Efficiency of a PLC-based PI controller in stabilization of a rotational motion affected by the chaotic disturbances

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Abstract: The popularity of programmable logic controllers (PLC), a large variety of standardized models and its programming methods are associated with the continuously growing experimental and industrial demands. These CPU-based units for logical operations can be successfully used to implement many algorithms that control linear and nonlinear dynamical states of real objects or physical phenomena. Control of rotational or linear periodic displacements generated by DC motors plays an important role in this field. In the analyzed self-excited dynamical system with two degrees-of-freedom and dry friction, one of the state variables becomes chaotic. This causes an irregular forcing of a frictional contact leading to destabilization of the discontinuous effect of a periodic stick-slip vibrations. In addition, as a result of existence of the irregularities, the precision of a dry friction model becomes uncertain. Stabilization of the motor speed requires to use a controller that would guarantee robustness of the control system maintaining the desired speed at a constant value. A method of programming of the selected FATEK PLC FBs-MC24T have been described, as well as basic PI algorithm of control applied.

1. Introduction

Programmable logic controllers carry out many instructions related to the user's program to be solved, hundreds points of I/O status to be updated, a few communication ports needed to be serviced, and other. In comparison with human responses, PLCs almost complete all instructions at the same time. Hence, they can meet the enumerated requirements of the most practical control tasks. This advantage has been extensively utilized in many fields of science. Some applications connected with experimental investigations performed in this work are described below.

Speed control of a separately excited DC motor using a PLC was taken into consideration in [4]. A variable DC voltage is provided to the armature circuit of the motor from a fixed DC voltage supply via the PLC, which acts as a DC-DC chopper. Pang-Pang control has been applied for *on*/*off* power switching to the DC motor depending on the reference speed.

dc-voltage supply via the PLC, which acts as a *dc*-*dc* chopper. Pang-Pang control has been applied for *on* or *off* power switching to the *dc*-motor depending on the reference speed. The approach is easy in application, fast and effective to control the speed from 0 to 100% of the the range. The proposed system is suitable for different industrial applications such as subway cars, trolley buses, or battery-operated vehicles.

The purpose of the study [14] was to analyze and implement PI control for the permanent magnet *dc*-motor. The control algorithm is realized using Siemens S7-200 PLC supplemented by EM235 analog input/output module. The complex motor system is composed of a *dc*-motor, driver and tachogenerator. The main objective was to achieve a satisfactory time response of the system output under disturbances like death zone, nonlinearity, measurement noise and external load acting. The PI controller is designed in the programming environment on a previously identified nonlinear motor system. Then the PI controller was embedded into the PLC taken into the control. The effectiveness of the control is tested in both numerical simulation and experiments.

Monitoring and control system for the induction motor based on a PLC technology was implemented in [6]. In the presented strategy the PLC correlates the operational parameters to the speed requested by the user and monitors the system during normal operation and under trip conditions. Tests of the induction motor system driven by an inverter and controlled by PLC proved a higher accuracy in speed regulation in comparison to the conventional V/f (voltage over frequency ratio) control system. The efficiency of PLC control increased at high speeds up to 95% of the synchronous speed. Thus, PLC proved themselves as a very versatile and effective tool in industrial control of electric drives.

In this reference [11], a method to develop and design a fuzzy-hybrid control on an industrial controller to control speed of an induction motor and implementing a constant V/f ratio control was developed. Detailed discussions on the controller for a PWM-driven induction motor drive system, the system identification for the model transfer function, and the analysis on output responses and the associated manipulated variables have been presented. The control objective was to provide an effective control action to sudden changes in reference speed and/or load torque. A switching type controller consisting of two control modes was devised: a PID-type fuzzy controller consisting of a PI-type and a PD-type fuzzy controller, and a conventional PID. At the early phase of the control action, the control task is handled by the PID-type fuzzy controller. At a later phase when the absolute of error is less than a threshold value, the input of integrator at the output side is no longer given by fuzzy action but fed by the incremental PID action. In term of control action, this is an enhanced proportional and derivative action when the actual value is closed to the reference value. Detailed evaluations of the controller's performance based on preliminary defined performance indices under several conditions were presented. The findings demonstrated the ability of the approach to provide a viable control solution in response to the different operating conditions and requirements.

