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PLC-Based Pressure Override Control for End-Barrel Pressure Regulation in PET Extrusion Systems

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ABSTRACT: Maintaining stable melt pressure is essential for ensuring product quality, process stability, and operational safety in polyethylene terephthalate (PET) extrusion systems. However, achieving effective pressure regulation through practical industrial Programmable Logic Controller (PLC)-based implementations remains a significant challenge. In this study, a pressure override control strategy for end-barrel pressure control of a PET extrusion system is developed based on a PLC. The innovation of the proposed approach is the use of a simplified first order process model in combination with a proportional-integral (PI) pressure override controller, which is implemented on a Siemens S7-1200 PLC, using the Totally Integrated Automation (TIA) Portal V15 environment. The control system was simulated in S7-PLCSIM in open loop and closed loop operating conditions and the transient-response characteristics along with Integral of Absolute Error (IAE), Integral of Squared Error (ISE) and Integral of Time-weighted Absolute Error (ITAE) were used to assess the performance of the control system. The results showed that the proposed controller was able to successfully preserve the end-barrel pressure close to the desired operating limit of 60 bar. The maximum pressure dropped from 95.9 bar to 64.6 bar and the pressure overshoot dropped from 59.9% to 7.7% compared to open-loop operation. Moreover, the settling time was shortened from 31.3 s to 11.3 s at 50% melt pump speed, while the IAE, ISE, and ITAE values were always decreased under all the investigated operating conditions, which showed that the pressure regulation and disturbance rejection were improved. Finally, the proposed PLC-based pressure override controller provides a practical, reliable, and computationally efficient solution for enhancing process stability, operational safety, and production reliability in industrial PET extrusion systems.

KEYWORDS: Polyethylene Terephthalate (PET) Extrusion, Pressure Override Control, Programmable Logic Controller (PLC), Proportional-Integral (PI) Control, Siemens TIA Portal, Industrial Automation.

1. INTRODUCTION

Polyethylene terephthalate (PET) extrusion is one of the most important polymer processing techniques in modern industry, due to the high productivity, continuous production and dimensional and mechanical property uniformity of the products [1]. PET extrusion is widely used to manufacture packaging films, sheets, fibers, pipes and engineering parts for the packaging, construction, automotive and textile sectors [2, 3]. With the growing demand of high quality polymer products by industries, it is expected that the extrusion systems to be operated at high production rates with stable processing conditions and consistent product quality [4].

In the various operating parameters of an extrusion process, melt pressure is one of the most important parameters that influence the process stability and product quality [5, 6]. The end barrel pressure directly affects the extrusion material homogeneity, dimensional accuracy, surface finish and melt flow rate of the extruded product [7]. High pressure fluctuations can result in unstable extrusion, higher mechanical stresses on the screw, barrel, and melt pump, equipment wear and in extreme cases, unexpected production stoppages [5]. On the other hand, if the pressure is not high enough, production efficiency will be affected and the quality of the finished product will be reduced [8, 9]. Hence, it is important to keep the melt pressure in a safe and predetermined operating range for reliable, safe and efficient PET extrusion.

In actual production, the melt pressure is usually controlled by changing the speed of the extruder screw based on the operating conditions [7]. The most common way to regulate pressure is with a proportional-integral (PI) or proportional-integral-derivative (PID) controller, which are simple, robust, and easy to implement in industrial automation systems [10]. Typically, these controllers are realized with a Programmable Logic Controller (PLC) which offers dependable real-time control, easy integration with field devices and simple maintenance. The flexibility and the broad acceptance of PLC-based control systems in industry have made them the preferred platform for monitoring, supervising and controlling extrusion processes [11, 12].

Although PLC based control systems are widely used, it is difficult to achieve effective pressure regulation in industrial extrusion [13]. Changes in material properties, production throughput and flow resistance may result in substantial pressure disturbances that are hard to compensate with the conventional operating strategies. Furthermore, solutions for industrial control systems must be dynamically acceptable, but also efficient, reliable, and easily integrated into existing automation systems [14]. Therefore, there is an ongoing demand for practical pressure control strategies which are both high performing and easily implemented in industry.

In this study, a pressure override control strategy for the end-barrel pressure of a PET extrusion system based on PLC is proposed to solve these problems. The proposed approach is a combination of mathematical model of the extrusion process and PI pressure override controller, which is implemented in Totally Integrated Automation (TIA) Portal V15 environment on Siemens S7-1200 PLC. The controller constantly checks the measured melt pressure and automatically adjusts the extruder screw speed via a Variable Frequency Drive (VFD) if the pressure is above the operating limit. The proposed system is tested by S7-PLCSIM and the transient-response characteristics are used to evaluate the performance along with the Integral of Absolute Error (IAE), Integral of Squared Error (ISE) and Integral of Time-weighted Absolute Error (ITAE) performance indices. The novelty of this work is the combination of a pressure override control strategy with a simplified model of the extrusion process and the implementation of the whole control algorithm in a standard industrial PLC platform, which is a practical and reliable solution for industrial PET extrusion applications.

The rest of this paper is structured as follows. The related literature of extrusion process modeling and pressure control strategies are reviewed in Section 2. The materials and methods are described in Section 3, which covers the description of the PET extrusion process, mathematical modeling, PLC implementation and controller development. The simulation results and performance evaluation are presented in Section 4 and the significance of the obtained results is discussed in Section 5. Finally, Section 6 concludes the paper and outlines potential directions for future research.

2. LITERATURE REVIEW

In polymer extrusion, one of the most critical factors for ensuring product quality and safe operation is stable melt pressure. Changes in melt pressure have a direct impact on the stability of melt flow, temperature distribution, mixing efficiency and dimensional accuracy of extruded products. Hence, a lot of research work has been devoted to the understanding of the extrusion behaviour, the development of process models and optimization of pressure regulation strategies.

Initially the research activities focused on modelling and optimising polymer extrusion processes in order to gain insight into the complex relationships between process variables. Hyvärinen, et al. [15] discussed the theoretical and numerical models describing the material transport, melting behavior, pressure generation, and die flow in single and twin screw extruders and called attention to the importance of accurate process modeling in order to improve the performance of the extrusion process. From this point of view, Nastaj and Wilczyński [16] emphasized the critical role of simulation based optimization and scale-up in the development process pointing out that mathematical models can be used to optimize the process more efficiently than traditional trial and error methods, thus saving time and cost.

