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Control System of the Continuous Extrusion Line Using PLC and Conventional Regulators

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Abstract— **This paper presents the functional characteristics of the line parameters based on the developed control software for speed, tension, regulation of traverse device for proper arrangement of the material on drum and temperature regulation. Speed and tension regulation is performed using the PLC controller S7 1500 series and conventional converters and inverters of the Sinamics DCM and G120 series. A control method was used where one device is the leader and all the others follow its speed with a given ratio and tensile control. Setting the parameters of conventional converters and inverters for controlling multi-motor drives was realized using the StartDrive tool. The temperature control of the extruder zones was done taking into account the mutual influence of the zones. Control and monitoring are implemented with software written in TIA Portal V15.1. software package.**

Keywords-component; multi-motor line; speed; tensile force; S7 1500 PLC controller; Sinamics DCM convertor; Sinamics G120 frequency converter; cascade regulation; PID 2 DOF

I. INTRODUCTION

Continuous lines are driven by individual drives coupled (connected) by the material processed on them. The material with which the devices are coupled usually behaves like an elastic coupling, where nonlinearities occur due to the influence of friction, the variable moment of inertia of the device due to changes in velocity during acceleration, deceleration, and changes in diameter during unwinding and winding. The fundamental problem to be solved is to control the speed of each line drive while maintaining a constant tensile force within the specified limits. The literature [1]-[4] explains the physical phenomena that occur due to the variation of the traction force on continuous line, as well as the control algorithms. The speed regulation and the maintenance of the traction force in operation are performed by combined control methods with a position sensor, whose signal is proportional to the tensile force [5]-[7] (dancer system) and a method of indirect control of the tensile force [8]-[9].

In this paper, the control software was implemented, which successfully replaces prefabricated solutions [10]-[11]. The aim of the work is not the modeling and detailed analysis of the system, but the description of the phenomena and the presentation of the obtained results on a real continuous extrusion line and similar processes.

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II. DESCRIPTIONS OF PROCESS

A simplified diagram of a continuous multi-motor line with a traction device is shown in Fig. 1. The material to be processed is unwound from the unwinder device, pulled by a traction device, and wound up onto the winder device. The unwinder device and the winder device are of the central type . The line consists of two tension zones, in which it is possible to set different tensile forces. Zone I consists of an unwinder device and a dancer, and zone II consists of a tension device and a winder device. The zones and the equipment within them are physically connected by the material being processed on them. The extruders are located between Zone I and II [12]. The insulation layer applied to the material has a constant thickness, provided that the line speed and tension force are maintained. By measuring the thickness of the insulation, the quality of the speed control is checked. The unwinder and winder devices consist of drive motors, reduction gears and drums with a core. The drum is clamped on both sides and is driven by the central shaft. The winder device has an additional motor with a reduction gear that is connected to the mechanism of the traverse device which serves for the proper arrangement of the material on the drum during the winding operation.

The dancer consists of fixed and movable rollers (wheels), a travel compensation system and a position sensor for the lower movable rollers. The signal from the transmitter is fed into the PLC (Programmable Logic Controller). The dancer receives the speed change and compensates for it.

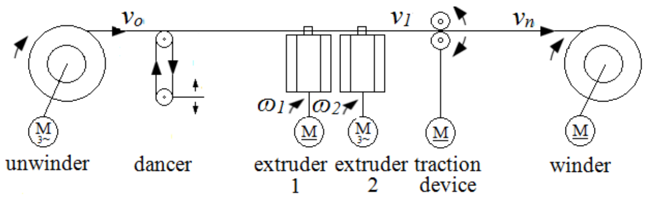

Figure 1. Principle diagram of a continuous multi-motor line

The cause of the change in position is the difference in the speed of the line in front of and behind the dancer. The traction device consists of a motor, a reduction gear, a gearbox and rollers (caterpillars) that drive the material to be processed. Its task is to maintain the set speed of the line as accurately as possible. Since it must also maintain the zero speed of the line, his drive torque is not limited. Extruders operate in the speed mode, with a change in line speed, the speed of rotation of the extruder screws of changes according to the given ratio.

The winder device operates in the mode of indirect regulation of the tensile force [13], it is supplemented by a block for calculating the current value of the drum diameter, a block for adaptation the parameters of the speed controller and a block for compensating the moment of inertia that occurs during acceleration and deceleration of the line and the change of the diameter. Fig. 2 shows the block diagram of the connection of PLC controller, converter and inverter for speed and tensile regulation. The following assumptions were made when developing the software for managing the continuous line:

1. The speed of the traction device (line) is set by the block that realizes the ramp function. In the stationary state of the line it is equal to zero,
2. The cross section of the material of the who is being processed and its density do not change,
3. The material being processed has a large Jung's modulus of elasticity, which means that the influence of the material on the tensile force is significantly neglected,
4. The lower dancer wheel moves strictly vertically, the material on both sides of the dancer wheels are parallel,
5. The signal for compensation of the traction force during acceleration and deceleration is set by the software,
6. The compensation of the moment of inertia due to the change of the diameter of the winding is calculated by the software,
7. The compensation of the frictional torque is performed in the Sinamics controllers.

Unwinder, extruders, traction device, winder and traverse devices are connected to the plc controller via Sinamics drivers that are used to start and control their drive motors.