In [10] modeling, simulation and PWM control of an electromechanical actuator (EMA) system for aerofin control (AFC) with permanent magnet (PM) brush *dc*-motor driven by a constant current driver are investigated. Nonlinear model of the EMA-AFC system has been developed and experimentally verified in actuator test bench. Model has been used as the starting point for PID position controller synthesis. To improve performances of the system, computational intelligence has been applied. Genetic PID optimization, genetic algorithm (GA) optimized fuzzy supervisory PID control and finally GA optimized nonlinear PID algorithm modification were proposed. Improved transient response and system behavior have also been experimentally validated.

Iterative feedback tuning (IFT) was used in [7] to tune the cascade speed and position controller of a PM servo drive. Several variants of experimentally obtained criteria for the test bed were analyzed. The results of the IFT controller, which was easily implemented on a programmable logic controller (PLC), were compared with the results of three tuning schemes commonly used in the industry. Experimental tests on the PM *dc*-motor with different types of load shown that IFT performance in transient conditions is as good as or better than other methods. The closed-loop transient responses to a step change were better than those of conventional position and speed controllers. The model-independent IFT controller tuning strategy can be easily incorporated in existing control loops.

PLC has proven its capability in handling fuzzy algorithms, see for instance [10, 11]. In the study [1], a fuzzy logic evaluation was simulated using a PLC oriented procedure shown in [11]. Implementation and analysis of a PLC-based self-tuning PI-fuzzy controller for linear and non-linear drives control were taken into consideration. The controller consisted of two fuzzy logic blocks responsible for main and gain tuning, respectively. The main fuzzy block acts as a speed controller, while the gain tuning block scales the output of main fuzzy. The output gain tuning has the same inputs as main fuzzy (i.e. speed error and change of error). By introducing output gain tuning, overshoot and settling time can be restrained. The objective of the controller was to provide stability, to reduce overshoot in responds to disturbance and sudden change in reference speed. The performance of this strategy has been proved. It was compared in a numerical simulation and while carrying out an experiment with conventional PI-fuzzy controller.

This paper [13] presents the control of induction motor via PROFINET network including a remote control using the OLE for Process Control (OPC) standard. This system was composed of an induction *dc*-motor, encoder, frequency converter, PLC and two PCs representing the hardware client-server connection. The motor control was PLC-based with PID controller, while PCs are used as human machine interface devices (HMI) for controlling and supervising the plant. PC which was representing the OPC server was connected with a PLC via Ethernet network, while connection between frequency converter and PLC was established via PROFIBUS DP protocol. Two PCs are connected using OPC standard, where physical connection between them is achieved using local area network (LAN). The obtained experimental results demonstrate a possibility to establish local and remote control over the analyzed system while ensuring its stability and efficiency.

A predictive control (MPC) algorithm with constraint handling capabilities has been embedded into Allen Bradley PLC (SCL500 processor family) and described in [12]. In order to achieve it, some parametric approaches to the MPC but differing from more conventional approaches in that it preliminary defines the complexity of the solution rather than the allowable suboptimality have been developed. The paper proposed a novel parameterization of the parametric regions which allows efficiency of definition, effective spanning of the feasible region and also highly efficient search algorithms. Despite the suboptimality, the algorithm retained guaranteed stability, in the nominal case. A laboratory test was carried out to demonstrate the code on real hardware and the effectiveness of the solution.

There are many industrial applications of the presented strategies of control based on the PLCs. Let us only mention about [5, 9].