With the growing knowledge of the extrusion processes, the focus was gradually changed to the study of the effect of operating parameters on the development of pressure. Maina, et al. [17] numerically investigated the relationship between screw speed, pressure and temperature and found that higher screw speed led to higher pressure and temperature in the extruder and hence the need to select the appropriate screw speed to ensure product quality. In a similar study, Weng, et al. [18] used ANSYS Polyflow to study the influences of screw geometry and operating conditions on pressure, temperature, and flow distributions in a counter-rotating twin-screw extruder. All of these studies contributed to the understanding of the extrusion behavior, but they were mostly devoted to process analysis and not to real time pressure control.

In addition to process analysis, much effort has been devoted to the development of advanced pressure control strategies. Perera, et al. [19] suggested an adaptive neuro-fuzzy inference system (ANFIS) based controller for the control of melt pressure by adjusting the extruder screw speed. They showed that their simulation results had better pressure regulation and less pressure fluctuation under various processing conditions. Later, Perera, et al. [20] designed an adaptive extremum-seeking controller that can keep the desired melt pressure in the extruder at the various different polymer materials, screw design and operating conditions pointing the potential of model-free adaptive control for highly nonlinear extrusion processes. Recently, a composite pressure control strategy was proposed by Ma, et al. [21] which uses inverse-model feedforward control, a Smith predictor, and variable-structure feedback for screw-extrusion additive manufacturing. Their experimental results showed that their method has less pressure overshoot, faster response to the screw speed and better product quality than conventional PID control.

However, the majority of the reported pressure control strategies have been designed and tested in MATLAB/Simulink or other simulation software and little work has been done in implementing these strategies on industrial PLC platforms. In addition, many of the current methods are based on advanced intelligent or model-based control methods, which makes the implementation more complex and requires more computation, which may hinder their use in industrial extruders. Consequently, not much effort has been spent in the development of a practical pressure override controller for use with a PLC, which can be realized with standard industrial automation hardware, with good pressure control and easy integration in existing extrusion lines.

In order to overcome these drawbacks, this study proposes a pressure override control strategy for PET extrusion systems based on the PLC programming approach, which is programmed on Siemens S7-1200 PLC in TIA Portal environment. The proposed controller constantly monitors the end-barrel pressure, and the extruder screw speed is automatically adjusted by a VFD to keep the pressure within the desired operating range. In contrast to previous studies that mainly focus on the advanced control algorithms, this work emphasizes a practical implementation in industry with a mathematical process model, real-time PLC execution and an extensive evaluation based on transient-response characteristics and the IAE, ISE and ITAE performance indices. A summary of the reviewed studies is presented in Table 1. As seen, past studies have primarily been concerned with modeling of the extrusion process, numerical analysis and advanced pressure control strategies. Nevertheless, not much effort has been made to directly implement pressure control on industrial PLC platforms. Moreover, many of the studies reported good control performance, but most of the validations were done in simulation systems and not in real-time industrial automation systems.

Table 1: Comparison of recent studies on extrusion pressure analysis and control

Study	Method	Validation	Key Finding	Research Gap
Hyvärinen, et al. [15]	Extrusion modeling	Not Reported	Comprehensive modeling framework for polymer extrusion	No pressure control strategy or industrial implementation
Nastaj and Wilczyński [16]	Simulation-based optimization	Simulation	Improved process optimization and scale-up	No real-time pressure regulation
Perera, et al. [19]	ANFIS controller	MATLAB/Simulink	Stable melt pressure under varying conditions	No industrial PLC implementation
Perera, et al. [20]	Extremum-seeking controller	MATLAB/Simulink	Validated using 2 materials, 2 screw designs, 3 temperatures, and 5 speeds	Simulation only; no PLC implementation
Maina, et al. [17]	ANSYS Polyflow analysis	Simulation	Pressure increased to 41 bar at 100 rpm	No closed-loop controller
Weng, et al. [18]	CFD/Polyflow analysis	Simulation	Optimum operation at 43 rpm and 439 kg/h	Focused on process analysis only
Ma, et al. [21]	VSFC–Smith controller	Experimental	Reduced overshoot to 17.37%	Complex control architecture; not PLC-based
This work	**PI pressure override controller**	**TIA Portal + S7-PLCSIM**	**Maximum pressure limited to 64.6 bar, overshoot reduced to 7.7%, and settling time reduced by 64%**	**Provides a practical PLC-based pressure override solution suitable for industrial implementation**

3. MATERIALS AND METHODS

The methodology used for the development, implementation, and evaluation of the proposed PLC-based pressure override control strategy for a PET extrusion system is described. A study that uses mathematical modeling, industrial control system design, and dynamic simulation to examine the effectiveness of controlling extruder screw speed by end-barrel melt pressure. The proposed control system was programmed in Siemens TIA Portal V15 and tested using S7-PLCSIM to simulate the operation of an industrial PET extrusion process under various operating conditions.

The methodology is comprised of three stages. First, the architecture of the simulated PET extrusion system is introduced, which involves the interaction between the melt pump, pressure transmitter, Siemens S7-1200 PLC, VFD and extruder screw motor. Secondly, a mathematical model of the pressure dynamics and the proposed pressure override controller is developed to describe the process behavior. Finally, the control strategy is realized in the TIA Portal environment, and both open-loop and closed-loop operating modes are set up and analyzed using conventional control performance indices.

3.1. PET Extrusion Process Description

The proposed PET extrusion system configuration and operation are described in this subsection for evaluation of the pressure override control strategy. The goal is to determine how the process parts interact with each other and how the control system controls the extruder screw speed when the end-barrel melt pressure changes. The simulated process is a good approximation of an industrial PET extrusion line, and it is a flexible process for controller development and performance evaluation.

The proposed PET extrusion system was designed and tested in a simulation environment with the help of Siemens TIA Portal V15 and S7-PLCSIM. The system comprises a single screw PET extruder, a melt pump, an end barrel pressure transmitter with a measurement range of 0-400 bar and a 4-20 mA output signal, a Siemens S7-1200 PLC and a VFD which controls the rotational speed of the extruder screw motor using a simulated 0-10 V analog control signal.

The speed of the melt pump is defined as the production setpoint during operation and is the desired production throughput. The PLC constantly reads the end-barrel melt pressure from the pressure transmitter and compares the value to a set pressure value. When the extruder is operating normally, the extruder screw motor runs according to the calculated base screw speed. But when the measured pressure is higher than the allowable operating pressure, the pressure override controller will automatically reduce the screw speed to avoid excessive pressure accumulation in the process, and ensure stable operation of the process.