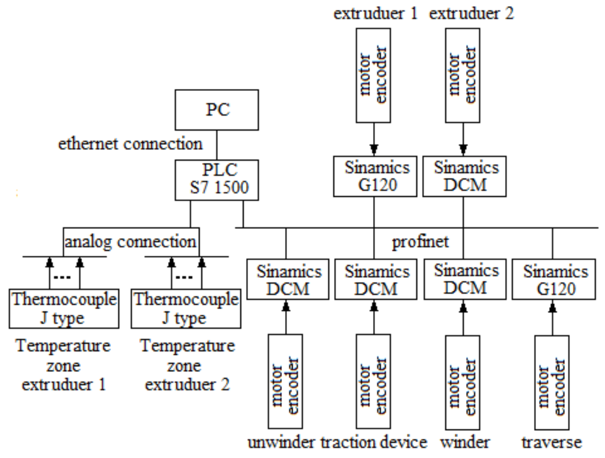

Figure 2. Block diagram of device connection

III. Regulation of Speed and Tensile Force

The main drive of the line is the traction device. It operates in speed mode, maintaining a constant speed by changing the motor current. The speed of the line is practically the speed of the traction device. The principle of speed synchronization is explained in Fig. 3 and implemented by logic in the PLC. The ramp set point signal is set by a potentiometer, the ramp block is written in SCL (structured control language) language, implemented in the PLC controller and applies to all devices on the line. The duration of the program cycle is calculated using the commands "RUNTIME" and "RT _INFO" of the PLC [14]. Their combination gives the total cycle time of programs, subroutines and interrupt routines. The ramp block generates a signal with certain rise (t_u) and fall (t_d) times (Fig. 3). The signal from the ramp is used as a reference for a potentiometer (for traction device) that defines the ratio of the signal sent to the traction unit's drive controller. The potentiometer (for extruder) determines the magnitude of the reference that is sent to the extruder controller. Fig. 4 shows the algorithm for implementing the ramp block.

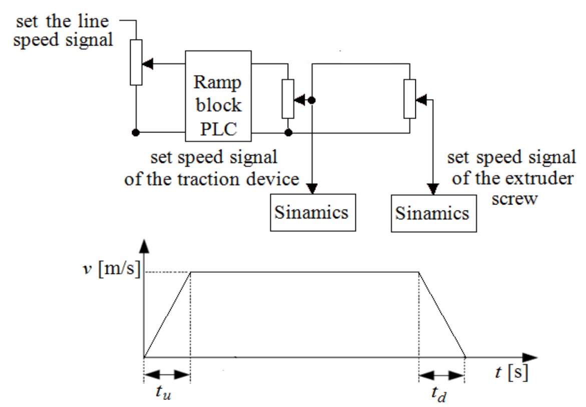

Figure 3. The principle of speed synchronization of the traction device and the extruder

The speed regulation of the unwinder device in zone I was performed by the method of speed compensation using a passive dancer as the current position sensor. An adaptive change of the controller parameters was applied with inclusion, exclusion of the I, D effect depending on the current position of the dancer from [15] using the PID (proportional-integral-derivative) controller (1) working as a position controller whose influence is added to the line speed signal and as such leads to the Sinamics input of the G120 inverter controller [16], , where y is the output of the PID controller, k_p is the proportional gain, b is the weighting coefficient of the proportional action, w is the set value, x is the measured value, T_i is the time constant of the integral action, T_d is the time constant of the differential action, and delay of the differential action, c is the weighting coefficient of the differential action [17]. The PID controller with two degrees of freedom (2 DOF) (1) is implemented in the PLC controller using the PID Compact block.

$$y = k_p\left[(bw-x)+\frac{1}{T_i s}(w-x)+\frac{T_d s}{aT_d s+1}(cw-x)\right] \qquad (1)$$

The parameters of the cascade loop of speed (PI controller) and current (PI controller) of the Sinamics G120 inverter were set using the StartDrive application in TIA Portal [18]. The blocks marked as PLC S7 1500 in Fig. 5 are implemented in the software written in the PLC, and blocks marked as Sinamics DCM [19] is implemented in the Sinamics converter. The regulation of speed and tension in the zone II is achieved by the method of indirect tension control without information of the tensile force (see Fig. 5), where the winder drive speed for a constant speed of the traction device is defined by the minimum diameter of the drum and for a constant tensile force, it is necessary to provide the maximum moment at the maximum diameter of the drum [20]-[21]. The calculation of the diameter was performed according to (2). The thickness of the material to be wound d, b drum width, core diameter D_{min} (inner diameter), maximum drum diameter D_{max} loaded on the winder is entered on the HMI panel, and step of arranging material t_{step} in winding process is set by a potentiometer.