According to the accurately synchronous technical requirement of fiber spinning multi-motor system, a fuzzy PID control method established on the basis of deviation compensation principle was applied in [5]. In a master-slave control strategy the system involved programming and debugging by using SIMENS s7-200PLC, as well as designing the deviation compensation controller in the PLC. PROFIBUS technology was applied to realize communication in the multi-motor drive system. Experimental results have been obtained while comparing the fuzzy PID control method and the traditional PID. Excellent performance of the proposed intelligent PID control have been demonstrated.

Fiber winding tension is an important factor in the molding techniques of composite materials [9]. The tension influences the quality of winding product directly, and its control is a key technique in fiber winding techniques. There has been introduced a closed-loop tension control system with the Panasonic FP-series PLC (denoted as FP0-C10RS, including a 12-bit FP0-A80 and an FP0-A04V auxiliary conversion module) with function modules as its control kernel, the alternating current (AC) digital servo driver and servo motor as the executing element and the radius-following device to accomplish the real-time radius compensation. The mechanism of the tension control system was analyzed and the numerical model was set up. Correctness of the compensation technique of the radius of the scroll was proved by experimental results. The system was well qualified with high control precision and high reaction speed.

2. The analysed dynamical model

The study and prevention of self-excited vibration of systems with friction is very important in industry and there is a need of friction pair modelling that could correctly describe dynamic and static friction forces change between two moveable surfaces [2].

The self-excited system presented in Fig. 1 is almost equivalent to a real experimental rig in which block mass m is moving on the belt in x_1 direction, and where the angle body represented by moment mass of inertia J is rotating around point s with respect to direction of angle φ. The analysed system consists of the following parts: two bodies are coupled by linear springs k_2 and k_3; block on the belt is additionally coupled to fixed base using linear spring k_1; angle body is excited only by spring forces; there is not extra mechanical actuators; rotational motion of the angle body is damped using virtual actuators characterizing air resistance and they are marked by constants c_1 and c_2; damping of the block is neglected; it is assumed that angle of rotation φ of the angle body is small and it is within interval $[0.09, -0.09]$ rad (in this case a rotation is equivalent to linear displacement y of legs a of the angle body); belt is moving with constant velocity v_p and there is not deformation of the belt in a contact zone.

We consider a discontinuous dynamical system with dry friction shown in Fig. 1. System of four first-order ordinary differential equations takes the form

$$\begin{aligned}
&\dot{x}_1 = x_2\,,\\
&\dot{x}_2 = -x_1 - \xi_1\left(\xi_2(x_2 + x_4) - x_3 - T(v)\right)\,,\\
&\dot{x}_3 = x_4\,,\\
&\dot{x}_4 = \xi_3(-x_1 - \xi_2 x_2 - \xi_4 x_3 - \xi_5 x_4)\,.
\end{aligned} \tag{1}$$

In Eq. (1) the state vector $\bar{x} = [x_1, x_2, x_3, x_4] \in \mathbb{R}^4$, relative velocity of contacting surfaces $v = x_2 - v_p$, and the constant parameters $\xi_1 = k_2/(\omega^2 m)$, $\xi_2 = c_1\omega/k_2$, $\xi_3 = k_2 r^2/(\omega^2 J)$, $\xi_4 = (k_2 + k_3)/k_2$, $\xi_5 = \omega(c_1 + c_2)/k_2$, $\xi_6 = \mu_0 k_3/k_2$, $\xi_7 = \omega c_2 \mu_0/k_2$, $\omega = \sqrt{(k_1 + k_2)/m}$, $J = m(a^2 + b^2)/3$ are assumed. The term $y = 1 - \xi_6 x_3 - \xi_7 x_4$ includes also the additional normal force subject to the mass m from the displacement of the bracket's end, and it has to be regarded to in the friction force model

$$\begin{aligned}
&|T(v)| \leq y\mu_0, && \text{for } v = 0\,,\\
&T(v) = \operatorname{sgn}(v) y \mu_k(v), && \text{for } v \neq 0\,,
\end{aligned} \tag{2}$$

