analysis of the time or frequency characteristics of the control object, requiring the construction of complex models and algorithms, calculation volumes and errors based on fuzzy theory and neural networks. Differently[10,11] use sustainability methods for adjusting regulators and the Linear Quadratic Gaussian (LQG) optimal control method. This solution requires sufficient information about the system parameters which is very difficult to deal with complex multi-motor systems.

Futhermore, the value of the belt tension is determined by the dynamic process that occurs in the conveyor. The value of the tension along the belt changes after the pulling force of the motors. As a result, the torques from the elastic belt conveyors react back to the engine with a nonlinear relationship. The difficulty in calculating the nonlinear relationship of the friction and the elasticity related to the transmission coefficient of the multi motor dive system requires a simulation program.

Therefore, modeling and simulation help to quickly assess the dynamic parameters of the whole system. Through the simulation program, controlling the conveyor speed and the ability to change the direction to adjust the conveyor's efficiency will be more economically efficient.

The study introduces a solution of modelling for a multi-motor automatic electric drive system and a control algorithm for the simulation that meets the technical requirements for the elastic belt conveyor allowing energy savings to take into account the random load changes from the motors. Simple summary recently, there have been a large number of control solutions for multi-motor drive systems with dynamic parameters changing over time and depending on the size of workspace. Control quality of such systems can be improved via the synthesis of control rules. However, the complexity of the rules relates to the nonlinear degree of transfer functions containing inertial and transcendent components. Therefore, this study focuses on a new solution of system synthesis based on widely published practical interpolation methods to reduce the complexity of the control rules while maintaining the required quality criteria.

MATERIALS AND METHODS

Modeling the system: The general structure of such drive systems is shown in Fig. 1. In particular, the elastic conveyor links the motors of the system with parameters (mass, elasticity, etc.) depending on the space size, described by partial differential equations, integral equations, differential-integrals and other forms. Therefore, the transfer function that describes this element ($W_o(s)$) will take the form:

$$W_O(s) = f(s, e^{\frac{A(s)}{B(s)}}, \sqrt{s}, \cos(s), \sin(s), sh(s), ch(s), ...,) \quad (1)$$

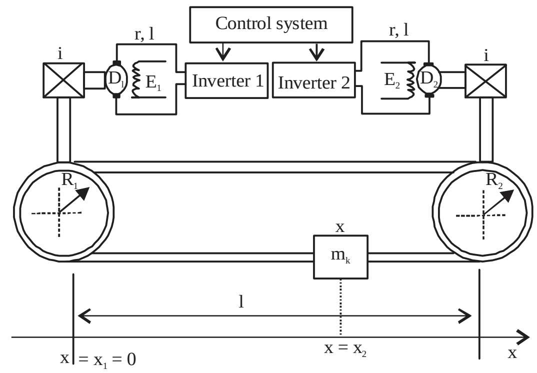

Fig. 1: The two-drive active drive system is linked by an elastic conveyor

Containing not only arguments of linear systems but also inertial and transcendent components (functions of) $s, \sqrt{s}, \cos(s), \sin(s), sh(s), ch(s), ...$ [12].

In order to improve the control quality of such a transmission, it is necessary to take into account the influence of the elastic conveyor linking the motors. However, the complexity of the transfer function in Eq. 1 makes the adjustment of the regulator much more difficult. A number of studies have done modeling and constructing controllers for multiple-drive drives containing elastic conveyors[6-13]. The works[9-11] propose the design of multiple tension motor driven controllers based on nonlinear models. The classical group of methods for synthesizing a regulator based on the analysis of the time or frequency characteristics of the control object, requires the construction of complex models and algorithms, calculation volumes and errors. For example, when using the frequency model must manipulate functions with virtual arguments jw, they are only suitable for linear systems. The realization of methods based on fuzzy theory and neural networks is highly dependent on the experience of the designer and has high computational costs based on the mathematical tools used[9-11]. Some methods for adjusting regulators based on, for example, standards H^{∞} can lead to unsustainable solutions. This restriction also exists in methods that use the standard asymptotic integral between the desired system and be aggregated in[14]. The Linear Quadratic Gaussian (LQG) optimal control method requires sufficient information about the system parameters which are very difficult to deal with complex multi-motor systems[3, 4, 15] (Fig. 1).

From the above analysis, the article proposes a solution for synthesizing and modulating modulators based on real interpolation methods with simple procedures, allowing to reduce calculation volume and preserve special binding properties with the effect of conveyors throughout the system, similar to.

Modeling of elastic conveyors: The transmission mechanism in the electric drive system (Fig. 1) is described by the hyperbolic differential equations. The conveyor is surveyed in a closed loop connected two motors. This conveyor has uniform mass and stiffness, with m_1- drive load linked to the engine, concentrated in point $x = x_1 = 0$ and m_2-the load of conveyor is concentrated at the point $x = x_2$. Its mathematical description is represented by equation:

$$L_t\left[u(x,t)\right] = \rho(x)\frac{\partial^2 u(x,t)}{\partial t^2} - E\frac{\partial^2 u(x,t)}{\partial x^2} = f(x,t); 0 \leq x \geq l, t^{3}0, \rho(x) > 0, E > 0 \quad (2)$$

With initial and boundary conditions:

$$\begin{cases} u(x,t)|_{t=0} = u_0(x); \dfrac{\partial u(x,t)}{\partial t}|_{t=0} = u_1(x) \\ u(x,t)|_{x=0} = u(x,t)|_{x=l}; \dfrac{\partial u(x,t)}{\partial x}|_{x=0} = \dfrac{\partial u(x,t)}{\partial x}|_{x=l} \end{cases} \quad (3)$$

Where:

L_t	=	Differential operator
u(x, t)	=	Displacement of a point on an elastic link conveyor with coordinates
x	=	At a time; t
E	=	Const elastic modulus of the conveyor to be surveyed
$\mu_0(x)$, μ_1 (x)	=	Displacement and movement speed of elastic conveyor section at coordinates x and at the time
t = 0; f (x, t)	=	Impact on input space and time
ρ(x)	=	Material density of elastic conveyor in coordinates x can be calculated through the weight t component
m_i	=	Corresponding to coordinates x_i as follows

$$\rho(x) = \rho_l + \sum_{i=1}^{n} m_i \delta(x - x_i) \quad (4)$$

With ρ_l = constis the density of the elastic link conveyor without load. The normalized transfer function for (2) is the solution to the boundary problem[5]:

$$\begin{cases} L[W] = [1+\sum_{i=1}^{n}\eta_i\delta(x - x_i)]\tilde{s}^2 W(x,\xi,\tilde{s}) - \dfrac{d^2W(x,\xi,\tilde{s})}{dx^2} \\ \delta(x - \xi); \tilde{s} = s/a \\ W(0,\xi,\tilde{s}) = W(l,\xi,\tilde{s}); W = aW, a^2 = E/\rho_l \\ \dfrac{dW(0,\xi,\tilde{s})}{dx} = \dfrac{dW(l,\xi,\tilde{s})}{dx}; 0£\xi£l; \eta_i = m_i/\rho_l \end{cases} \quad (5)$$

Use discrete Fourier transforms N_k to the convey W (x) function (period time T = l) as follows:

$$W_k = N_k[W(x)] = \frac{1}{l}\int_0^l W(x)e^{-j\omega_k x}dx; \omega_k = 2\pi k/l, k = 0, \pm 1, \pm 2, ..., \quad (6)$$

And the calculation results in[6] as follows:

$$W(x) = \Phi(x\text{-}\xi)\text{-}s^2\sum_{i=1}^{n}\eta_i W(x_i)\Phi(x - x_i); \Phi(z) = \frac{1}{l}\sum_{k=-¥}^{¥}\frac{e^{j\omega_k z}}{s^2 + \omega_k^2} \quad (7)$$

In the drive system (Fig. 1) the number of components associated with the motors and the conveyor is n = 2. The main output point is the conveyor position with coordinates x_2 and the weight m_2 and the engine is located at the point of coordinates $x_1 = \xi = 0$. By replacing the coordinates (x_1, x_2) to (Eq. 7), the W (x_i) are calculated as follows:

$$\begin{cases} W(x_1)[1+s^2\eta_1\Phi(0)] + W(x_2)s^2\eta_2\Phi(x_2) = \Phi(x_1) \\ W(x_1)s^2\eta_1\Phi(x_2) + W(x_2)[1+s^2\eta_2\Phi(x_1) = \Phi(x_2) \end{cases} \quad (8)$$

From here, we get the transfer function that represents the relationship between the force at the point of coordinates $x_1 = 0$ and weight $m_1(F_d\ (0, s))$ with velocity at the point of coordinates x_2 and weight m_2 (V_λ (x_2, s)):

$$W_O(s) = W(x_2,0,s) = \frac{V_\lambda(x_2,s)}{F_d(0,s)} = \frac{q.\text{shsch}\lambda s}{\text{sh}^2 s+\mu_1\mu_2 s^2(\text{ch}^2 s\text{-ch}^2\lambda s)+(\mu_1+\mu_2)s.\text{sh}2s} \quad (9)$$

where, $\mu_1 = \eta_1/l = m_1/m_k$, $\mu_2 = \eta_2/l = m_2/m_k$, $m_k = p_i^l$, load weight q = 1/2α- transmission coefficient of elastic conveyor also $\lambda = 1\text{-}2x_2/l$-coordinates of the system's output space. The calculation is performed in a similar manner for the input-output coordinates, $x_1 = \xi = 0$; $x_2 = 0$ the function of conveyor relationship between the force on the active motor (F_d (0, s)) and the velocity V_d (0, s) is computed as follows:

$$W_O^*(s) = W(0,0,s) = \frac{V_d(0,s)}{F_d(0,s)} = \frac{q[\text{sh}2s+s\mu_2(\text{ch}^2 s\text{-ch}^2\lambda s)]}{[\text{sh}^2 s+(\mu_1+\mu_2)s.\text{sh}2s+\mu_1\mu_2 s^2(\text{ch}^2 s\text{-ch}^2\lambda s)]} \quad (10)$$

Proposal of structual diagram: The kinematic processing of a multi-motor electric drive with elastic bonding in a channel is expressed by the following linear equations (Fig. 2):

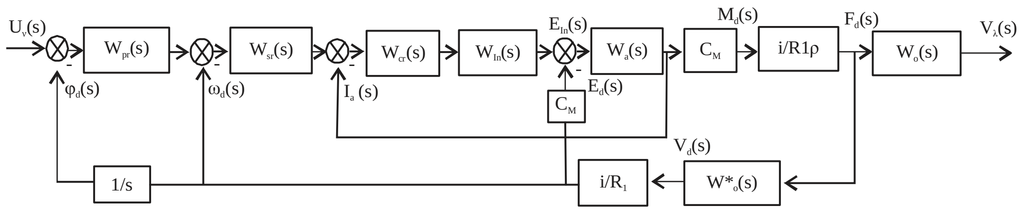

Fig. 2: The structural diagram of the system with elastic belt conveyors

$$\begin{cases} \Delta E_{tp}(t) = r\Delta I_1(t) + L\dfrac{d\Delta I_1(t)}{dt} + \Delta E_d(t) \\ \Delta E_d(t) = \dfrac{c_M i}{2\pi R_1}\Delta v(x,t)|_{x=0} \\ \Delta F(x,t)|_{x=0} = \dfrac{c_M i}{2\pi R_1 \rho_1}\Delta I_1(t) \\ \dfrac{\partial \Delta u(x,t)}{\partial t} = \Delta v(x,t) \\ \rho(x)\dfrac{\partial^2 \Delta u(x,t)}{\partial t^2} - E\dfrac{\partial^2 \Delta u(x,t)}{\partial x^2}(t) = \Delta F(x,t) \\ \Delta u(x,t)|_{t=0} = \Delta u_0(x); \dfrac{\partial \Delta u(x,t)}{\partial t}|_{t=0} = \Delta u_1(x) \\ \Delta u(x,t)|_{x=0} = \Delta u(x,t)|_{x=l} \\ \dfrac{\partial \Delta u(x,t)}{\partial x}|_{x=0} = \dfrac{\partial \Delta u(x,t)}{\partial x}|_{x=l}; 0 \le x \le l, t \ge 0 \\ \rho(x) = \rho_1 + \sum_{i=1}^{2} m_i \delta(x - x_i); \rho(x) > 0, E > 0, \rho_1 = const \end{cases} \quad (11)$$