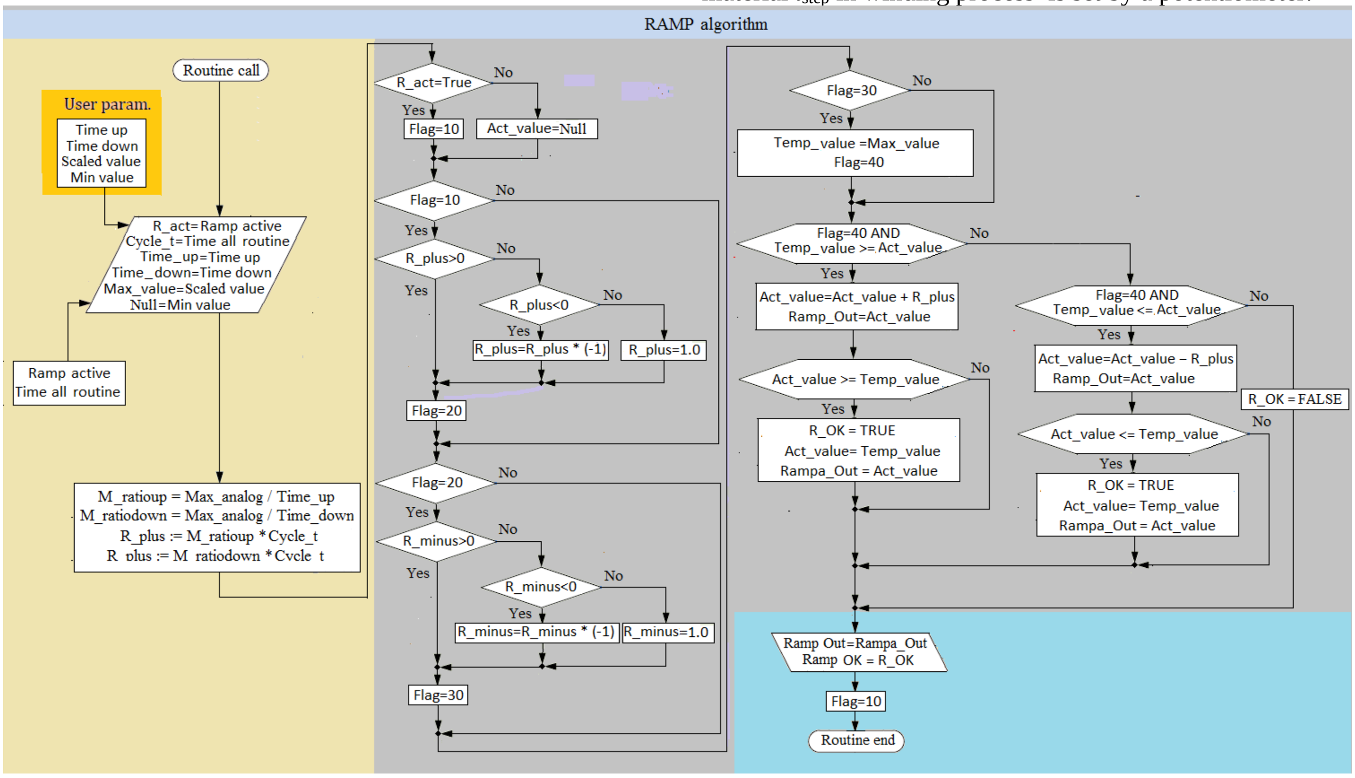

Figure 4. Algorithm of ramp block

The diameter (Fig. 6) is increased by twice the material thickness when the entire row is wound, which is detected by the limit switches of the traverse device. Each time an empty drum is loaded to the end, the current diameter is reset to the value D_{min}, where N is the number of wound layers.

$$D = D_{min} + N2d \qquad (2)$$

The PI controller of the winder device speed was implemented in the software of the PLC using the PID Compact block (1) for a=b=c=1, adjusting the parameters k_p and T_i. The parameters of the PI controller are determined for the empty and full drum, using the setting procedure of the PID Compact block in the TIA Portal [22]. The parameters of the PI drum speed controller have been adjusted according to the current diameter, assuming that the drum's moment of inertia changes linearly.

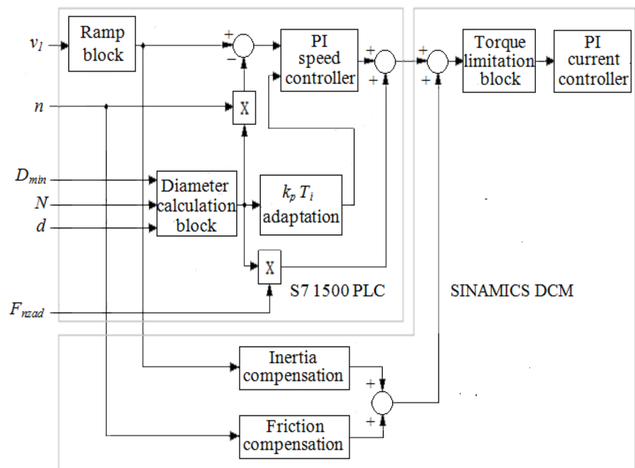

Figure 5. Block diagram of the speed and tension force control of the winding device

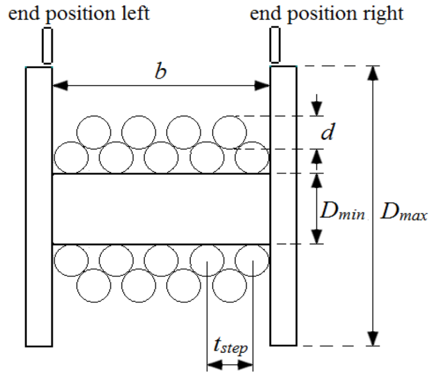

Figure 6. Display of the drum parameters on the winder

The transmission ratio of the rotation speed of the motor and the drum on winder device represents the transmission ratio of the reduction gear (see Fig. 7), given by following equation:

$$i_n = \frac{n_m}{n_n} \tag{3}$$

For precise regulation of the process, it is necessary to maintain the tensile force. Fig. 7 shows a schematic diagram of the winder device and the physical quantities on which the tension force depends.

