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THE WINDER DANCER POSITION CONTROL MODEL USING DIFFERENT PID CONTROL STRUCTURES AND MICROLOGIX PLC

UDC (681.518.52+621)

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Abstract. *In the cable industry, improper regulation of the winding speed of the conductor cable, i.e. the position of the tensioner (dancer) leads to improper stretching of the conductor, which significantly affects the characteristics of the final product. Winding speed control is directly related to tensioning which is an additional problem. This paper presents a system for control a cable winding device using a linear PID controller with and without control signal limitation. The system parameters were determined using integral time-weighted absolute error (ITAE) criteria and realized using a conventional PLC controller.*

Key words: *Winder dancer, PID controller, PLC controller, ITAE criteria*

1. INTRODUCTION

In the cable industry, the improper regulation of the winder speed or the dancer position leads to the stretching of the conductors, which significantly affects the final product's characteristics. The winder speed control is directly related to the tightening, which becomes an additional issue. The complexity of the regulation is reflected in nonlinearities that exist due to the influence of friction, stretching, sliding, variation of the moment of inertia of a drum during work, etc. Due to importance in this type of industry, such regulation problems attract the attention of many researchers.

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For the regulation of the winder speed in earlier systems, the PI regulation [1] was used mostly. Due to significant variations of parameters in the system dynamics which is reflected in the change in diameter of the winder's drum due to the accumulation of windings, the regulation using PI regulator turned out as inadequate. As an improvement, K. Reid, K. Shin and K. Lin [2, 3] proposed a method of changing amplifications in dancer's working range.

Practically all PID controllers in the industry today are based on some of PLC controller's regulation or its modified variants [4]. PLC controllers offer commands for the realization of linear PID control in the form of a monitoring error with fixed amplifications [4, 5]. As a result, it often reduces the system performance because the compromise between the exceeding value and the response speed is being made. For improving the performances of the system significantly, the non-linear controller should be used, which inevitably makes the system more complex.

2. DANCER AND WINDING SYSTEM MODEL

The winding device [6] consists of a dancer, a winder drive engine and a winder with drums (Fig. 1). The dancer is also a provider of the current position. The moving roll is connected to a position giver by the pneumatic cylinder. The signal from the position giver is brought to the regulator which generates the control signal. Basically, the simplest type of regulation is reflected in the following: The dancer position signal is sent as a reference to the regulator which accelerates or decelerates the winder drive engine depending on the position of the dancer itself. The dancer position converts to an analog signal. As a position giver, the analog output sensor, or some modern angle position sensor is used.

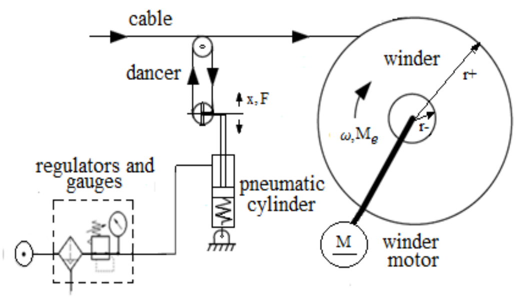

Fig. 1 Principal scheme of winder speed and line-up device step regulation

The DC engine is harnessed via a moment transmission system with a drum. The cause of the position change of the dancer is the difference between the speeds of the winder and the part of the line that delivers conductor to it.

The recording of the dancer's bouncing response is performed using KepwareEx server [7] that is set to read and write the values from the register of the N7 PLC controller, which are the signals of the dancer's position, the position set point and the control signal, respectively, into suitable fields of the base. The jumping change of the speed is achieved using the DC regulator for the winder drive engine that is started manually with the acceleration ramp of 0.1s. For the recording of the bouncing response, the dancer's starting position is set to x=0.6m. The value of the incentive signal changes for each recording. The dancer's working range is from 0 to 1.2m. Recording is performed for three different control signal values. In Fig. 2 a real dancer and model are shown.

Based on the recorded feature, the dancer model is determined. The dancer is basically NSMD [6] (*Non-linear Spring Mass Dumping*) system consisting of the upper fixed roll and a lower moving roll coupled with a pneumatic cylinder (Fig. 2). The dancer model is presented with a mass m, a damping coefficient B with the function of spring elasticity: $f(x) = k_1x_1 + k_2x_1^3$. The position of the dancer is converted to the value corresponding to the position of the dancer using the analog module of the PLC controller. Scaling commands are used to convert to engineering units. The value of 8196 corresponds to the working position (0.6m) and the value of 16000 corresponds to the lower position of the dancer (1.2m).