Where:

E_{tp}, E_d	=	Oltage of the Thyristor converter and the electromotive resistance of the motor
I (t)	=	Current of the converter of Thyristor
I, R_1	=	Transmission ratio of the reducer and the radius of the active motor
F (x, t)	=	Tension in conveyor
v(x, t), μ (x, t)	=	The speed and displacement of the conveyor cross section at x coordinates at the time
t; ρ_1	=	Linear density of conveyor under consideration

Thus, the structure diagram showing the electric drive system taking into account the elastic link conveyor (9,10), built on the principle of dependent adjustment is shown in Fig. 2 in which $W_{pr}(s)$, $W_{sr}(s)$, $W_{cr}(s)$-transmission function of the position, speed and current regulators W_{in} (s)-transmission function of the Thyristor converter T_α, R_α. The electromagnetic constant of the armature circuit and its impedance; C_M-Mechanical constant of motor; i-Gear ratio of gearbox; R_l-Radius of rudder; ρ-material density of conveyor belt ω_d (s), φ_d (s) angular velocity and angle of rotation of the motor. Its differences from the structure diagram when not taking into account the conveyor include an open system and output signals. The inverse relationship is removed from the motor in the presence of an elastic coupling conveyor which does not contain information about the actual change of output coordinates which is due to the movement of the motor shaft. The elastic conveyor affects the motor movement through the action of feedback circuits by the conveying function $W_o^*(s)$. In addition, the presence of components 1/s, i/R_1 is due to the conveying function describing the elastic bonding conveyor received for the tension forces removed by linear density and output velocity. For the system on the Fig. 2, the transfer function describes the inverter as an inertial form:

$$W_{In}(s) = \frac{k_{In}}{T_{In}s+1} \quad (12)$$

With k_{in}-amplification factor, T_{in}-time constant of the inverter. Transfer function of engine armature $W_\alpha(s)$ as follows:

$$W_a(s) = \frac{1}{R_a(T_a s+1)} \quad (13)$$

Synthesis of system using real interpolation method: The task is to determine the tuning of each loop has a general form:

$$W_i(s) = \frac{b_m s^m + b_{m-1}s^{m-1} +,....,+ b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1} + ... + a_1 s + a_1}(m \le n, i = 1 \div 3) \quad (14)$$

And feedback coefficients K_i (I = 1, 3), so that, the quality criteria of each loop and the system meet the conditions:

$$\begin{cases} \sigma_R - \Delta\sigma \le \sigma_S \le \sigma_R + \Delta\sigma \\ t_{ST}^S \le t_{ST}^R \end{cases} \quad (15)$$

$$\begin{cases} \sigma_R - \Delta\sigma \le \sigma_S \le \sigma_R + \Delta\sigma \\ t_{ST}^S \to t_{ST}^{min} \end{cases} \quad (16)$$

Where:

σ_R	=	Required adjustment of the system
σ_s	=	The overshoot of the system is synthesized
$\Delta\sigma$	=	Permissible deviations between the desired system and the synthesis
t_{St}^R	=	Transient required time of the desired system
t_{St}^S, t_{ST}^{min}	=	Transient time and minimum achievable transient time of the system are summarized accordingly

In fact, if a regulator (Eq. 14) does not exist for the system to satisfy the tight condition (Eq. 15), it is possible to move to condition (Eq. 16) where the overshoot follows the tightness limit and the transition time is the smallest (this value is still greater than the required value $t_{ST}^{min}>t_{ST}^{R}$). The transition from condition (Eq. 15 and 16) ensures that the general problem always has a solution without losing the generality.

To solve the problem, first determine the desired transfer function of the closed system W_D^C (s) according to the required quality criteria S_R, t_{ST}^R. From method developed by Allaoua *et al*.[17], lets get the transfer function W_D^C (s) as follows:

$$W_D^C(s)=\frac{\frac{\alpha_1}{2}s+1}{\alpha_0 s^2+\alpha_1 s+1}H^{\infty};\alpha_0=\frac{[\ln(\frac{H^{max}}{H^{\infty}}-1)]^2}{\frac{9}{(t_{ST}^R)^2}\{[\ln(\frac{H^{max}}{H^{\infty}}-1)]^2+\pi^2\}};\alpha_1=\frac{6\alpha_0}{t_{ST}^R} \quad (17)$$

Where:

H^{∞}, H^{max}	=	The corresponding set and maximum value of the transient characteristics are determined based on the required correction
σ_R	=	The desired static mode of the system

Then, establish a general equation that represents the relationship between the desired transfer function of the closed system W_D^C(s) with the regulators (W_{pr}(s), W_{sr}(s), W_{cr}(s)), feedback coefficient (K_i) and part transfer function of each loop (W_i^{UN} (s), I = 1, 3), related to the engine (Wa (s)), inverter (W_{in} (s)), elastic conveyor (W_{cr}^*) and known gearboxes:

$$W_D^C(s)\cong F[W_{pr}(s), W_{sr}(s), W_{cr}(s), K_1, K_2, K_3, W_1^{UN}(s), W_2^{UN}(s), W_3^{UN}(s)] \quad (18)$$

With W_1^{UN} (s), W_2^{UN}(s), W_3^{UN}(s) the transfer function of the constant portion of the current, the speed and the corresponding rotation angle of the system (Fig. 2) as follows:

$$W_1^{UN}(s)=\frac{k_{In}}{T_{In}s+1}.\frac{1}{R_a(T_a s+1)}$$
$$W_2^{UN}(s)=\frac{C_m.i^2}{R_1^2\rho}.W_O^*(s);W_3^{UN}(s)=1/s \quad (19)$$

There is practically no general method of solving (Eq. 18) because: Firstly, (Eq. 18) contains three unknown transfer functions (W_{pr} (s), W_{sr} (s), W_{cr} (s)), so the number of coefficients to find is very large. Secondly, many nonlinear coefficients are included (18) in their product form. Thirdly, the transmission function structure of the regulator is usually first or second order when taking into account the physical requirements. Therefore, the approximate solution according to the defined criteria of the structure is found and evaluated as (Eq. 18). That means (Eq. 18) needs to be simplified to the extent that there is resolved by known methods. The essence of the synthesis method to apply real interpolation method is to convert the synthesis (Eq. 18) to the form with real arguments[20]:

$$W_D^C(\delta)\cong F[W_{pr}(\delta), W_{sr}(\delta), W_{cr}(\delta), K_1K_2, K_3, W_1^{UN}(\delta), W_2^{UN}(\delta), W_3^{UN}(\delta)] \quad (20)$$