where μ_k is expressed by

$$\mu_k(v) = \frac{\mu_0}{1 + \delta|v|} \,. \tag{3}$$

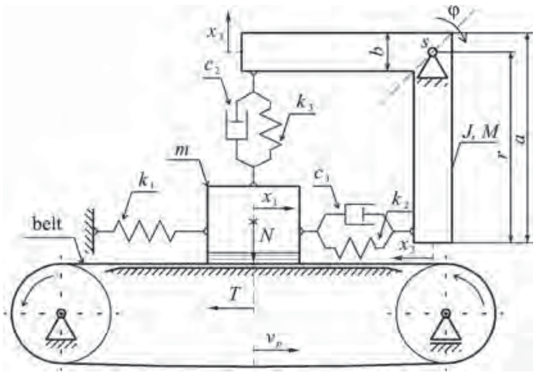

Figure 1. The two degree-of-freedom mechanical system

The self-excited system presented in Fig. 1 is equivalent to a real experimental rig (see [3]), where block mass m moves on the belt in x_1 direction, and the bracket characterized by moment mass of inertia J rotates about point s with respect to angle φ. Two bodies are coupled by linear springs k_2, k_3 and dampers c_1, c_2. The block on the moving belt is additionally attached to a fixed wall by means of a linear spring k_1. One assumes that angle of rotation of the second body (the bracket) is small, therefore $\sin(\varphi) \approx \varphi \approx y/r$ is assumed.

It has been shown in [3, 8], that the system's dynamics is irregular. It exhibits periodic, quasi-periodic and chaotic changes of the normal force acting in the frictional contact between the belt and the vibrating body. The force depends on the displacement y of the angle body's arm (see Fig. 1) and significantly influences motion of the moving belt. An estimation of the kinetic friction force model requires to have the velocity of the moving base as constant as possible. In addition, as a result of existence of the irregularities, the precision of a dry friction model becomes uncertain. Stabilization of the motor speed requires to use a controller that would guarantee robustness of the control system maintaining the desired speed at a constant value. Therefore, a PLC-based control system described in the next sections have been developed.

3. The experimental stand

Figure 2 presents the laboratory station on which the experiments have been carried out. Regulation of the angular velocity of the *dc*-motor (3) is made by the system of the PLC (1) and the RN12 driver (2). Characteristic parameters of the PWM wave driver input are as follows: frequency $f_p = 20$ [kHz], amplitude $U_p = 15$ [V]. An auxiliary electronic circuit (6) shown in Fig. 3 is designed in a way to form the amplitude U_p and switching frequency of the modulated signal taken as input by the motor driver. The circuit consists mainly of three high density mounting type optocouplers PC817A (typical response time $t_r = 4$ [μs] at $V_{CE} = 2$ [V]) included in a LTV-847 integrated circuit and resistors reducing current to the levels required by the integrated circuit and the PLC inputs. Together with the incremental encoder (4) it closes the control loop of the designed control system. Proportional-Integral (PI) regulator has been implemented on the PLC (1) by means of the ladder diagram shown in Fig. 4 controlling the PWM duty cycle.

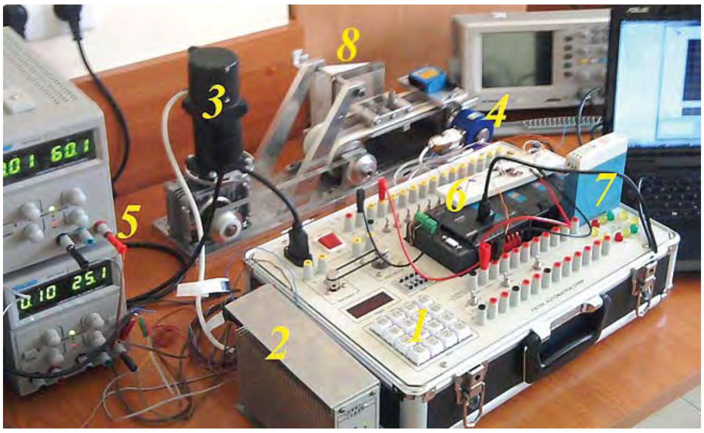

Figure 2. Picture of the experimental stand: 1 - a PLC by FATEK in the FBs-MC24T training box, 2 - RN12 *dc*-motor driver, 3 - the *dc*-motor PZTK 62-42 J, 4 - IVO GI333 incremental encoder, 5 - MATRIX 60V and 30V regulated power apliflers, 6 - an electronic circuit to form the PWM signal, 7 - voltage source for the electronic circuit, 8 - the physical object under control