This control strategy allows the extrusion system to counteract disturbances that may occur due to fluctuating melt viscosity, material feed rate, or increased flow resistance due to partial filter clogging. Thus, the controller stabilizes the process, prevents the extrusion equipment from high pressure, and keeps the production rate as required without changing the melt pump operating parameters. The overall control architecture and the signal flow of the proposed PET extrusion system is shown in Figure 1. The melt pump speed is used as the production reference to determine the base screw speed as illustrated in the figure. The end-barrel pressure transmitter is used to continuously measure the melt pressure and feedback the signal to the PLC via the analog input module. The PLC performs the pressure override algorithm and outputs 0-10V analog signal to control the VFD, thereby controlling the extruder screw motor speed to keep the pressure within the operating limit.

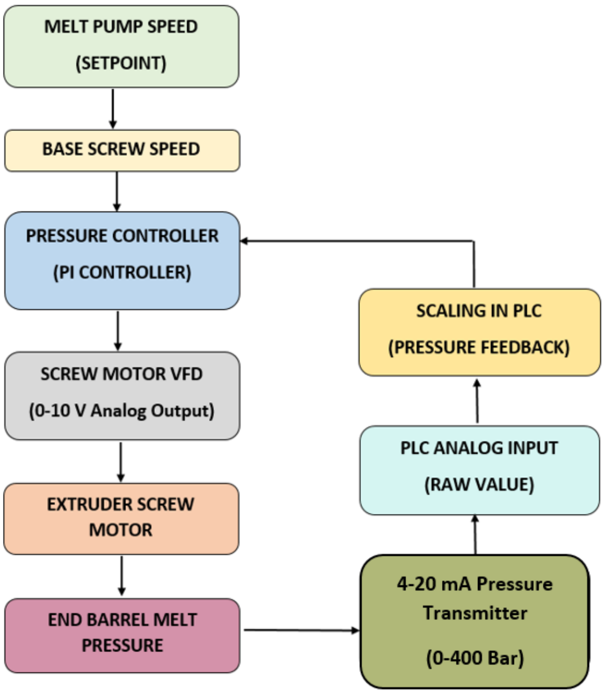


Figure 1: Control architecture of the proposed PET extrusion system

3.2. Mathematical Model of the Proposed Control System

A mathematical model of the PET extrusion system was created to assess the proposed pressure override strategy. The model represents the relationship between the melt pump speed, screw speed and end-barrel pressure, and also represents the behaviour of the PI pressure override controller. This model is used as a theoretical foundation to implement the control algorithm in the PLC and to evaluate the performance of the control algorithm under various operating conditions.

3.2.1. Base Screw Speed Reference

The melt pump speed is used to set the base reference for the extruder screw speed, which is the production rate required. The screw is normally operated at this base speed until a pressure correction is needed. The melt pump speed and base screw speed are related as shown in Equation (1).

$$N_b(t) = K_r N_p(t) \quad (1)$$

Where, $N_b(t)$ is the base screw speed (%), K_r is the screw to melt pump speed ratio, $N_p(t)$ is the melt pump speed setpoint.

3.2.2. Pressure Error

The pressure override controller is constantly monitoring the end-barrel pressure against the maximum allowable operating pressure. The pressure error will indicate if corrective action is needed. The pressure error is calculated using Equation (2) [22].

$$e_p(t) = P_{limit} - P(t) \quad (2)$$

Where, P_{limit} is the allowable pressure limit (bar) and $P(t)$ is the measured end barrel pressure. Since pressure correction is required only when the measured pressure exceeds the allowable limit, the effective pressure error is defined by Equation (3) [23].

$$e_o(t) = \max[0, P(t) - P_{limit}] \quad (3)$$

The controller will therefore not intervene when the measured pressure is below the set bound, thus avoiding unnecessary adjustment of the screw speed.

3.2.3. PI Pressure Override Controller

The pressure override controller is activated to decrease the screw speed whenever the measured pressure is greater than the allowable pressure. Due to the simplicity, robustness and the fact that it is widely used in industrial process control, a PI controller was chosen. The proportional term acts quickly to pressure deviations, and the integral term removes any steady state errors. The required reduction in screw speed is calculated using Equation (4) and the result is the controller output [22].

$$\Delta N(t) = K_p e_o(t) + K_i \int_0^t e_o(\tau) d\tau \quad (4)$$

Where, K_p and K_i are the proportional and integral gains, respectively. The controller is enabled only when the measured pressure exceeds the allowable pressure limit, as defined by Equation (5). Otherwise, the controller output is zero and the screw operates at its nominal speed.

$$P(t) > P_{limit}. \quad (5)$$

3.2.4. Screw Speed Command

Final screw speed command will vary depending on the operating mode. In open loop operation the screw is operated at the base speed reference without pressure compensation. Closed loop operation: The controller slows down the screw speed based on the pressure correction value generated by the PI controller. In open-loop operation, the command of the screw speed is calculated from Equation (6). In addition, the pressure correction is added for closed loop operation as indicated in Equation (7). Finally, the screw speed command calculated is limited to the range of operation 0-100% and passed to VFD.

$$N_{cmd}(t) = N_b(t) \tag{6}$$

$$N_{cmd}(t) = N_b(t) - \Delta N(t) \tag{7}$$

3.2.5. PET Extruder Pressure Model

A simplified first order dynamic model was used to simulate the pressure response of the extrusion process. The model correlates the end-barrel pressure with the commanded screw speed and considers external process disturbances like filter clogging, melt viscosity fluctuations and material feed rate fluctuations. The target pressure is assumed to be proportional to the screw speed and is given by Equation (8) [24].

$$P_{target}(t) = K_{process} N_{cmd}(t) + D(t) \tag{8}$$

Where, $K_{process}$ is the process gain, $D(t)$ is the disturbance input representing filter clogging, viscosity changes, or feed variation. Moreover, the pressure dynamics of the extrusion process are represented by the first-order differential equation shown in Equation (9) [25].

$$\tau \frac{dP(t)}{dt} + P(t) = P_{target} \tag{9}$$

The continuous model was discretized according to Equation (10) to aid in implementation in the PLC [25]. Where, τ is the process time constant and Ts is the PLC sampling time.

$$P(k) = P(k-1) + \frac{Ts}{\tau}\left[P_{target}(k) - P(k-1)\right] \tag{10}$$

3.2.6. Performance Indices

Three popular performance indices: IAE, ISE, and ITAE were used to assess the performance of the controllers. These indices measure the overall accuracy of control, the size of the pressure deviations and how long the error remains during the simulation [26]. The IAE, ISE and ITAE are computed from Equations (11) – (13).

$$IAE = \int_0^T |e(t)|dt \tag{11}$$

$$ISE = \int_0^T e^2(t)dt \tag{12}$$

$$ITAE = \int_0^T t|e(t)|dt \tag{13}$$

Smaller values of these indices correspond to better control performance, specifically, more accurate control of the pressure and better rejection of disturbances.