Select the rule of distribution of interpolation nodes, for example, according to the law of uniform distribution:

$$\delta_i=i\delta_1, i=1\div\eta \quad (21)$$

Or set the value of nodal points $\{\delta_i\}_\eta$ coincide with the zero point of the Chebyshev polynomials to increase the total accuracy[5]:

$$\delta_i=\frac{1+x_i}{1-x_i}a, i=\overline{1,\eta} \quad (22)$$

Where:

h	=	Number of interpolation points
α	=	Real parameters used to correct general errors
$\{x_i\}_\eta$	=	Are zeros in a quadratic Chebyshev polynomial
η ($T_\eta(x)=0$)	=	Determined by the equation[21]

$$T_0(x)=1;T_1(x)=x;T_2(x)=x^2-\frac{1}{2};...;T_{\eta+1}(x)=xT_\eta(x)-\frac{1}{4}T_{\eta-1}(x);x\in[-1,1] \quad (23)$$

Then, calculate the digital characteristics $\{W_D^C(\delta_i)\}_\eta$ $\{W_{pr}(\delta_i)\}_\eta$, $\{W_{sr}(\delta_i)\}_\eta$ corresponding to the selected node set. Then the system of equations is established:

$$\begin{cases} W_D^C(\delta_1) = F[W_{pr}(\delta_1), W_{sr}(\delta_1), W_{cr}(\delta_1), K_1, K_2, K_3, W_1^{UN}(\delta_1) \\ W_2^{UN}(\delta_1), W_3^{UN}(\delta_1)] \\ W_D^C(\delta_2) = F[W_{pr}(\delta_2), W_{sr}(\delta_2), W_{cr}(\delta_2), K_1, K_2, K_3 \\ W_1^{UN}(\delta_2), W_2^{UN}(\delta_2), W_3^{UN}(\delta_2)] \\ \qquad \ldots \\ W_D^C(\delta_\eta) = F[W_{pr}(\delta_\eta), W_{sr}(\delta_\eta), W_{cr}(\delta_\eta), K_1, K_2, K_3 \\ W_1^{UN}(\delta_\eta), W_2^{UN}(\delta_\eta), W_3^{UN}(\delta_\eta)] \end{cases} \quad (24)$$

To determine feedback coefficients K_i and the unknown coefficients of the regulators. To make sure the system (Eq. 24) has a unique solution, then h must have a numerical value of the coefficients of the regulators to be searched. To solve (Eq. 18), two methods can be used including sequential or concurrent synthesis. These methods will be described in detail in the next sections.

Sequential synthesis: In this case, the basic summary is to solve (Eq. 18) for each current, speed and position based on the general procedure including the following main stages. Firstly, Define the transfer function that describes the constant portion of each loop (W_i^{UN}(s), i = 1, 3). In the general case, they are searched in such a way: firstly, the feedback links are opened, the feedback coefficients K_i, i = 1, 3 is not included and the initial state of all regulators is equal one (W_{pr}(s), W_{sr},(s). W_{cr}(s) = 1). Then, the input signal system x (t) and determine the corresponding output signal (y_i(t), i = 1, 3) of each loop is set up. In this case, the actual transfer function is determined according to the received data as follows:

$$W_{y_ix}(\delta) = \frac{\int_0^T y_i(t)\times\exp(-\delta t)dt}{\int_0^T x(t)\times\exp(-\delta t)dt}(i = 1 \div 3) \quad (25)$$

Where:

T = The time to observe the signal

y_i (t) = The time T is not less than the transient time in the circuit under consideration

In fact, functions y_i (t) and x (t) given in tabular form. In (25), the integrals can be performed by numerical methods on the control object with the transfer function W_{CO} (d):

$$W_{CO}(\delta) = W_{y_3x}(\delta) \quad (26)$$

Is represented by the product of the transfer functions of the constant:

$$W_{CO}(\delta) = \prod_{i=1}^{3} W_i^{UN}(\delta) \quad (27)$$

From (Eq. 26 and 27), the real transfer function of the constant portion in each loop W_i^{UN} will be defined:

$$W_1^{UN}(\delta) = W_{y_1x}(\delta); W_2^{UN}(\delta) = \frac{W_{y_2x}(\delta)}{W_{y_1x}(\delta)}; \quad W_3^{UN}(\delta) = \frac{W_{y_3x}(\delta)}{W_{y_2x}(\delta)}. \quad (28)$$

Secondly, determine the desired transfer function of the system W_D^C (s) and of each loop W_i^D (s), describe the quality of the transiting process in the ith loop according to Eq. 17. Due to the quality of the processing process does not just appear on the outer loop W_D^C (s) but also within internal loops, making it difficult to determine the desired transfer function of each loop. This problem can be solved by using the known time constant quantity of the corresponding constant W_i^{UN} (s). Time constant T_i is approximated by a factor α_i of function W_i^{UN} after removing components whose order is greater than two. Dependence of transient time in the i-loop (t_i^R) into the maximum time constant T_i is represented by Equation[2]:

$$t_R^i = 3\times d\times T_i \quad (29)$$

With d = 0.5.10-adjustment parameters are used to change the transition time t_R^i when performing the procedure of adjusting calibration parameter to optimize the quick impact of the circuit. As such (Eq. 29) allows the evaluation of the quick impact of the circuit to be synthesized and the overshoot S_R^i can be used as a calibration parameter. Finally, the desired transfer function of each loop is defined in Eq. (17) based on transitional time,t_R^i over adjustment found S_R^i.

Thirdly, the computation is performed sequentially for each loop on the basis of solving (Eq. 18) according to the algorithm cited in. Note that the feedback coefficient of each loop K_i can be defined from the static mode of the system as follows:

$$K_i < \frac{1}{H_i^{¥} - \Delta H_i}; \frac{1}{H_i^{¥}}, i = 1 \div 3 \quad (30)$$

Where:

ΔH_i = Systematic error in setting mode in loop i and nodal points

d = Evenly distributed, the first node can be defined as[4] by the expression

Forthly, the system calibration is aggregated to meet the required quality criteria under conditions (Eq. 15 or 16). In RIM, basic ways of calibrating a system include[20]: Calibrate the system to achieve over-correction (Eq. 15) by changing the interpolation node points $\{d_i\}_h$ and/or different structures of regulators (m, n).