The PLC has inputs of the SINK IN type, which are sources of +24 [V]. Opposite situation occurs in the RN12 dedicated driver. It receives a PWM signal of amplitude 12-15 [V], but in the PLC the outputs are of SINK OUT type being the outflows for the current. A problem of connection of that two units has been solved by the electronic circuit shown in Fig. 3. In the LTV-847 based circuit a high state generated by the encoder causes the flow of current through the photodiode on input U1. Thanks to that the corresponding transistor switches into the conduction state and couples PLC'c input X1 with its ground GND. Such realisation at a frequency dependent on the velocity of the belt drive changes the input into the high states allowing measurement of actual rotational velocity in time T_i [ms]. In Fig. 4

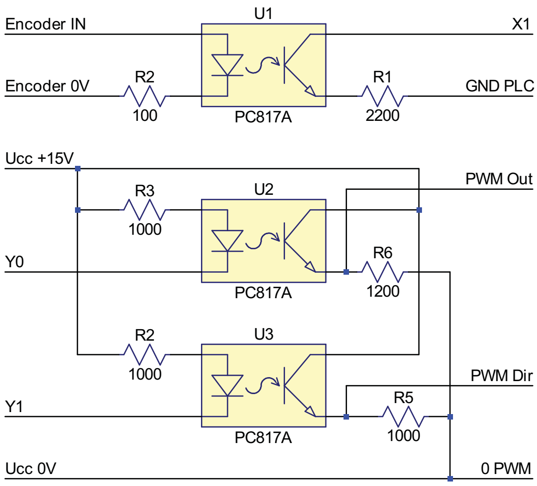

Figure 3. The electronic circuit to form the PWM signal

it corresponds to the function "83.SPD" and the two subsequent functions "13.(*)", "14.(/)" calculating the velocity by the formula $N = R0 \cdot /(n \cdot T_i) \cdot 10^3$ [rpm], the register R0 stores the number of impulses being counted on the X0 input. The fourth function on the ladder has been used to transform the velocity into the format that is acceptable by the "30.PID" function. The register R4 has been multiplied by $237 \approx 16383/69$ and the result stored in the R12 register. Function "30.PID" is suitable to cooperate in the range 0-16383, that is relative to the minimum and maximum number of readings from the measuring sensor. The highest measured velocity was 69 rpm.

The next function "30.PID" states the basic PID controller on which the reduced PI controller has been built. Its parameters follow: $T_s = 10^{-2}$ [s] the time of algorithms execution, SR - number [n] of the first register containing settings of the PID algorithm, PR - number [n] of the first register containing parameters of the algorithm, WR - first operating register, OR - the register storing the controller's output. The value stored in OR will be in the range 0-16383. To transform it on the PWM duty cycle's value included in the required range the function "33.LCNV" has been applied. From a linear transformation the function "33.LCNV" computes the an output included in the range from 0 to 100%. The PWM duty cycle is finally stored in the register R31.

4. PI control of a belt drive system

A general schematic view of the control system is visible in Fig. 5. The reference angular velocity of the belt drive should be maintained at constant value. Without any control the velocity significantly varies because of the high stiffness of the belt and the frictional contact described in Section 3, that causes irregular forcing of the belt drive. Applying the described PI control with parameters $P = 3000$ and $I = 8000$ the rotational velocity is stabilized much better. Results have been shown in Fig. 6 and 7.