The moment of inertia reduced to the winder motor shaft is given by:

$$M_m = M_t + M_u + M_{tr} \tag{4}$$

M_t is the moment required to maintain tensile force (5), M_u is the moment of inertia due to acceleration and deceleration, M_{tr} is the moment of loss due to friction.

$$M_t = \frac{F_t D}{2i_n} \tag{5}$$

$$D(t) = \frac{D_{\min}}{2} + \frac{\theta_n d}{2\pi} \tag{6}$$

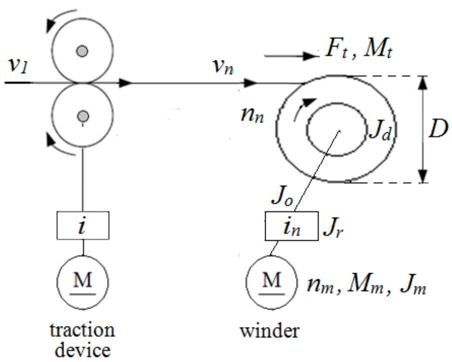

Figure 7. Principle scheme of winder regulation

The diameter of the drum on the winding device changes during the winding process from the minimum according to (6), where θ_n is the angle of rotation of the drum on the winder device.

The acceleration and deceleration of the line generates an additional moment that depends on the current diameter of the drum.

In the zone II the material is located between the tracks (caterpillars) of the traction device and the winder device. When the tracks are closed, the engine torque is transmitted through the reduction gear (i) to the pulleys and then to the tracks. The traction caterpillar device consists of the following parts: motor, belt, gearbox, track and opening and closing system.

$$J_{d\min} = \frac{\pi \rho D_{\min}^4}{32} b \tag{7}$$

$$J_d = \frac{\pi \rho b (D^4 - D_{\min}^4)}{32} \tag{8}$$

where $J_{d\min}$ is the inertia of the empty drum (at $D_{\min}$), J_d is the variable inertia of the drum, J_o is the torque of the drive shaft, J_r is the torque of the reduction gear.

The total inertia reduced to the motor shaft is given by:

$$J = J_m + \frac{J_o + J_{d\min} + J_r}{i_n^2} + \frac{J_d}{i_n^2} \tag{9}$$

The moment of acceleration and deceleration is calculated according to the following equation:

$$M_u = J\frac{d\omega_m}{dt} = J\frac{2i_n}{D}\frac{dv_1}{dt} \tag{10}$$

To keep the tensile force constant, it is necessary to measure it or somehow determine the current value of the tensile force. For this purpose, a tension observer can be designed, but its realization is complicated and connected with the difficulties of realization using only a PLC, it is necessary to determine the transfer functions of the armature and the mechanical part of the DC motor, DC converter, the part for measuring the armature current and the pre-filter. Instead, the speed and armature current can be easily read from the output of the applied DC converter. These values are scaled to match the current and speed values using appropriate PLC instructions. The motor torque is directly related to the armature current (11). The electromotive force constant is determined by measuring the armature voltage, armature current, and motor speed when the idling mode of the motor. On this basis, the coefficient k_t was calculated assuming that the change in armature current (i_a) is negligible, which is perfectly acceptable since the recording was made at no load.

$$M_n = k_t i_a \tag{11}$$

The set value of the tension force F_t is entered into the HMI panel and multiplied by half of the current diameter and added to the output of the PI speed controller (see Fig. 5), and this signal leads to the Sinamics DCM controller. The tensile force is not only a function of the diameter in the software, but it is also set to be reduced by the value of the experimentally determined coefficient from half of the wound drum, so that the material coils are not wound too tightly. This function is activated by the software as soon as the current diameter reaches twice the value of the minimum diameter.

Inertia compensation [23] during acceleration and deceleration of the material is done within the Sinamics DCM controller (Fig. 5), (9) can be ignored when the line accelerated, decelerated according to the ramp signal. The smaller the value of the speed change, the smaller the effect. The friction of the traction device and the winder depends on the speed, it is not linearly related to the speed, and therefore the compensating torque is also nonlinear. The friction losses can be measured manually. Instead, the current corresponding to the torque of the motor is measured. The measurement was performed at 10 points (Fig. 8). The friction losses are compensated using a parametric polygon function with 10 interpolation points. The interpolation points are defined during the initial setup of the Sinamics DCM converter in the setup procedure activated with parameter P50025=28 (Friction compensation) and can be recorded automatically. Friction compensation is activated with parameter P50223=1. In addition to the torque compensating for friction losses, the torque compensating for inertia during acceleration and deceleration must also be determined. For this purpose, the speed change (acceleration) signal is used. Compensation of inertia during acceleration and deceleration of the network material is done within the Sinamics DCM converter and can be ignored when the line is accelerated and decelerated on the ramp signal.