The desired correction is achieved by changing the required transient time (t_{ST}^R) is known to evaluate the operation of the control system, there are two most important quality criteria: the over-adjustment and the transient time. These indicators have a mutual relationship with each other, i.e., increasing/decreasing this indicator will change the remaining one. Thus, one can use this indicator as a tool variable to adjust the other. Here, to achieve targets σ_s small enough to reduce the requirement for fast impact, i.e., increase the required transition time t_{ST}^R. Quantitative dependence of parameters σ_s into t_{ST}^R ($\sigma_s = f(t_{ST}^R)$) is stated as follows: quantity increase t_{ST}^R will reduce the lower bound of the quantity σ_s.

Achieving the required overshoot using special-weight weights: Another way to calibrate the overshoot of a synthesized system is by using special form weight functions w(t). In order to form these weight functions, synthesis (Eq. 18) in continuous integral forms is:

$$\int_0^\infty k_D^C(t)e^{-\delta t}dt \cong \int_0^\infty k_S^C(t)e^{-\delta t}dt \tag{31}$$

And clearly discrete:

$$\int_0^\infty k_D^C(t)e^{-\delta_i t}dt \cong \int_0^\infty k_S^C(t)e^{-\delta_i t}dt, i = 1, 2, ..., \eta \tag{32}$$

With, $k_D^C(t)$, $k_S^C(t)$ the impulse transient responses of the desired system and are summed accordingly and expressions $e^{-\delta t}$ is the weight function that affects the convergence rate of integrals and errors $\Delta k(t) = k_D^C(t) - k_S^C(t)$. It allows to change the dynamical properties of the system synthesized when moving interpolation nodes (δ_i, i = 1, 2...). So, in specific cases, weight functions can be included, for example $w(t) = e^{-\delta t}(1-e^{-\delta t})$. This method allows to achieve the required adjustment without depending on changes to the original information σR, t_{ST}^R. However, the use of such a weight function loses the correlation and does not allow the conversion between the integral and the Laplace transform. Also, there is not a general rule for setting these weight functions. It is defined according to each specific problem and mainly based on the experience of the designer. Here, the function $w(t) = e^{-\delta t}(1-e^{-\delta t})$ is set, so that, the transient function graph of the desired system $h_D^C(t)$ and w(t) are congruent with each other and interpolate nodes δ_i be defined from the condition: the time of reaching the maximum value of the function $h_D^C(t)$ and w(t) duplicated. Therefore, this method is only used in specific cases.

Achieve a given correction based on the desired extrapolation transfer functions: Experimental calculation of the regulators shows that under certain conditions of association between the original data (desired properties of the system and the parameters of the control object) may present difficulties in obtaining the correction with the required precision and thus the problem is only approximated. At the result received, the over adjustment σ_s of the synthesized system is smaller or bigger than the required value σ_R. Moreover, changing interpolation nodes (with the law of uniform distribution) may not lead to the solution to be sought provided that the requirements of sustainability and quick impact. Therefore, the problem of finding a solution does not relate to the use of the required amount of time transition t^{STR}. One of the solutions to this situation is to pre-change the value of the desired correction in the vicinity of the given correction $\sigma_s > \sigma_{R+\Delta}\ \sigma_R$. If the results in a reduction of the desired correction σ_R to value σ_{R_min} at which the synthesized system will satisfy the condition (15). In the opposite case when $\sigma_S < \sigma_R - \Delta\ \sigma_R$, this means that the desired value needs to be increased σ_R to value σ_{R_max}.

When summarizing each control loop separately, the desired properties of the entire system in advance provide the desired properties of each internal loop to calculate its controller. Therefore, it is necessary to determine the desired properties for each loop. This has no exact (or impossible) solution, leading to increased overall error.

Concurrent synthesis: For simultaneous synthesis of the current, speed and position regulators of the system in Fig. 2, (Eq. 18) are rewritten in a clear form for closed systems:

$$W_D^C(s) \cong \frac{W_{pr}(s)W_{SL}(s)W_3^{UN}(s)}{1 + K_3 W_{pr}(s)W_{SL}(s)W_3^{UN}(s)} \tag{33}$$

With $W_{SL}(s)$ The transfer function describes the speed loop be defined according to the current loop $W_{CL}(s)$ as follows:

$$W_{SL}(s) = \frac{W_{sr}(s)W_{CL}(s)W_2^{UN}(s)}{1+K_2 W_{sr}(s)W_{CL}(s)W_2^{UN}(s)}\left(W_{CL}(s) = \frac{W_{cr}(s)W_1^{UN}(s)}{1+K_1 W_{cr}(s)W_1^{UN}(s)}\right) \tag{34}$$

Or with open system:

$$W_D^O(s) \cong W_{pr}(s)W_{SL}(s)W_3^{UN}(s) \quad (35)$$

With $W^O_D(s)$ desired transfer function of the open system is defined by the expression:

$$W_D^O(s) = \frac{W_D^C(s)}{1 - K_3.W_D^C(s)} \quad (36)$$

Clearly, solving the synthesis (Eq. 35) instead of (Eq. 33) will reduce the complexity of the algorithm and the calculated mass. Substituting the expression (Eq. 34) into (Eq. 35), a generalized equation for the synthesizers of the system is:

$$W_D^O(s) \cong \frac{W_{pr}(s)W_{sr}(s)W_{cr}(s)W_1^{UN}(s)W_2^{UN}(s)W_3^{UN}(s)}{1 + K_1W_{cr}(s)W_3^{UN}(s)+K_2W_{sr}(s)} \quad (37)$$
$$W_{cr}(s)W_1^{UN}(s)W_2^{UN}(s)$$

The basic stages of solving (Eq. 37) by real interpolation method are not different from when synthesizing each loop separately. The difference is that (Eq. 37) contains many coefficients to find and nonlinear coefficients. This makes solving it difficult. Therefore, it is necessary to simplify (Eq. 37) to the extent that it can be solved by known methods.