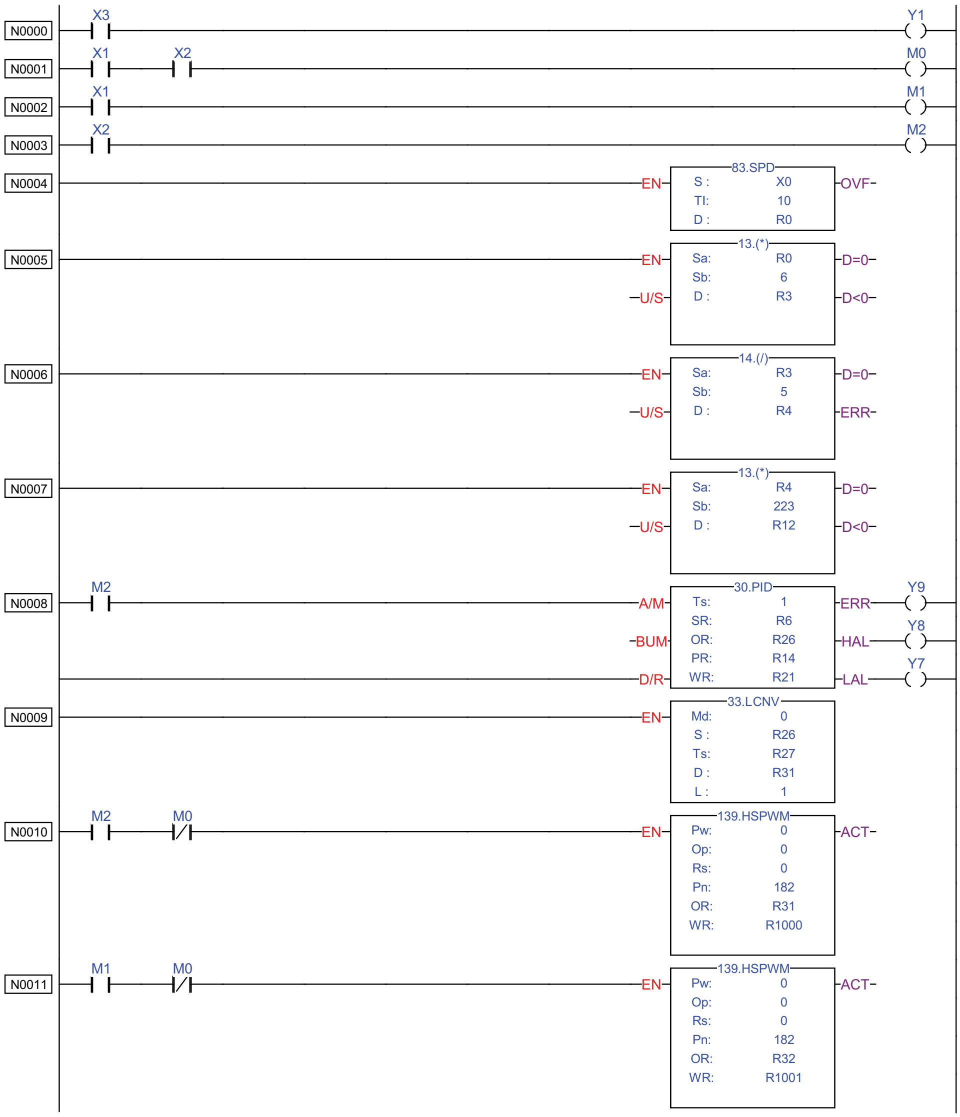

Figure 4. FATEK ladder diagram controling the PWM duty cycle in the PI control

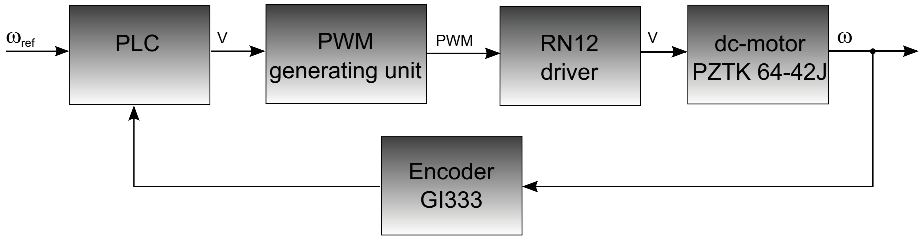

Figure 5. A schematic diagram of the control system

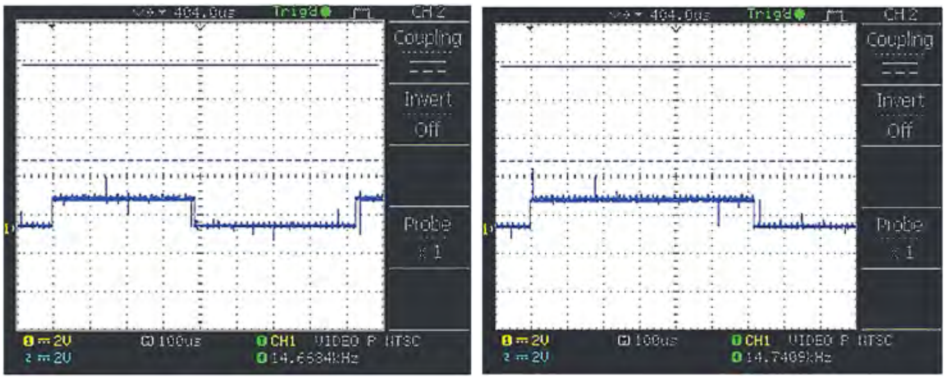

Figure 6. The minimum and maximum pulse width in the non-controlled velocity speed

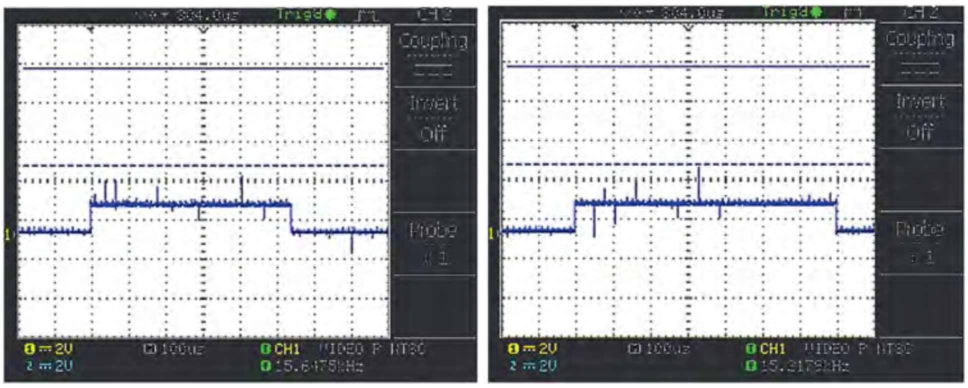

Figure 7. The minimum and maximum pulse width in the PI-controlled velocity speed

5. Conclusions

A first attempt of programming of the selected PLC controller has been described, as well as a basic PI algorithm of realizing the PWM control applied. As the literature overview presents, the PWM control is not so popular, therefore the approach applied in this work becomes very interesting. The obtained results are promising showing better response of the controlled system subject to chaotic disturbances of the driving system caused by the discontinuous stick-slip vibrations. In comparison to the PI-controlled belt-drive system, the non-controlled one was not capable to maintain the velocity at a sudden appearance of the external moment of force. The PLC controller is not programmed so intuitively as one could expect, but the aim of the work has been achieved. Presently, there are conducted some experiments to regulate the velocity at very low levels and at much higher frequencies of the PWM wave (in this work it was performed only at 1 [kHz]) - up to the maximum acceptable by the RN12 motor driver. Testing of improved and more accurate control will be done by realisation of known and repeatable moment of force applied directly to the belt.

Acknowledgements

The authors have been supported by the National Center of Science under the grant MAESTRO 2, No. 2012/04/A/ ST8/00738 for years 2012-2015 (Poland).

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