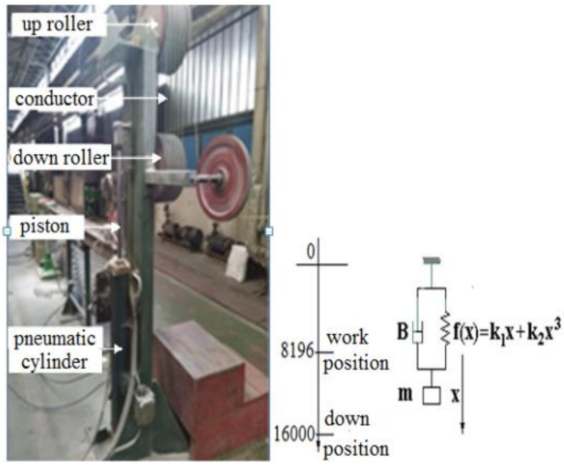

Fig. 2 A real dancer and the dancer model with a pneumatic cylinder with a spring

The parameters of the motor come from the nameplate of the engine, by the measurement of the characteristic values of the engine, doing the idling experiment and the experimentation for the determination of the moment of inertia and viscous friction coefficient.

The dancer model is given as follows:

$$\frac{d^2x}{dt^2} + f\left(x, \frac{dx}{dt}, B, k_1, k_2, r\right) = F$$
$$r \in (r^-, r^+). \tag{1}$$

The DC motor with the rotor current regulation model is given by:

$$u_a = R_a i_a + L_a \frac{di_a}{dt} + k_e \omega. \tag{2}$$

By arranging previous equations, the following relations are obtained:

$$\frac{d^2x}{dt^2} = \frac{k_m}{mr} i_a - \frac{B}{m}\frac{dx}{dt} - \frac{f(x)}{m} x, \tag{3}$$

$$\dot{i}_a = \frac{1}{L_a} u - \frac{k_e}{L_a \mathrm{r}}\frac{dx}{dt} - \frac{R_a}{L_a} i_a. \tag{4}$$

By introducing: $x_1 = \mathrm{x}$, $x_2 = \dot{x}$, $x_3 = i_a$, and by arranging, we get a system model in state space:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{k_1 x_1 + k_2 x_1^3}{m} - \frac{B}{m} x_2 + \frac{k_m}{mr} x_3 \\ \dot{x}_3 &= -\frac{k_e}{L_a \mathrm{r}} x_2 - \frac{R_a}{L_a} x_3. \end{aligned} \tag{5}$$

i.e., $x = F(x) + g(x)u$, in matrix form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} x_2 \\ -\frac{k_1 x_1 + k_2 x_1^3}{m} - \frac{B}{m} x_2 + \frac{k_m}{mr} x_3 \\ -\frac{k_e}{L_a \mathrm{r}} x_2 - \frac{R_a}{L_a} x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_a} \end{bmatrix} u \tag{6}$$

Based on Eq. (6), the winder system is drawn. In Fig. 3, the Simulink winder system is shown, with the value of the diameter (r) as a constant value.

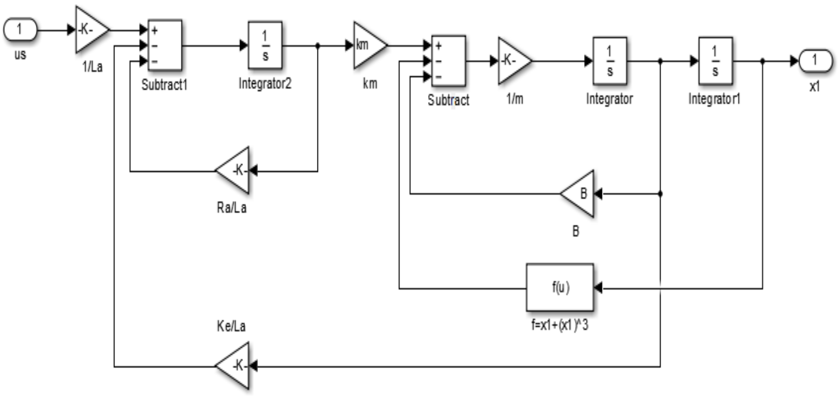

Fig. 3 Dancer and drive engine model

3. DESCRIPTION OF THE METHOD FOR ADJUSTING THE CONTROLLER PARAMETERS

Setting the controller parameters is performed using ITAE criteria. The optimal values k_p, k_i, and k_d of the PID controller are determined [7]-[10] which minimize the goal function:

$$J = \int_0^{\infty} t\left|e(t)\right| dt \ . \tag{7}$$

The integral (7) is calculated using Simpson's 1/3 rule (8) and represents the approximate solution of the integral, and in accordance with it, the program is written in Matlab. The program in Matlab as variables uses controller's parameters [11, 12]:

$$\begin{aligned} &\int_a^b f(x)dx \approx \frac{h}{3}\left(f_0 + 4\sum_{i=1}^{m} f_{2i-1} + 2\sum_{i=1}^{m-1} f_{2i} + f_{2m}\right) \\ &h = \frac{b-a}{m}. \end{aligned} \tag{8}$$

where represents *a* and *b* are the endpoints of integrations, interval of integration [a, b] split up into m sub-intervals, *m* is an even number, *h*=(*b*-*a*)/*m* is the step length, *m* is the midpoint of integration interval [a, b].

The adjustment of the linear PID regulator of the winder system is performed using Matlab and Simulink. The setting procedure consists of the following steps:

1. For a closed loop feedback system with the known transmission function, the critical gain $(k_p)_{kr}$ and cross phase frequency $(\omega_\pi)_{kr}$ are determined by using a suitably written program in Matlab,
2. For the initial values of the regulator parameters, the values for k_p, k_i, and k_d are determined by the Ziegler-Nichols rule for a closed loop system [8],
3. The values of parameters from the point 2 k_p, k_i, and k_d are used as the initial values for solving the integral (8),
4. In Simulink, the model of the process with the appropriate regulator is drawn,
5. Using the suitably written Matlab script for the integral solution (7), the toolbox optimization and Simulink system model, the optimal parameter values of the controller k_p, k_i, and k_d are determined by the criterion (8).

4. Realization of the Control System

Control was realized using control scheme with PID regulator (9), Fig. 4. and Fig. 11 with their modifications in terms of the control signal limit [13]. In Figs. 5-10, and Figs. 12-

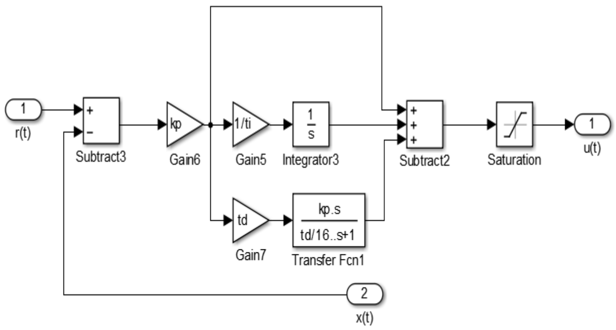

Fig. 4 Block scheme with PID control

17 the response and control signals are shown for all control scheme and their modifications, respectively.

PID regulator per error signal, with a limited output and a positively limited output is described with Eqs. (9)-(11):

$$u = u_s = k_p e + k_i \int e dt + k_d \frac{de}{dt}. \tag{9}$$

$$u = \begin{cases} +\mathrm{u}_{\mathrm{smax}}, & \mathrm{u} > u_{\mathrm{smax}} \\ k_p e + k_i \int e dt + k_d \frac{de}{dt}, & -\mathrm{u}_{\mathrm{smax}} \le \mathrm{u} \le +u_{\mathrm{smax}} \\ -\mathrm{u}_{\mathrm{smax}}, & \mathrm{u} < u_{\mathrm{smax}} \end{cases} \tag{10}$$

$$u = \begin{cases} +\mathrm{u}_{\mathrm{smax}}, & \mathrm{u} > u_{\mathrm{smax}} \\ k_p e + k_i \int e dt + k_d \frac{de}{dt}, & 0 \le \mathrm{u} \le +u_{\mathrm{smax}} \\ 0, & \mathrm{u} < 0 \end{cases} \tag{11}$$

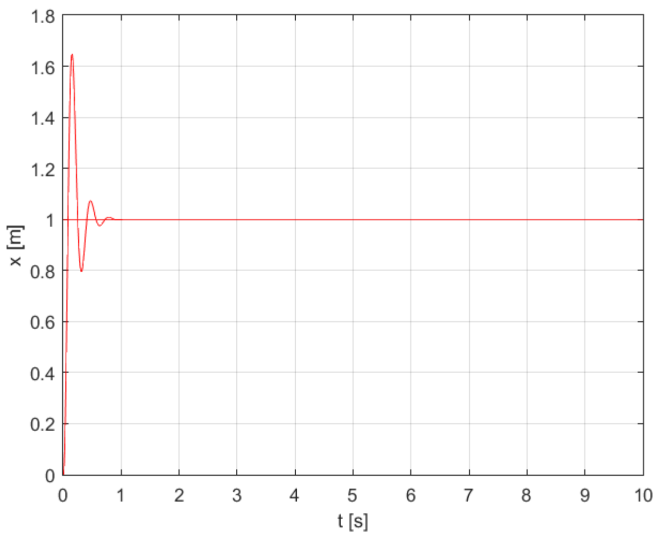

Fig. 5 Current dancer position characteristic for PID regulation per error signal according to (9)