3.3. PLC-Based Control System Design and Implementation via TIA Portal

Once the mathematical model was developed, the proposed pressure override control strategy was simulated in the Siemens TIA Portal environment to assess its feasibility. The implementation included the configuration of the PLC hardware, creation of the control program and integration of the process model with the controller. The whole system was tested by S7-PLCSIM, and the controller was tested under various operating conditions without any physical equipment.

3.3.1. Hardware Configuration

The hardware architecture was designed to be similar to a typical industrial PET extrusion system. It is composed of a Siemens S7-1200 PLC, end-barrel pressure transmitter, VFD and extruder screw motor. The pressure signal is sent to the PLC that carries out the pressure override algorithm and outputs an analog signal to the VFD that controls the screw motor. The pressure transmitter delivers a standard 4-20mA signal for the pressure range 0-400bar as shown in Figure 2. This signal is then fed to the PLC analog input module and converted to engineering units. The controller then produces an analog output signal (0-10V) which is used as a speed reference for the VFD. The PLC continuously adjusts this reference based on the measured pressure, so as to keep the end-barrel pressure in the desired operating range while maintaining the necessary production rate.

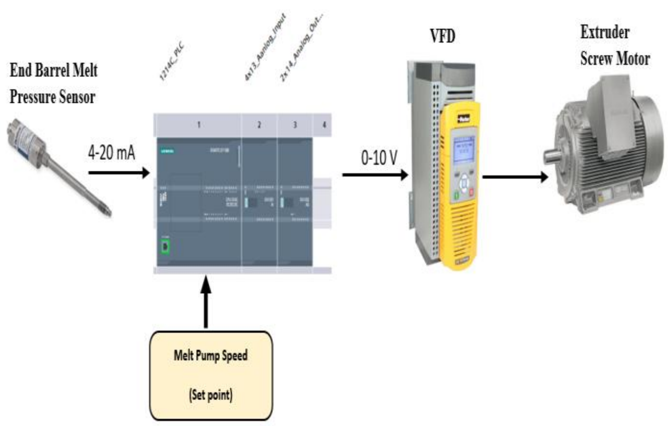
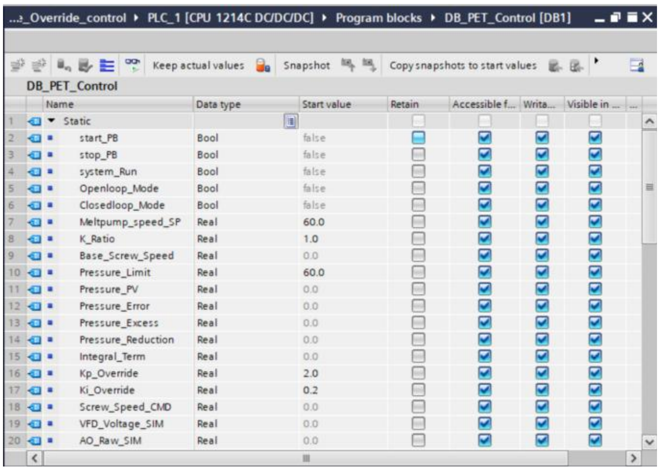


Figure 2: Hardware configuration of the proposed PET extrusion control system

3.3.2. PLC Implementation via TIA Portal

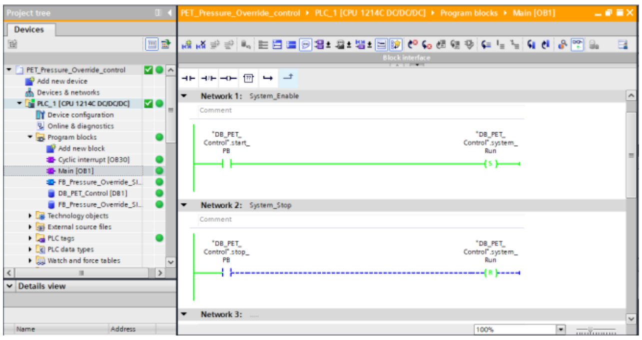
The proposed controller was programmed in Siemens TIA Portal V15 with S7-1200 CPU 1214C DC/DC/DC and S7-PLCSIM was used to simulate the entire control system. The PLC program was written in Ladder Diagram (LAD) and Structured Control Language (SCL) to enable the control logic and process model to be combined in the same program. In order to organize the program and to make maintenance easier, the control software was split into a number of functional blocks, each of which was assigned to a specific task in the control system. Global data block DB_PET_Control (DB1) contains operating commands, controller parameters, process variables, simulation data and alarm flags that are needed during execution. The internal states of the function block are stored in the corresponding instance data block, so that the PI controller can continue to operate between successive execution cycles. The organization of these variables is presented in Figure 3.