The simplification procedure (Eq. 37) begins with the elimination of the feedback coefficients thanks to the a priori information. Then set up the conditions, so that, the current circuit can be individually synthesized. Thanks to that, the transfer function ($W_{CL}(s)$) will be excluded from (Eq. 37). Note that the load change is due to the change of inertia and static moment. However, the moment of inertia does not affect the current, i.e., the flow regulator $W_{cr}(s)$ does not need to reset. In fact, the transition in the electric part of the engine is faster than in the mechanical part. Therefore, based on the principle of dividing the "fast" and "slow" movements in the control system[4], the synthesis of the flow controllers will be separated. In addition (Eq. 37) is solved by an interpolation method consisting of a series of operations with real numbers, so, the condition for removing the current loop from (37) will be inequality:

$$W_{CL}(\delta)^3K_{CL}^S(1\text{-}e), d\hat{I}[d_1, d_h] \quad (38)$$

With $K^s_{CL} = W_{CL}(0)$ Static transmission coefficient of current loop e ⅊ 1-. The deviation ensures the permissible error between the real transfer function $W_{CL}(d)$ and static transmission K^s_{CL} in the real variable domain d. If the desired properties of the current loop are summed as follows, the inertial stage with static transmission coefficient K^s_{CL} and time constant T_{CL} then (Eq. 38) as follows:

$$\frac{K_{CL}^S}{T_{CL}\delta+1}{}^3K_{CL}^S(1\text{-}\varepsilon), d\hat{I}[d_1, d_\eta] \quad (39)$$

Will allow defining the bounding area of the real variable d:

$$d£\frac{e}{T_{CL}(1-e)} \quad (40)$$

Condition (Eq. 40) complies with the principle of dividing the "fast" and "slow" motions indicating that: the system has a high fast action (small time constant) and vice versa in the region of small real variables is expressed by the static transmission coefficient K^s_{CL} with given deviation e. In the case, the desired properties of the current loop are described by the higher-order stages, the removal of the current loop from (Eq. 37) remains true under the condition (38). When taking into account the above conditions (Eq. (37) is rewritten to:

$$W_D^O(s) \cong \frac{K_{CL}^S W_{pr}(s)W_{sr}(s)W_2^{UN}(s)W_3^{UN}(s)}{1 + K_2K_{CL}^S W_{sr}(s)W_2^{UN}(s)} \quad (41)$$

Clearly, solving the synthesis (Eq. 41) instead of (Eq. 37) will be simpler and without any significant difficulties. However, this way of synthesizing leads to nonlinear equations/systems of tuner parameters. Solving these systems will be difficult in the time domain and Fourier or Laplace image domain[4]. Therefore, it is necessary to set additional conditions for the coefficients to be searched. One of them is the defined domain of the modifier coefficients and the other conditions are defined depending on the specific problem without a common algorithm.

RESULTS AND DISCUSSION

Setup the synthesis algorithm: From the analysis in section 2.2, the flowchart of the algorithm for synthesizing the drive system of two active motors interlocked by elastic conveyor by real interpolation method is shown in Fig. 3.

Setup the simulation conditions: To verify the correctness of the algorithm and the program, below we summarize the regulators with the quality indexes of expected systemare shown in Table 1 and motors, inverters, conveyors with parameters.

Table 1: The parameters of synthesized regulators

		Quality criteria					
		Desired system			Synthesized system		
Loops	Regulators	t^R_{ST}(s)	σ_R (%)	Settling output	t^S_{ST}(s)	σ_S (%)	Settling output
Current	0.06103s+1.468/sec	0.08	4	1 (A)	0.0766	4.0095	1 (A)
Speed	2.368s+0.3438/sec	0.5	4	3 (rad/s)	0.3881	1.0027	3 (rad/s)
Rotation angle	6.2201		1	12	6(rad)	0.7134	1.45116(rad)

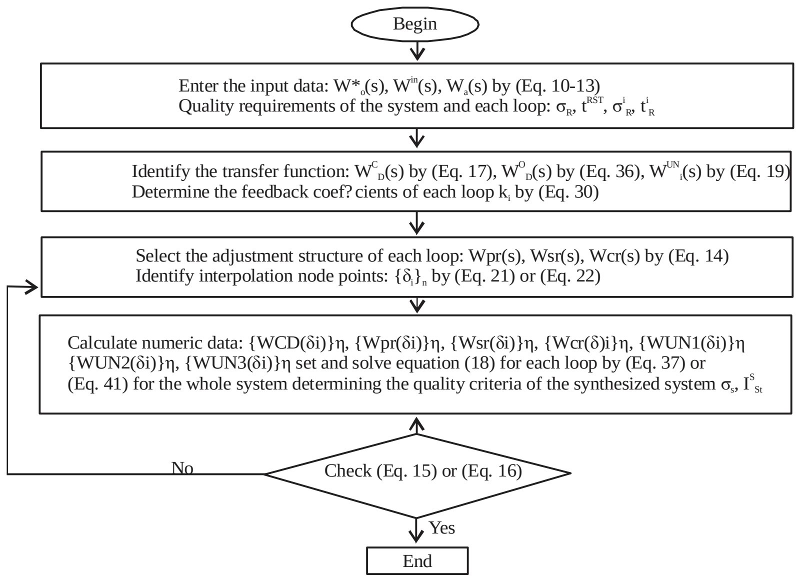

Fig. 3: Flowchart for synthesis on a set of real interpolation operations

Motor: Rated power of electric motor P_r = 4.5 kW rated armature voltage U_a = 220 Vrated speed n_r = 1000 rpm rated armature current I_a = 25.2A armature coil R_a = 0.632Ω Resistance; R_f = 560 (Ω) Resistive coil resistance; motor inertia torque J = 2.8 kg.m^2 and the inverter are given parameters. Inverter: outputvoltage, U_{dm} = 230(V) control voltages U_{dk} = 10 (V) witching frequency f = 500 (Hz), K_{in} 22; T_{in} = 0.01s. Elastic conveyor with q = 1/2a = 7, λ = 1-2x_2/l = 0.4, $\mu_1 = m_i/m_k$, $\mu_2 = m_2/m_k$ = 0; R = 1; i = 4 are as follows:

$$W^*_O(p) = \frac{14ch(s)}{sh(s)+22s.ch(s)} \qquad (42)$$

User interface of simulation program: The entire program automatically synthesizes the adjustment of the control system according to the algorithm in Fig. 3 written on the Guide programming tool of MATLAB 2017b. The main interface of the program is shown in Fig. 4. The GUI consists of 5 subroutine modules: Module "Object" allows to enter parameters, calculate and display the corresponding transmission function of the motor, inverter and elastic conveyor.