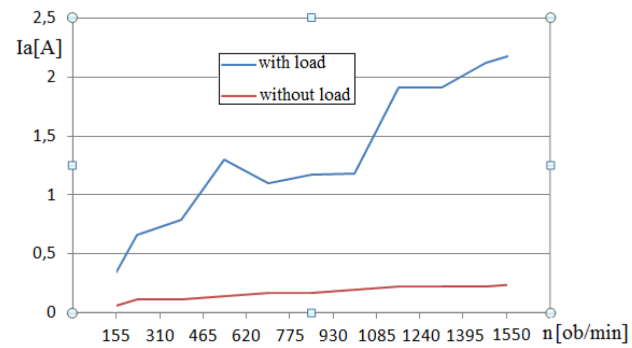

Figure 8. Friction characteristic of traction caterpillar device for load and non load motor

This control is necessary for materials with a low Jung's modulus. Fig. 6 also shows the parameters important for the arrangement of conductors in the winding process. The size of the stacking step was chosen in the range of 1.3 to 1.6 times the diameter of the conductor to be wound, which was determined empirically. Realization of the traverse drive is implemented by an routine in the PLC. Part of the control algorithm of traversing device for arranging material in winding process is shown in Fig. 9.

The encoder is directly coupled to the drive shaft of the drum behind the reduction gear. The signal from the encoder, which also detects the rotation of the winding drum, is fed to the high-speed counter input of the PLC controller. The pulses are counted by the HSC (High Speed Counter), which is implemented by a corresponding routine for traversing device. When the number of pulses corresponding to one revolution of the drum (or a part of the revolution, empirically 3/4 revolution) is reached, the software generates a signal whose duration is determined by the potentiometer for the move step of traverse device. In such a defined time interval, one movement of the traverse device is executed. Then the counter is reset and a new counting cycle is initiated. When the set number of pulses is reached, another movement of the traverse device is performed. The process is further repeated until the winding drive stops together with the line. The sequence of pulses with an amplitude of 10V (16384) is routed via the Profinet network to the Sinamics G120 controller to drive the traverse motor. The traverse motor operates in pulse width modulation mode with a 10V amplitude signal. Changing the fill factor changes the traverse step. Changing the traverse direction is done automatically when the traverse device reaches one of the end positions (right or left limit), or manually by pressing the change direction button. When the sensor of the extreme left or right position is active, the traverse drive stops for a while to wind another coil in the same place, so the arranging of the material continues in the opposite direction.

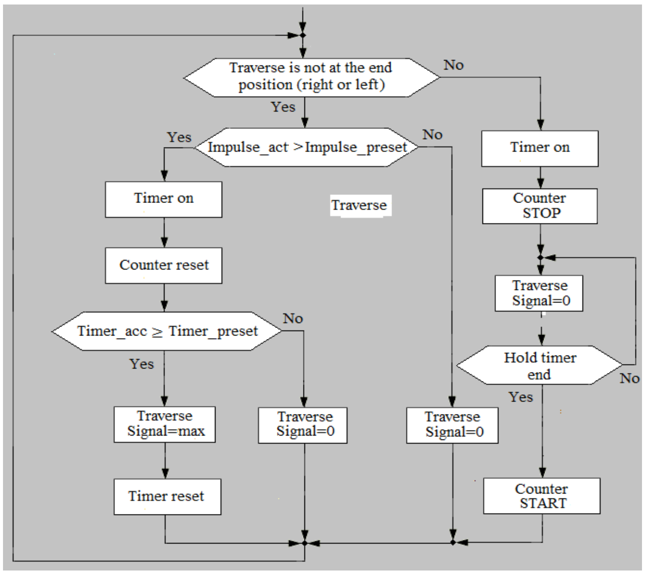

Figure 9. Part of the algorithm for traversing device

In the optimization procedures of the Sinamics inverters and converters, the parameters of the cascade motor controllers of all the drives, the PI speed controllers, were determined by the symmetric optimum method, and the PI current controllers were determined by the technical optimum method.

During the first start-up of the system, the parameters of the controller were determined and adjusted according to the characteristics of the drive motors according to the instructions of the controller manufacturer. Control commands, signals and status values between the PLC and the inverters are transmitted through the Profinet network. Each of the devices is assigned static IP addresses and numbers identifying the device (hardware identifier). The configuration of the Profinet network is shown in Fig. 10. The Profinet telegram 352 was selected for communication, which has 6 words for sending and receiving data. The transmit telegram consists of words in the order: word1=command word, word2=set device speed, word3=set tension force and word4=current diameter, (words 3 and 4) are defined only for the winder, words 5, 6 are not defined.

The receive telegram consists of words in the order: word1=status bits, word2=actual speed, word3=actual current, word4=actual motor torque, word5=active alarm, word6=active error.