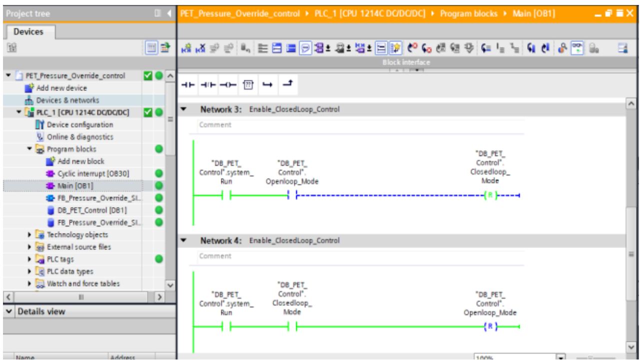
Name	Data type	Start value
Static		
start_PB	Bool	false
stop_PB	Bool	false
system_Run	Bool	false
Openloop_Mode	Bool	false
Closedloop_Mode	Bool	false
Meltpump_speed_SP	Real	60.0
K_Ratio	Real	1.0
Base_Screw_Speed	Real	0.0
Pressure_Limit	Real	60.0
Pressure_PV	Real	0.0
Pressure_Error	Real	0.0
Pressure_Excess	Real	0.0
Pressure_Reduction	Real	0.0
Integral_Term	Real	0.0
Kp_Override	Real	2.0
Ki_Override	Real	0.2
Screw_Speed_CMD	Real	0.0
VFD_Voltage_SIM	Real	0.0
AO_Raw_SIM	Real	0.0

Figure 3: Control parameters and simulation variables stored in DB PET Control

The main organization block OB1 is responsible for the overall control system operation. It implements the Ladder Diagram logic for system start-up and shut-down, and for switching between open-loop and closed-loop operating modes. An interlocking logic is used to prevent unintended controller behavior during operation, as shown in Figure 4, only one operating mode may be active at any one time.



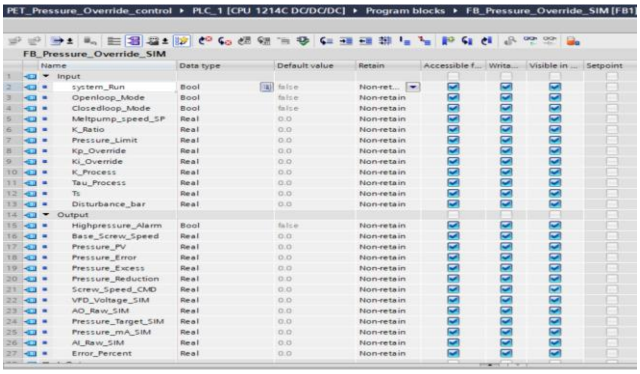
(a)



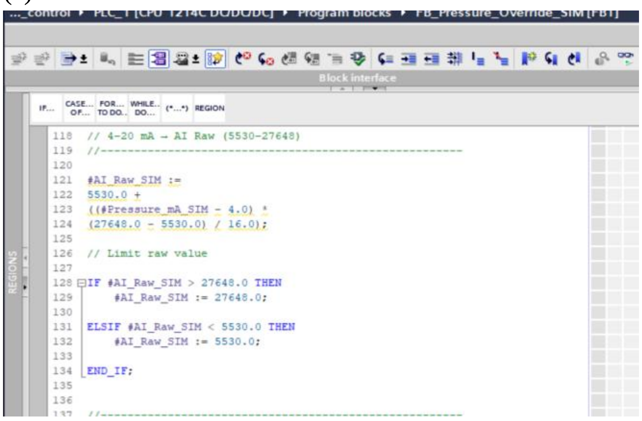
(b)

Figure 4: Main organization block (OB1): (a) start/stop logic, (b) mode selection

The FB_Pressure_Override_SIM is a function block that integrates the pressure signal processing, the PI controller, the calculation of the screw speed, the simulation of the process and the evaluation of the performance in one program module and is the heart of the proposed controller. In each execution cycle, the function block computes the base screw speed based on the melt pump setpoint, converts the simulated pressure transmitter signal to engineering units and implements the pressure override algorithm when the measured pressure is above the specified limit. This screw speed command is then constrained within the limits of the operating range and then translated into the VFD reference signal. The function block also includes the first order PET extrusion model and the computation of the IAE, ISE, and ITAE performance indices, allowing the simultaneous simulation and evaluation of the controller in the PLC program, as shown in Figure 5.



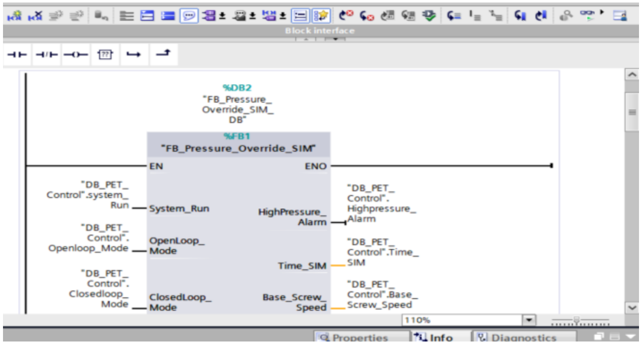
(a)



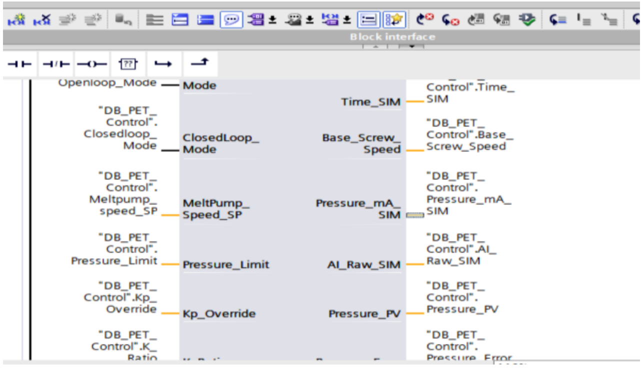
(b)

Figure 5: FB_Pressure_Override_SIM: (a) block interface, (b) SCL code

To provide deterministic controller execution, the function block is executed at a fixed sampling interval by the cyclic interrupt block OB30. The interrupt routine ensures a fixed execution time, which will increase the accuracy and repeatability of the control algorithm, unlike the normal PLC scan cycle. The PI controller, process model, analog signal processing, and performance index calculations are updated consistently throughout the simulation by the periodic call to FB_Pressure_Override_SIM as shown in Figure 6.



(a)



(b)

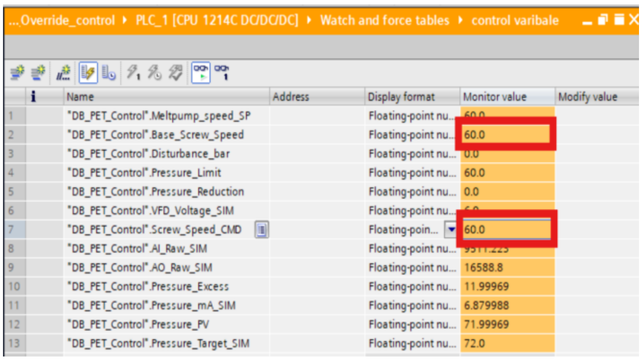
Figure 6: LAD implementation of the cyclic interrupt block (OB30): (a) OB30, (b) FB_Pressure_Override_SIM call

4. RESULTS AND DISCUSSION

To achieve deterministic controller execution, the function block is executed by the cyclic interrupt block OB30 at a fixed sampling interval. The interrupt routine is different from the normal PLC scan cycle as it will always be executed in the same time period, which will increase the accuracy and repeatability of the control algorithm. The PI controller, process model, analog signal processing, and performance index calculations are updated consistently throughout the simulation by the periodic calls to FB_Pressure Override_SIM.