Module "Quality Index" allows entering the required quality criteria: transient time, over adjustment, set error, set value of each control loop.

The module "Synthesis of Controller" performs the adjustment of the controller structure, the interpolation interval and the parameter calculation of the controllers, evaluates and displays the quality criteria of each current, speed and angle. rotation of the system received. Module "Quality Index of synthesized system" displays the quality indicators of the system after synthesis and shows the structure diagram of the system on simulink. The "Step Respones" module draws transient characteristics of each synthesized control ring.

Simulation results: Calculation results of the regulator parameters in each current loop, speed and position are shown in the following table while the structure diagram of the system after synthesis and the simulation results are shown in Fig. 5 and 6, respectively.

From the analysis of the graphs in Fig. 6, we determine the settling time and the overshoot of transient processes in each loop: With the current loop t^S_{ST1} = 0.0766 (s), s $_{s1}$ = 4.0095% speed loop t^S_{ST2} = 0.3881 (s), s, s_2 = 1.0027% position loop t^S_{ST3} = 0.7134 (s), s s3 =

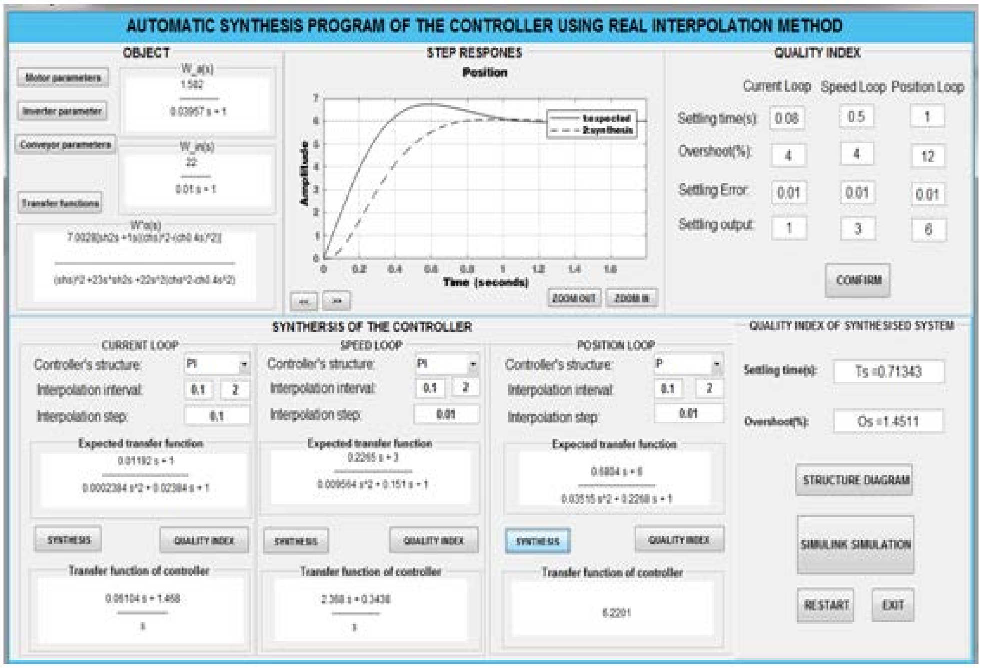

Fig. 4: GUI for automatically synthesizing the regulators

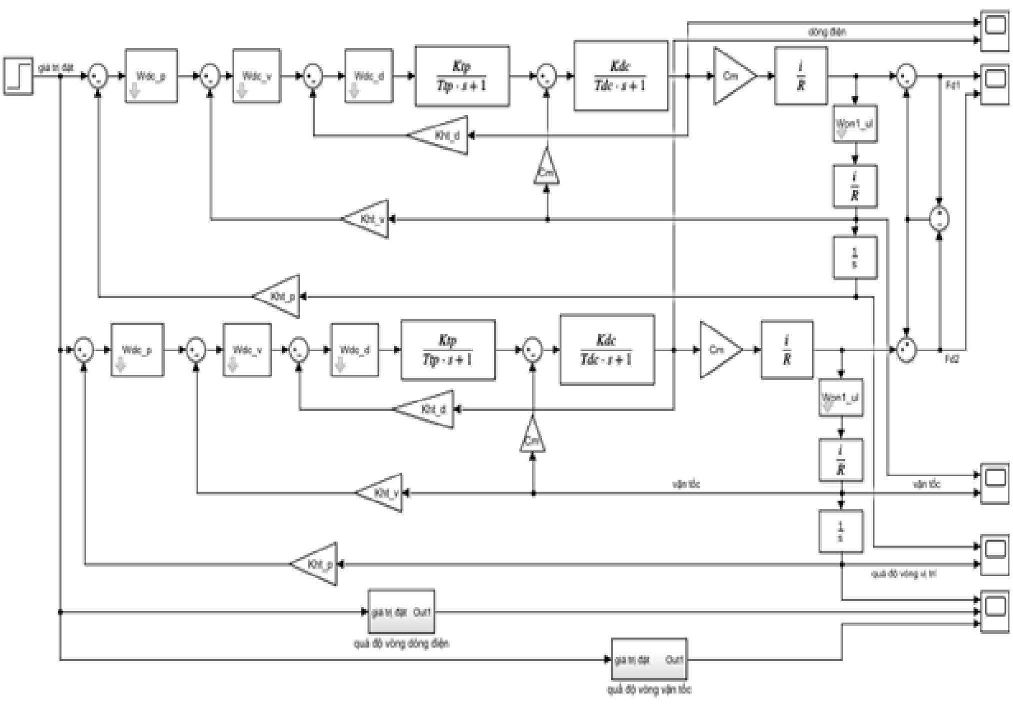

Fig. 5: Structure diagram of the synthesized system

1.4511%. This result shows that the regulators received meet the quality requirements of the transitional processes in the multi-loop control system. Thus, the method reviewed in the paper provided a feasible way to solve the problem of synthesizing the regulators of the active multi-motor electric drive containing elastic conveyors.