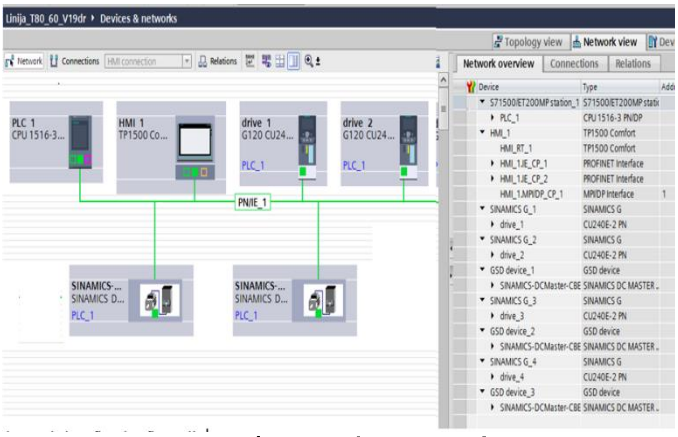

Figure 10. Profinet network, connection diagram

Fig. 11 shows the appearance of the StartDrive tool commissioning wizard when setting up the unwind converter with Sinamics StartDrive software, driven by a 4-pole AC motor of 11kW, 400V, 25A, 1495 rpm. After the initial parameterization, it is possible to additionally set the parameters of the PI speed and current controller. The traction device is driven by a 15hp DC motor, armature voltage and current 400V 27.2A, excitation voltage and current 300V 1.6A, 1550 rpm. The extruder is driven by a 125HP DC motor, armature voltage and current 500V 203A, excitation voltage and current 300V 2.2A, 1000 rpm. The winder is driven by a 7.5kW DC motor, armature voltage and current 500V 25.2A, excitation voltage and current 300V 1.28A, 1750 rpm. The traverse drive is realized by a 2.2kW, 400V, 5.7A, 1440 rpm 4-pole AC motor with a 27.5-speed gearbox.

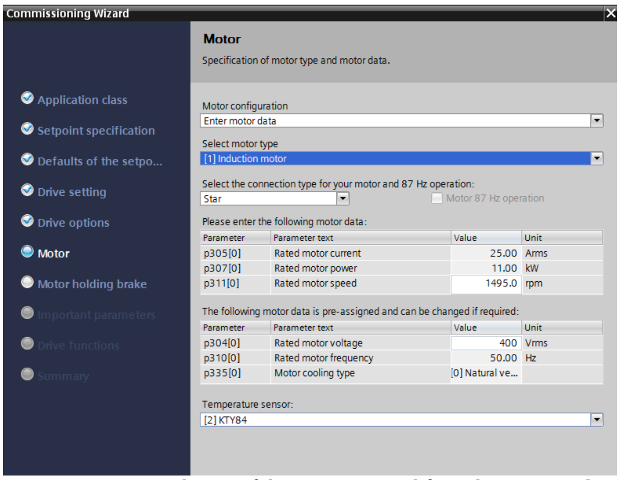

Figure 11. Screen layout of the StartDrive tool from the TIA Portal

The current temperatures of extruder were measured with type J thermocouples connected to the analog modules of the PLC (see Fig. 2). Temperature control [24] of each zone is realized using PID control with PWM (pulse width modulation) output. The PID control is realized by the Siemens block FB1132 (see Fig. 12). A temperature zone is assigned to each block. The configuration of the parameters of the temperature block is done in the TIA Portal, each zone has its own instance (InstPIDTemp), which is assigned a data block (DB), where the settings are stored. The instances are called by the OB30 block (cyclic interrupt), the call time is set to 0.1s.

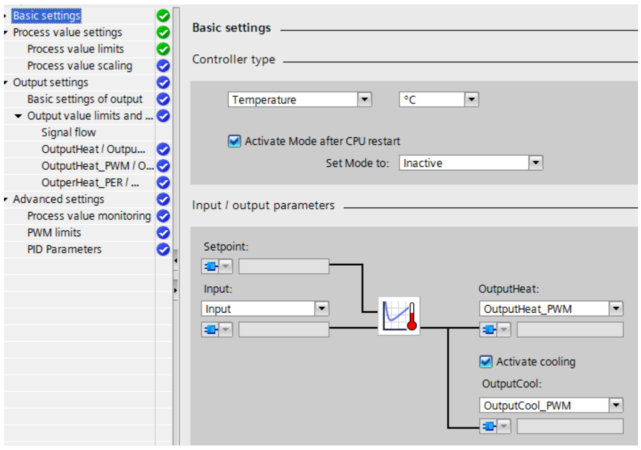

Figure 12. Setting the parameters for the zone temperature control

To control the temperature of the extruder zone, the control algorithm from [25] was used. The heaters and fans are controlled by a PWM signal that turns on the heaters and fans through the solid state relay (SSR). Applied SSR relay is instant ON SSR (switches on the load circuit when a input voltage is applied). Zones 1 to 4 on the extruder cylinder are equipped with 9.6kW heaters and fans driven by 0.55kW, 2900 rpm three-phase motors, and the dynamic section, head and tool heaters are respectively 2.4kW, 3kW and 570W.

IV. EXPERIMENTAL RESULTS

The experimental results were obtained on a real continuous line. Engineering units represent the values of the corresponding registers (tags) of the PLC controller which correspond to the real values of speed, current and tension force. Fig. 13 shows the characteristic of the realized ramp line with a rise time of 12s, where the error in tracking the set point is 249 eng. unit which corresponds to a voltage of 0.0152V. The value of 4.75V corresponds to the set value of 7800 eng. units. The maximum value of 16384 eng. units corresponds to a voltage of 10V and a line speed of 100 m/min. The response characteristic of the position of the dancer of the unwinder device is shown in Fig. 14. The default position of the dancer is set to 10000 eng. units, which corresponds to a voltage of 6.1 V. The position control signal is sent from the PLC to the Sinamics G120 controller.