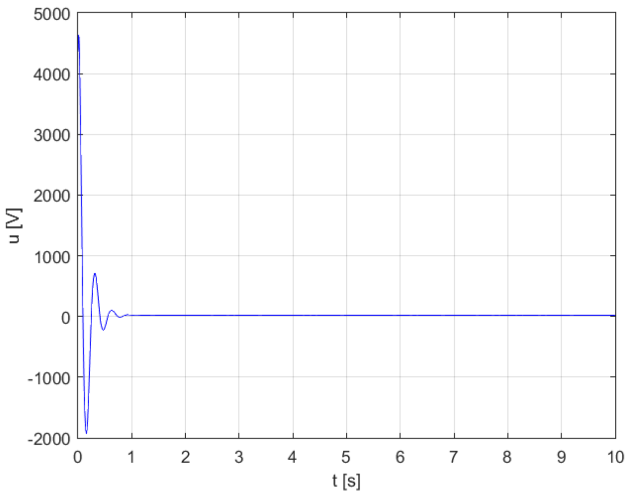

Fig. 6 Control signal characteristic for PID regulation per error signal according to (9)

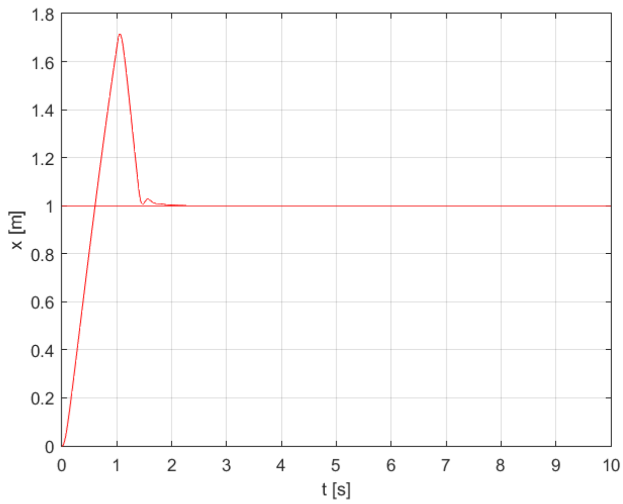

Fig. 7 Current dancer position characteristic for PID regulation per error signal with the control signal limitation on both sides (-m, +m) according to (10)

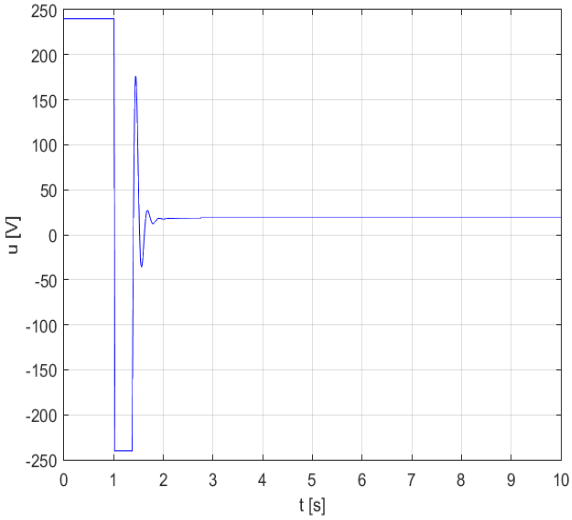

Fig. 8 Control signal characteristic for PID regulation per error signal with the control signal limitation on both sides (-m, +m) according to (10)

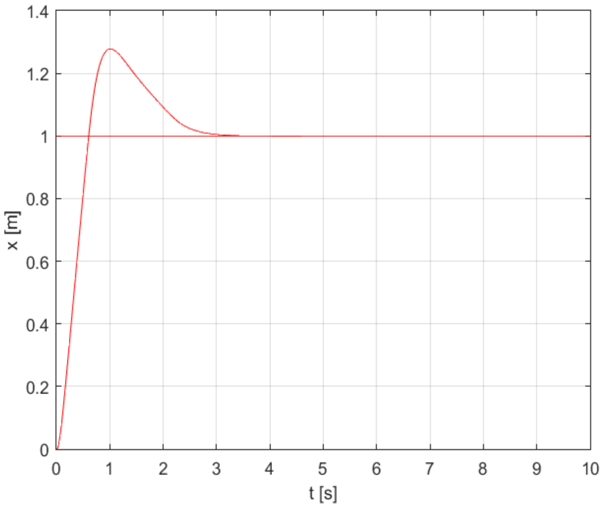

Fig. 9 Current dancer position characteristic for PID regulation per error signal with the control signal limitation on both sides (0, +m) according to (11)