4.1. Controller Verification

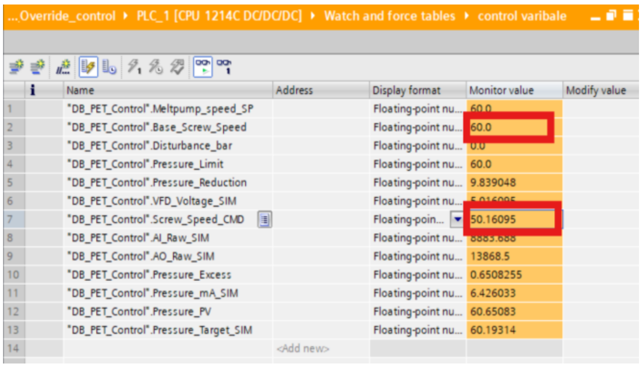
The proper implementation of the proposed control strategy was first verified by using the online diagnostic and monitoring tools in Siemens TIA Portal before the performance of the controller was evaluated. These tools allow for real-time monitoring of the controller variables, the sequence of execution and the communications between the blocks of the PLC program, giving confidence that the control algorithm is working properly. Figure 7 shows some of the watch table results during the simulation. The variables shown are melt pump speed, measured pressure, screw speed command, pressure reduction, simulated VFD output and the calculated performance indices. In open loop operation, the screw speed is independent of the measured pressure and is controlled by the base reference. If closed-loop operation is enabled, the controller automatically slows down the screw when the measured pressure is above the set pressure. Watch table also provides real time update of IAE, ISE and ITAE values so that the performance of the controller can be monitored throughout the simulation.



…Override_control ▸ PLC_1 [CPU 1214C DC/DC/DC] ▸ Watch and force tables ▸ control varibale

	i	Name	Address	Display format	Monitor value	Modify value
1		"DB_PET_Control".Meltpump_speed_SP		Floating-point nu...	60.0	
2		"DB_PET_Control".Base_Screw_Speed		Floating-point nu...	60.0	
3		"DB_PET_Control".Disturbance_bar		Floating-point nu...	0.0	
4		"DB_PET_Control".Pressure_Limit		Floating-point nu...	60.0	
5		"DB_PET_Control".Pressure_Reduction		Floating-point nu...	0.0	
6		"DB_PET_Control".VFD_Voltage_SIM		Floating-point nu...	[illegible]	
7		"DB_PET_Control".Screw_Speed_CMD		Floating-poin...	60.0	
8		"DB_PET_Control".AI_Raw_SIM		Floating-point nu...	[illegible]	
9		"DB_PET_Control".AO_Raw_SIM		Floating-point nu...	16588.8	
10		"DB_PET_Control".Pressure_Excess		Floating-point nu...	11.99969	
11		"DB_PET_Control".Pressure_mA_SIM		Floating-point nu...	6.879988	
12		"DB_PET_Control".Pressure_PV		Floating-point nu...	71.99969	
13		"DB_PET_Control".Pressure_Target_SIM		Floating-point nu...	72.0	

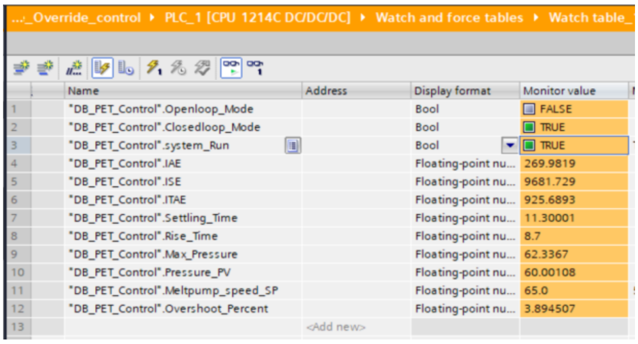
(a)



…Override_control ▸ PLC_1 [CPU 1214C DC/DC/DC] ▸ Watch and force tables ▸ control varibale

	i	Name	Address	Display format	Monitor value	Modify value
1		"DB_PET_Control".Meltpump_speed_SP		Floating-point nu...	60.0	
2		"DB_PET_Control".Base_Screw_Speed		Floating-point nu...	60.0	
3		"DB_PET_Control".Disturbance_bar		Floating-point nu...	0.0	
4		"DB_PET_Control".Pressure_Limit		Floating-point nu...	60.0	
5		"DB_PET_Control".Pressure_Reduction		Floating-point nu...	9.839048	
6		"DB_PET_Control".VFD_Voltage_SIM		Floating-point nu...	[illegible]	
7		"DB_PET_Control".Screw_Speed_CMD		Floating-poin...	50.16095	
8		"DB_PET_Control".AI_Raw_SIM		Floating-point nu...	[illegible]	
9		"DB_PET_Control".AO_Raw_SIM		Floating-point nu...	13868.5	
10		"DB_PET_Control".Pressure_Excess		Floating-point nu...	0.6508255	
11		"DB_PET_Control".Pressure_mA_SIM		Floating-point nu...	6.426033	
12		"DB_PET_Control".Pressure_PV		Floating-point nu...	60.65083	
13		"DB_PET_Control".Pressure_Target_SIM		Floating-point nu...	60.19314	
14			<Add new>			

(b)



…_Override_control ▸ PLC_1 [CPU 1214C DC/DC/DC] ▸ Watch and force tables ▸ Watch table_