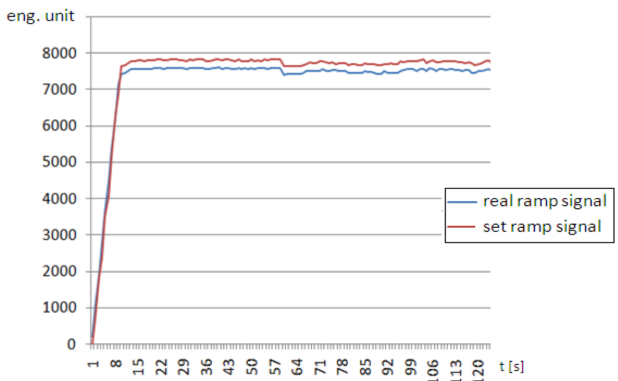

Figure 13. Realization of the ramp for a rise time of 12s

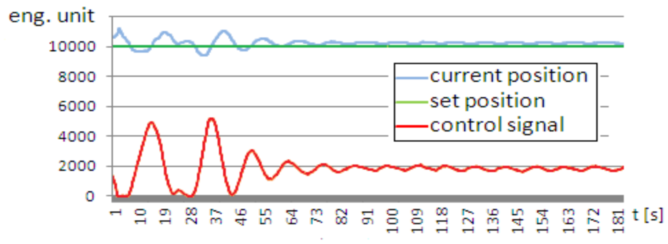

Figure 14. Response of the position of the unwinder device dancer at the beginning of the line

Fig. 15 shows the characteristic of the actual line speed (which corresponds to the traction device speed) and the traction device motor current. From Fig. 15 it can be seen that the traction device works in the speed mode, the speed is maintained by the current. A value of 1000 eng. units corresponds to a drive motor current of 1.6 A.

Fig. 16 shows the characteristics of the synchronization of the realized ramp and the number of revolutions of the extruder screw, where you can see how the current of the extruder's drive motor changes and how the speed of rotation of the screw changes.

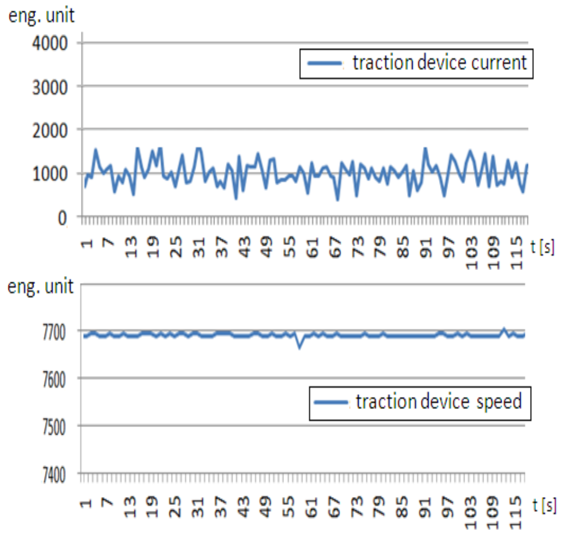

Figure 15. Characteristics of the speed of the traction device and the current of the traction device drive motor

Fig. 17 shows the synchronization between the realized ramp signal, the speed of the line (traction device), the number of revolutions of the extruder screw, and the resulting change in the currents of the traction device drive motors and the extruder when changing the value of the ramp signal

The characteristic of the tensile force, the set tensile force and the control signal are shown in Fig. 18. The tension force is indicated by the current of the drive motor. 1250 eng. unit corresponds to a current of 2A.

Fig. 19 shows the time dependence of the voltage applied to the traverse drive motor, with the longer duration of the pulse directly dependent on the traverse step. A time of 4.5 seconds corresponds to a step length of 30 mm when arranging the material in the winding process.

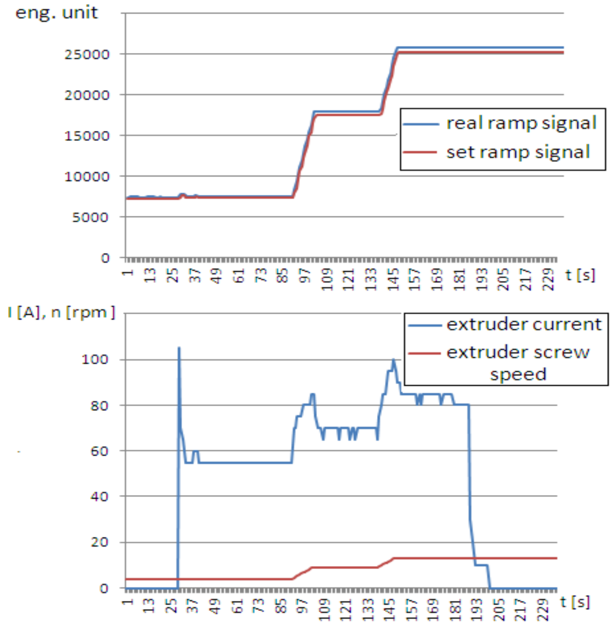

Figure 16. Display of the synchronization of the given ramp and the speed of rotation of the extruder and the current of the drive motor of the extruder

The temperature dependence of the zones during heating and cooling for the following set temperature values: zona1=120^{0}C, zona2=120^{0}C, zona3=122^{0}C, zona4=123^{0}C, dyn. section =130^{0}C, head=132^{0}C, tool=138^{0}C is given in Fig. 20. Changing the speed of the line (changing the ramp signal), the number of revolutions of the extruder screw will change automatically.