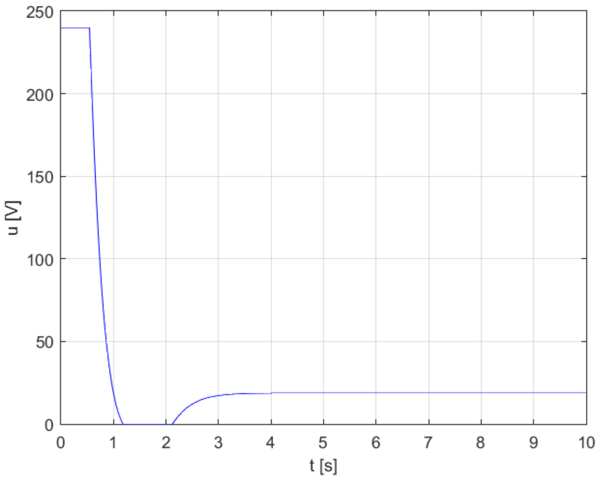

Fig. 10 Control signal characteristic for PID regulation per error signal with the control signal limitation on both sides (0, +m) according to (11)

PID with differential effect per the controlled variable, with a limited output and a positively limited output of Eqs. (12)-(14):

$$u = u_{s1} = k_p e + k_i \int edt + k_d \frac{dx}{dt} . \tag{12}$$

$$u = \begin{cases} +\mathrm{u}_{s1\max}, & \mathrm{u} > u_{s1\max} \\ k_p e + k_i \int edt + k_d \frac{dx}{dt}, & -\mathrm{u}_{s1\max} \le \mathrm{u} \le +u_{s1\max} \\ -\mathrm{u}_{s1\max}, & \mathrm{u} < u_{s1\max} \end{cases} \tag{13}$$

$$u = \begin{cases} +\mathrm{u}_{s1\max}, & \mathrm{u} > u_{s1\max} \\ k_p e + k_i \int edt + k_d \frac{dx}{dt}, & 0 \le \mathrm{u} \le +u_{s1\max} \\ 0, & \mathrm{u} < 0 \end{cases} \tag{14}$$

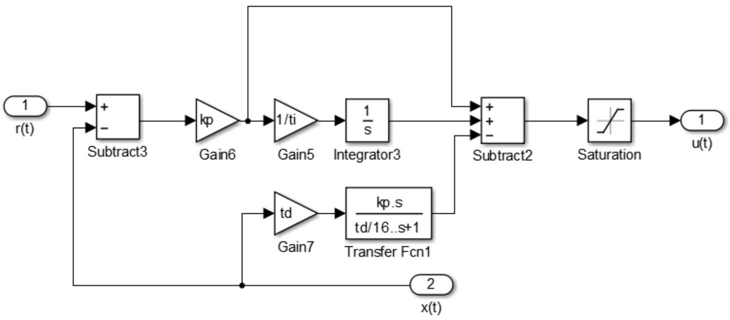

Fig. 11 PID with differential effect per position

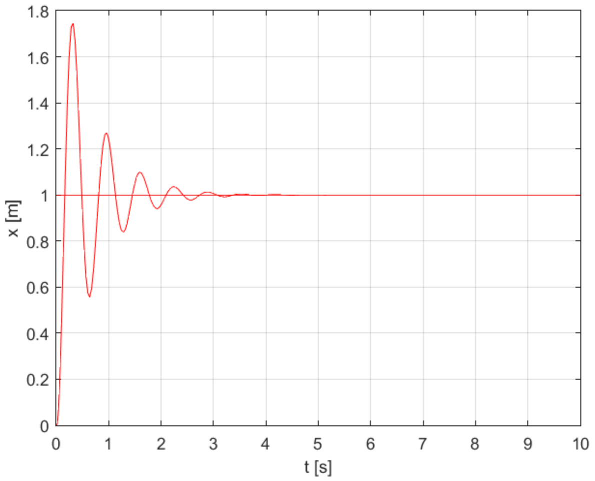

Fig. 12 Current dancer position characteristic for PID regulation with differential effect per position according to (12)