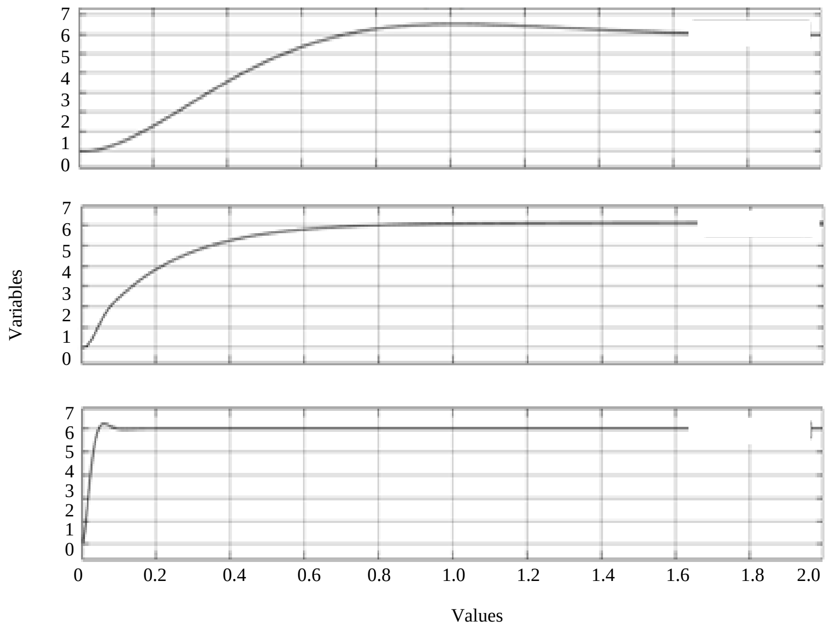

Fig. 6: The transitional processes of the synthesizedsystem

Calculation and simulation results show the authenticity of the proposed method, it allows direct operation with the original model describing the conveyor (Eq. 10) without any significant difficulties.

CONCLUSION

The study presented a new control solution to solve the problem of multi-motor automatic electric drive systems operating with elastic conveyors. The proposed adjustment algorithm is used for modeling the transmission functions organized by the structural diagram. The system is implemented on the simulation environment in order to test performance of the proposed algorithm. The simulation results proves that this algorithm is able to apply for the multi-motor automatic electric drive systems.

RECOMMENDATIONS

In the near future, the algorithm will be improved for the multi-motor automatic electric drive systems in the real condition of production.

REFERENCES

01. Mohsenimanesh, A.A., C.C. Lague, C.C. Luo and R.R. Habash, 2014. Electric multi-motor drives with improved induction machine for agricultural Wide-Span Implement Carrier (WSIC). Proceedings of the ASABE and CSBE Annual International Meeting, July 13-16, 2014, ASABE, Montreal, Canada, pp: 1-7.
02. Kovalchuk, M.S. and S.V. Baburin, 2018. Modelling and control system of multi motor conveyor. IOP. Conf. Ser. Mater. Sci. Eng., Vol. 327.
03. Allaoua, B., A. Laoufi and B. Gasbaoui, 2010. Multi-drive paper system control based on multi-input multi-output PID controller. Leonardo J. Sci., 9: 59-70.
04. Angermann, A., M. Aicher and D. Schroder, 2002. Time-optimal tension control for processing plants with continuous moving webs. Proceedings of the Conference Record of the 2000 IEEE Industry Applications Conference and Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No. 00CH37129) Vol. 5, October 8-12, 2000, IEEE, Rome, Italy, pp: 3505-3511.
05. Abutheraa, M.A. and D. Lester, 2007. Computable function representations using effective chebyshev polynomial. Proc. World Acad. Sci., 25: 103-109.
06. Subari, H., S.H. Chong, W.K. Hee, W.Y. Chong, M.R.M. Nawawi and M.N. Othman, 2015. Investigation of model parameter variation for tension control of a multi motor wire winding system. Proceedings of the 2015 10th Asian Control Conference (ASCC), May 31-June 3, 2015, IEEE, Kota Kinabalu, Malaysia, pp: 1-6
07. Shi, T., H. Liu, Q. Geng and C. Xia, 2016. Improved relative coupling control structure for multi-motor speed synchronous driving system. IET Electr. Power Appl., 10: 451-457.

08. Baumgart, M.D. and L.Y. Pao, 2004. Robust lyapunov-based feedback control of nonlinear web-winding systems. Proceedings of the 42nd IEEE International Conference on Decision and Control (IEEE Cat. No. 03CH37475), December 9-12, 2003, IEEE, Maui, USA., pp: 6398-6405.
09. Liu, G., P. Liu, Y. Shen, F. Wang and M. Kang, 2008. Experimental research on decoupling control of multi-motor variable frequency system based on neural network generalized inverse. Proceedings of the 2008 IEEE International Conference on Networking, Sensing and Control, April 6-8, 2008, IEEE, Sanya, China, pp: 1476-1479.
10. Jinmei, L., L. Xingqiao and L. Guohai, 2008. Application of an adaptive controller with a single neuron in control of multi-motor synchronous system. Proceedings of the 2008 IEEE International Conference on Industrial Technology, April 21-24, 2008, IEEE, Chengdu, China, pp: 1-6.
11. Salem, F. and E.H.E. Bayoumi, 2013. Robust fuzzy-PID control of three-motor drive system using simulated annealing optimization. J. Electr. Eng., 13: 284-292.
12. Alahakoon, S., 2000. Digital motion control techniques for electrical drives. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden.
13. Abjadi, N.R., J. Soltani, J. Askari and G.A. Markadeh, 2009. Nonlinear sliding-mode control of a multi-motor web-winding system without tension sensor. IET Control Theory Appl., 3: 419-427.
14. Koc, H., D. Knittel, M. De Mathelin and G. Abba, 2002. Modeling and robust control of winding systems for elastic webs. IEEE. Trans. Control Syst. Technol., 10: 197-208.
15. Glaoui, H., A. Hazzab, B. Bouchiba and I.K. Bousserhane, 2013. Modeling and simulation multi motors web winding system. Int. J. Adv. Comput. Sci. Appl., Vol. 4, No. 2. 10.14569/IJACSA.2013. 040217.