		Name	Address	Display format	Monitor value
1		"DB_PET_Control".Openloop_Mode		Bool	FALSE
2		"DB_PET_Control".Closedloop_Mode		Bool	TRUE
3		"DB_PET_Control".system_Run		Bool	TRUE
4		"DB_PET_Control".IAE		Floating-point nu...	269.9819
5		"DB_PET_Control".ISE		Floating-point nu...	9681.729
6		"DB_PET_Control".ITAE		Floating-point nu...	925.6893
7		"DB_PET_Control".Settling_Time		Floating-point nu...	11.30001
8		"DB_PET_Control".Rise_Time		Floating-point nu...	8.7
9		"DB_PET_Control".Max_Pressure		Floating-point nu...	62.3367
10		"DB_PET_Control".Pressure_PV		Floating-point nu...	60.00108
11		"DB_PET_Control".Meltpump_speed_SP		Floating-point nu...	65.0
12		"DB_PET_Control".Overshoot_Percent		Floating-point nu...	3.894507
13			<Add new>		

(c)

Figure 7: Controller watch table: (a) open-loop, (b) closed-loop, and (c) performance indices

The PLC program was also verified by using the online Ladder Diagram (LAD) monitoring function. The energized network (see Figure 8) proves the cyclic execution of the interrupt block (OB30) and the successful exchange of information between the organization blocks, function block and data block when the controller is in operation. The online monitoring ensures that the pressure override algorithm is called periodically, as per the sampling interval defined, which ensures deterministic and reliable controller operation during the simulation.

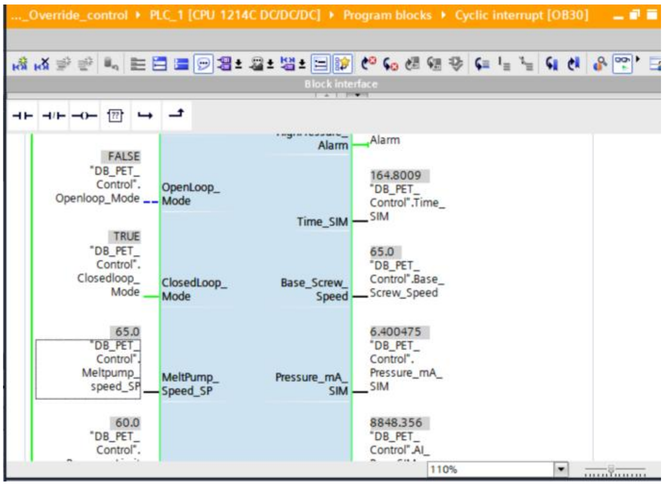


Figure 8: Online monitoring of the cyclic execution of FB_Pressure_Override_SIM

4.2. Simulation Results

After verification, the proposed controller was tested in various operating scenarios that correspond to different production conditions. The simulations were conducted by changing the operating mode, the setpoint of the melt pump speed, the pressure limit and the level of disturbance and observing the process response. The variables measured were: end-barrel pressure, screw speed command, pressure reduction, simulated VFD output voltage, and high pressure alarm status. Table 2 presents the simulation results for the operating cases studied.

Table 2: Simulation results of the pressure override controller under different operating conditions

Case	Operating mode	Melt pump speed SP (%)	Pressure limit (bar)	Disturbance (bar)	Pressure PV (bar)	Screw Speed CMD (%)	Pressure reduction (%)	VFD voltage (V)	High pressure alarm
1	Open loop	60.0	70.0	0.0	71.99	60.0	0.0	6.0	ON
2	Open loop	80.0	70.0	10.0	106.0	80.0	0.0	8.0	ON
3	Closed loop	60.0	70.0	0.0	70.0	53.3	5.1	5.5	OFF
4	Closed loop	60.0	70.0	10.0	70.0	50.0	9.9	5.0	OFF
5	Closed loop	70.0	100.0	30.0	100.0	58.3	11.6	5.8	OFF
6	Closed loop	80.0	120.0	40.0	120.0	63.7	16.7	6.3	OFF
7	Closed loop	90.0	150.0	50.0	150.0	72.3	18.7	7.2	OFF

Table 2 indicates that the controller responded properly for all the operating conditions investigated. In the open-loop operation (Cases 1 and 2), the screw speed was kept at the reference value, which resulted in the end-barrel pressure being higher than the specified pressure limit and the high-pressure alarm was activated. These results show that the open-loop configuration is not able to compensate the pressure variation due to increased production demand or due to external disturbances.

The proposed pressure override controller, on the other hand, was able to keep the measured pressure within the desired operating limit by automatically decreasing the speed of the screw if the pressure was too high. As the disturbance level rose, the controller sent out a greater speed reduction command and the VFD output voltage decreased proportionately. As a result, the high-pressure alarm was not activated in all closed-loop operating cases, which verified the capability of the controller to keep the process in safe operating conditions and at the same time keeping the production rate.

4.3. Performance Evaluation

In order to quantify the effectiveness of the proposed pressure override strategy, further simulation experiments were carried out with the pressure limit set to 60 bar and the melt pump speed varied through different operating conditions. The maximum pressure, steady-state pressure, overshoot, rise time, settling time, IAE, ISE, and ITAE were used to evaluate the controller performance. The comparative results for open loop and closed loop operation are shown in Table 3.

Table 3: Performance evaluation of the pressure override controller under open and closed-loop operation

Control Mode	Melt pump SP	Maximum Pressure (bar)	Steady State Pressure (bar)	Overshoot (%)	Rise Time (s)	Settling Time (s)	IAE	ISE	ITAE

Open Loop	50	59.8	59.8	0	17.5	31.3	470	14485	3472
	60	71.9	71.9	19.9	10.4	13.6	308	10817	1241
	70	85.1	85.1	41.9	7.5	9.7	240	8779	724
	80	95.9	95.9	59.9	5.8	7.6	199	7424	485
Closed Loop	50	60	60	0	8.7	11.3	269	9681	925
	60	61.5	60	2.5	6.6	8.5	217	8041	586
	70	63.1	60	5.1	5.4	6.9	183	6900	409
	80	64.6	60	7.7	4.6	5.8	159	6055	304

Table 3 shows that the proposed pressure override controller significantly enhanced the pressure regulation performance as compared to open loop operation. The maximum pressure, overshoot and settling time were significantly increased with the increase in melt pump speed in the open-loop mode, suggesting that the extrusion process could not meet the increased production demand. As an example, the overshoot rose from 0% to 59.9% and the maximum pressure rose from 59.8 bar to 95.9 bar when the melt pump speed was increased from 50% to 80%. These results show the limitations of the operation of the extrusion system without pressure feedback.
With the proposed pressure override controller turned on, the end-barrel pressure was maintained at the desired operating pressure over the range of operating conditions. With the highest melt pump speed, the maximum pressure was only 64.6 bar, which is only 7.7% overshoot, and shows the capability of the controller to suppress pressure fluctuations by automatic screw speed regulation.
Closed-loop operation also led to significant improvement in the dynamic response. The rise time and settling time were consistently smaller than the open loop control, which means that the system responded faster to the pressure disturbances, and the extrusion process stabilized faster. Such enhancements are especially significant in industrial extrusion processes, where continuous pressure fluctuations can negatively affect product quality and mechanical stresses on the equipment.
The same is true for the control performance indices. It was observed that the IAE, ISE and ITAE values were always lower for all closed-loop operating conditions, which shows that the proposed controller was able to reduce the magnitude and duration of the pressure error. Disturbance rejection and pressure regulation are more accurate across the operating range, as shown by these reductions.