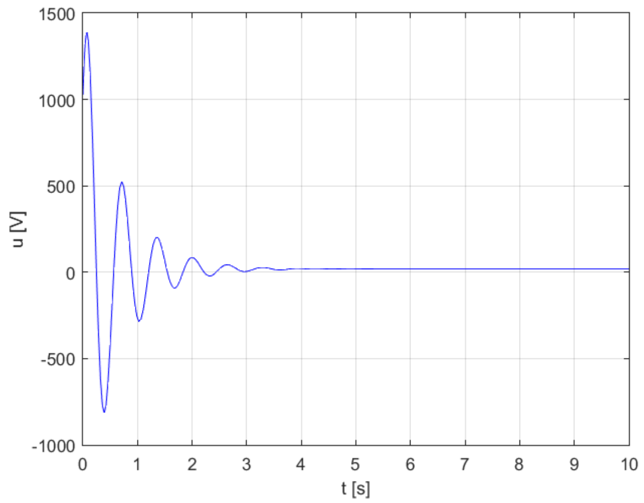

Fig. 13 Control signal characteristic for PID regulation with differential effect per position according to (12)

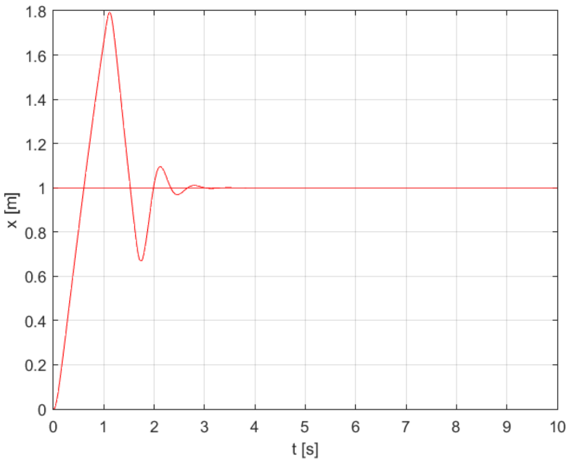

Fig. 14 Current dancer position characteristic for PID regulation with differential effect per position with the control signal limitation on both sides (-m, +m) according to (13)

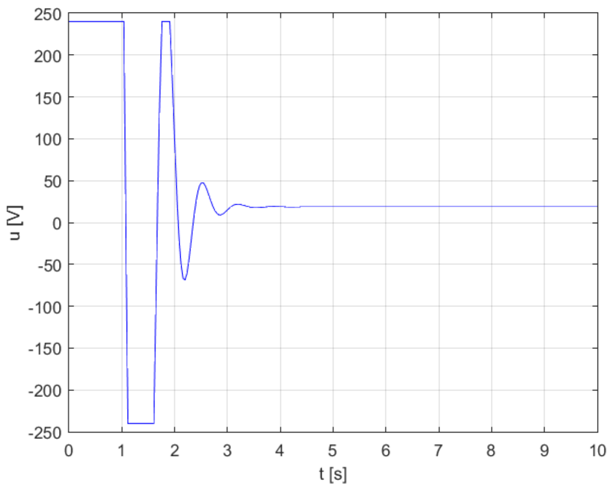

Fig. 15 Control signal characteristic for PID regulation with differential effect per position with the control signal limitation on both sides (-m, +m) according to (13)

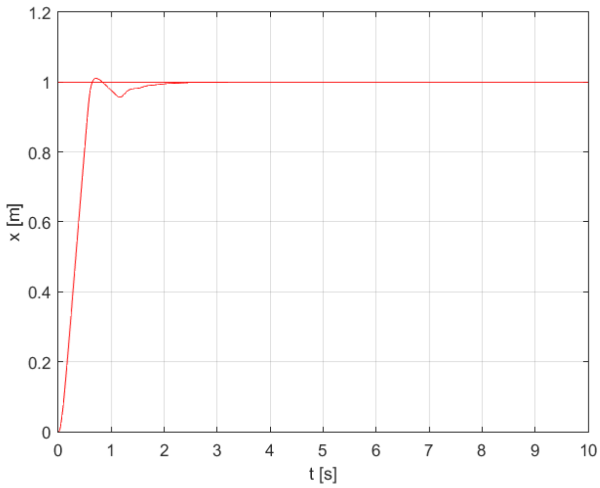

Fig. 16 Current dancer position characteristic for PID regulation with the differential effect per position with control signal limitation on both sides (0, +m) according to (14)