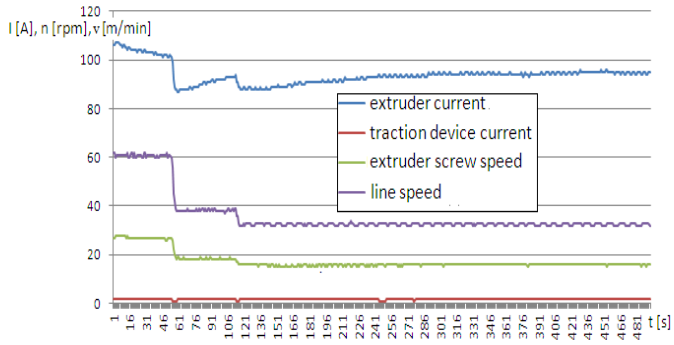

Figure 17. Display of the synchronization of the motor of the traction device and the extruder

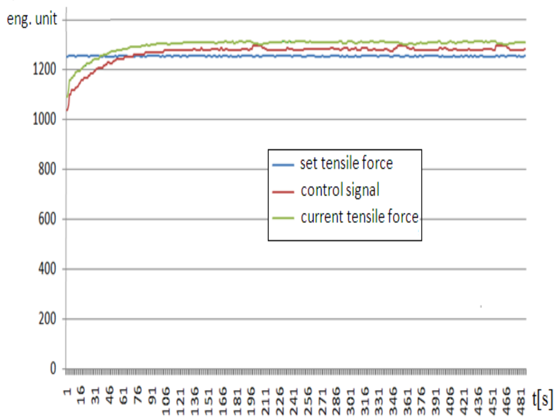

Figure 18. Traction characteristics on the winder

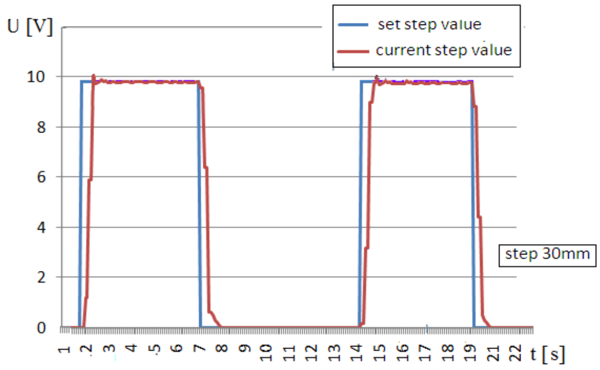

Figure 19. Characteristic of stacking on the winder

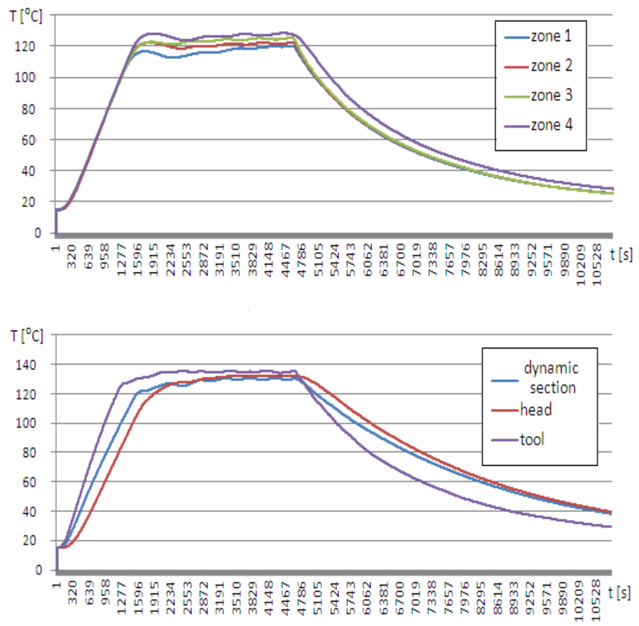

Figure 20. Temperature characteristics of the extruder zones, heating and cooling

V. Conclusion

To control the operation of the continuous line in terms of the speed of all drive motors and the tension force between the parts of the production line that they drive, control methods with the use of dancers and methods of indirect control of the tension force were used. Based on them, the control software for the plc controller of the line was developed as well as a software block for proper arranging the material on the winding drum. The companies Siemens and ABB offer ready-made solutions for the realization of control of unwinders devices, traction devices and winders devices. The paper presents the result of the developed software for the PLC controller, which achieved significant savings. The mentioned software can also be used for more complex lines with more traction devices, more unwinders and winders. Regulation of the speed and force of the tension and the steps of the arrangement material in winding proces directly affects the quality of the final product. The better regulation of speed and temperature gives a more constant flow of mass through the extruder, which achieves a better quality of insulation applied to the material being processed.

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