Lastly, the results show that the proposed pressure override control strategy based on PLC is an effective and practical solution to control the end-barrel pressure in PET extrusion systems. The controller can automatically adjust the extruder screw speed, and the melt pump is used as the production reference, which can prevent excessive pressure accumulation in the barrel during the production process and improve the stability of the production process, effectively improve the reliability of the extruder production process.

5. DISCUSSION

The simulation results show that the end-barrel pressure can be successfully controlled using the proposed pressure override strategy by dynamically adjusting the extruder screw speed based on the real-time pressure measurement. The proposed controller is different from the traditional open-loop controller in that the screw speed is not fixed, but is automatically adjusted based on the feedback mechanism to compensate for the pressure disturbance before it escalates into unsafe operating conditions. This feedback action allows the extrusion process to be operated in a stable manner over a broad range of production rates and disturbance levels.
The most prominent improvement obtained with the proposed controller is the considerable reduction in pressure overshoot. In open-loop operation, there is no corrective action possible, so that any change in the melt pump speed or process disturbance directly leads to an increase in the end-barrel pressure. The pressure override controller will reduce the screw speed as soon as the measured pressure exceeds the set pressure, to avoid excessive pressure build-up in the extruder barrel. This means that the pressure will be kept close to the desired operating limit, thus decreasing the mechanical load on the extrusion equipment and making the process safer.
The controller also showed better dynamic response compared to the open loop system. The shorter rise and settling times means that the feedback controller is fast to respond to pressure deviations and stabilizes the process more effectively. In practical terms, this quick stabilization reduces the variation of the melt pressure, which is especially significant in PET extrusion as pressure variation may impact the melt homogeneity, the dimensional accuracy of the product and the overall production consistency.
The improvement in the performance indices of IAE, ISE and ITAE also confirms the effectiveness of the proposed control strategy. The smaller the values of these indices, the greater the ability of the controller to decrease the pressure error amplitude and also its time of action during the operating cycle. This behavior demonstrates the PI controller's ability to deliver fast corrective action via the proportional term and precise steady-state regulation via the integral term, which helps to achieve smoother and more stable pressure control.
The overall performance shows that sophisticated control algorithms are not necessary for good pressure regulation. The proposed system, which is a combination of a conventional PI controller with a pressure override strategy, was able to maintain the barrel end pressure within the safe

operating range and also gave the fast and stable dynamic response. The results show that such a simple control structure can be used to realize reliable pressure regulation with low computational load and simple implementation when it is integrated with an industrial PLC.

A further significant result of this study is that the controller has been successfully implemented in a standard industrial PLC environment. The proposed approach was not only simulated in simulation software like MATLAB/Simulink, but was also implemented in Siemens TIA Portal with an S7-1200 PLC architecture. The implementation shows that the proposed control strategy can be easily integrated into the current industrial automation system without the need of special hardware and complex computing resources, which is attractive to be practically deployed in the PET extrusion line.

The present study has some limitations, but the results of the simulation are promising. A simplified first-order dynamic model was used to represent the extrusion process, which is not able to describe all nonlinear properties of industrial PET extrusion. Further, the controller was tested in a simulated PLC environment and not on a real production line. Future research should thus be directed towards experimental validation of the proposed method in an industrial scale extrusion system and the development of more sophisticated control strategies including adaptive, model predictive or intelligent control algorithms to achieve better pressure control under highly nonlinear operating conditions.

6. CONCLUSIONS

The design, implementation and evaluation of a pressure override control strategy based on PLC was presented to control the end-barrel pressure in a PET extrusion system. The proposed approach is a combination of a mathematical process model and a PI pressure override controller, which is programmed on a Siemens S7-1200 PLC using the TIA Portal environment. The controller continuously checks the melt pressure and varies the screw speed of the extruder with the help of a VFD, so that the melt pressure remains within the specified operating range and the desired production throughput is not affected.

The simulation results showed the effectiveness of the proposed control strategy under a wide range of operating conditions. The maximum pressure in the case of open loop operation increased from 59.8 bar to 95.9 bar when the melt pump speed increased from 50% to 80%, while the proposed controller kept the pressure near the desired limit of 60 bar with a maximum pressure of only 64.6 bar. Thus, the pressure overshoot was decreased from 59.9% during open-loop operation to 7.7% during closed-loop control. The controller also reduced the transient response with a settling time of 31.3 s to 11.3 s at 50% melt pump speed and 7.6 s to 5.8 s at 80% melt pump speed. Furthermore, the IAE, ISE and ITAE values were always reduced for all operating conditions, which indicated more accurate pressure regulation and better disturbance rejection.

From a practical point of view, the proposed controller is a simple and industrially applicable solution for the improvement of the safety and stability of PET extrusion systems. Implementation was done completely in the Siemens TIA Portal environment with standard PLC programming techniques, showing that good pressure regulation can be achieved without the need for special hardware or complex control algorithms. This makes the proposed approach appropriate for both retrofitting of an existing extrusion line and for new industrial automation systems.

The results obtained are encouraging, despite of the study was conducted in a simulated PLC environment with a simplified first order process model. Further research will involve laboratory-scale or industrial PET extrusion line validation of the proposed controller, study of nonlinear process dynamics, and study of higher order control techniques like adaptive control and model predictive control. The use of Industrial Internet of Things (IIoT) technologies for real-time monitoring, remote diagnostics, and predictive maintenance is another area of potential future research.

Finally, the proposed PLC based pressure override control strategy can be used effectively to control the end-barrel pressure of PET extrusion systems, so as to improve the stability of the PET extrusion process, and enhance the safety of operation and production reliability.

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