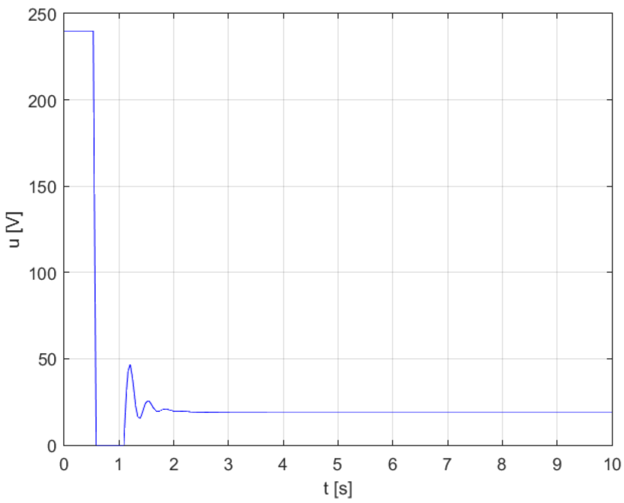

Fig. 17 Control signal characteristic for PID regulation with differential effect per position with control signal limitation on both sides (0, +m) according to (14)

5. DESCRIPTION OF HARDWARE AND SOFTWARE SOLUTIONS

To manage the process of winding the conductors on coils and drums uses, as a regulator, PLC Micrologix 1400 with SimoreG DC Master controller type 6RA7025 [5] for the drive of the engine [14]-[16]. The current dancer position is turned into a voltage signal by a 10 KΩ potentiometer. The control signal from PID command of the PLC controller is sent to the analog input of the DC engine regulator, which regulates the speed of the drum on the winder and thus the position of the dancer.

The PID controller was realized using the Micrologix 1400 PLC's PID command with the following equation [14]:

$$u(t) = k_p \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{dc(t)}{dt} \right] + bias \,, \tag{18}$$

where: $u(t)$ - control signal, $e(t)$ - error signal, $c(t)$ - size management, k_p - proportional coefficient, T_i - integral time constant, T_d - differential time constant, *bias* - value to compensate the impact of interference on the controlled variable.

The transfer function of the differential action of Eq. (18) was realized using a low-pass filter whose transfer function is given by equation:

$$G_d(s) = \frac{sT_d}{1 + s\dfrac{T_d}{N}} \,. \tag{19}$$

Parameter N defines the measure of the influence of the low-pass differential action filter. The value of parameter N of the Micrologix series of PLC controllers is set to N = 16. The manufacturer of the PLC controller does not provide any other data regarding the value for N and the methods for discretization of the PID control law (18) [11].

The PID is set to operate on an error signal (bit DA = 1). The Fig. 19 shows the PID command of the PLC controller with differential effect per position with the control signal limitation in the range of 0-10V which is suitable for the voltage of the engine's armature of 0-240V.

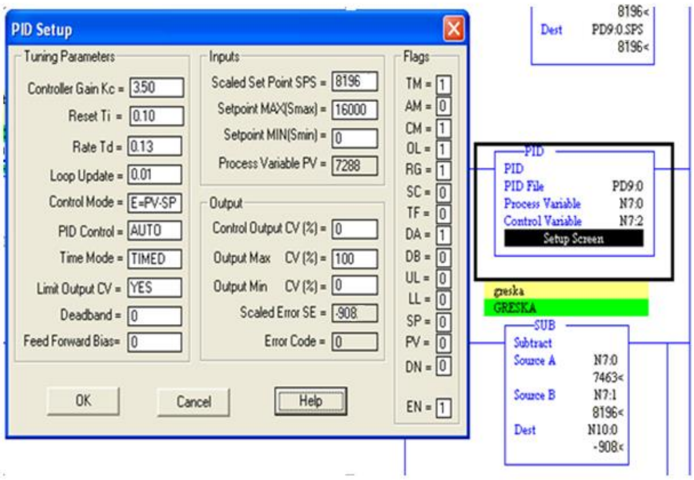

Fig. 19 PID command of the PLC controller

6. Experimental Results

The Fig. 20 shows the PID controller control signal values and the difference between the setpoint and actual position for the dancer performed in the lower end position values of PLC memory register.

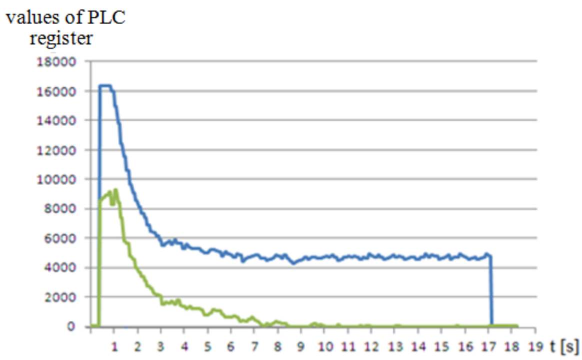

Fig. 20 Control signal (blue) characteristic and the difference between the setpoint and the actual dancer position (green) when the dancer positioning in lower position (16384 units = 10V, x=0,6m or 8192 units)

The Fig. 21 shows the values of the control signal of the PID regulator and the difference between the setpoint and the actual dancer position performed in the middle of the setpoint and lower position.

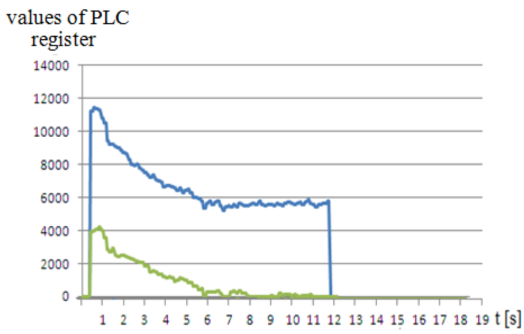

Fig. 21 Control signal (blue) characteristic and the difference between the setpoint and the actual (green) when the dancer positioning in the middle of the setpoint and lower position (16384 units = 10V, x=0,6m or 8192 units)

Figures 22 and 23 show the values of the control signal, the setpoint and actual values of the position for the dancer in the event of a random disturbance. The accidental disturbance was performed by intentionally stopping and starting the part of the line that delivers the cable to the dancer and the winder.

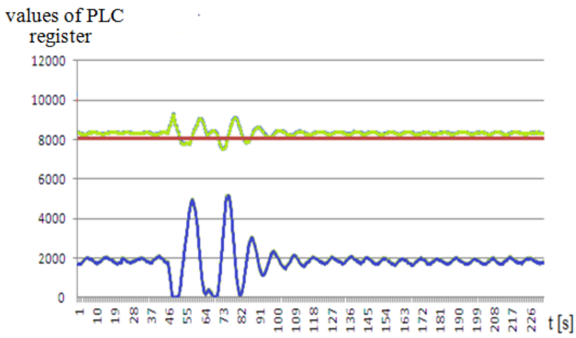

Fig. 22 Characteristics of the control signal (blue), setpoint (red) and actual values of the position (green) for the dancer in the event of an accidental disturbance (16384 units = 10V, x=0,6m or 8192 units)

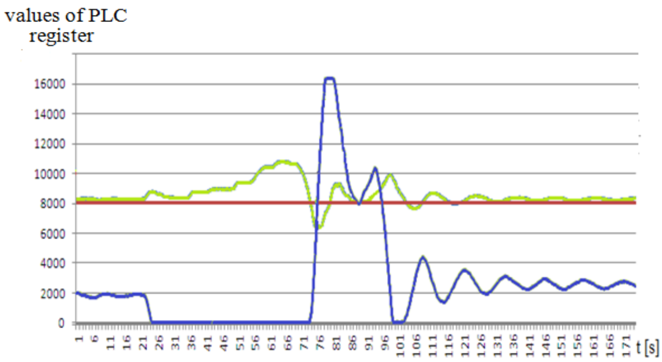

Fig. 23 Characteristics of the control signal (blue), setpoint (red) and actual values of the position (green) for the dancer in the event of an accidental disturbance (16384 units = 10V, x=0,6m or 8192 units)

7. Conclusion

The main problem in regulating the winder speed or current dancer's position in industrial conditions arises due to the limit of resource restricting the quality regulation. As the high accuracy of the regulation is not an absolute imperative, some PLC controllers of reputable manufacturers are used for the PID regulation. The proposed method for regulating the current position of the winder's dancer for PID with differential effect per position signal gives satisfying results.

Appendix

The Table 1 contains DC motor's parameters, the Table 2 gives dancer model's parameters.

Table 1 Parameters of the DC motor

P	5 HP
R_a	2.581 Ω
L_a	0.0281 H
V_a	240 V
R_f	281.3 Ω
L_f	156 mH
V_f	300 V
J_m	0.0221 kgm^2
B_m	0.002953 Nms
K_e	1.25 Vs/rad
K_m	0.516 Nm/A
n	1750 rpm

Table 2 Parameters of the dancer's model

m	1.4 kg
B	17.789 Ns/cm
k_1	1.5 N/cm
k_2	1.172 N/cm^3

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