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EXPERIMENTAL STUDY ON ENERGY CONSUMPTION OF TEMPERATURE CONTROL BY USING ON-OFF INTELLIGENT FUNCTION

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Abstract. *In order to save electrical energy for on-off temperature control, a useful concept of on-off intelligent function to execute in a programmable logic controller (PLC) is presented. An implementation of PLC-based control system based on electric heating is also described as a case study to demonstrate the performance of the proposed function. IEC 61131-3-based ladder diagrams were created by using Studio 5000 software to run in the PLC modeled CompactLogix L30ER. Compared with the traditional on-off control action, the proposed on-off intelligent function can minimize energy consumption of a heater used in the implemented temperature control by 4.57%-6.65%.*

Keywords: Energy consumption, Intelligent function, On-off control, Programmable logic controller, Temperature control

1. **Introduction.** As an essential system to industrial manufacturers, temperature control should be well designed and properly installed for maintaining optimal conditions on a manufacturing process. Recently, various techniques to enhance operating efficiency, safety, and availability of hardware components used in temperature control have been introduced [1-5]. An optimal control method to design a temperature controller for improving transient responses of thermal inertia systems has been proposed [1]. In addition, for improving input tracking and load regulating responses of electric furnace temperature control, an optimization technique to design a proportional-integral-derivative-accelerated (PIDA) controller has also been suggested [2]. In order to demonstrate advantages of diagnostic capability of digital field instruments used in temperature feedforward control, practical techniques for Foundation Fieldbus-based device configurations to enhance process safety and production availability have been presented in [3,4], respectively. Moreover, to demonstrate advantages of diagnostic capability of WirelessHART devices for operations and maintenance, an engineering technique for system integration of temperature control based on proportional-integral-derivative (PID) algorithm and supervisory control and data acquisition (SCADA) has been proposed [5]. Additionally, an on-off controller is widely used for temperature control in heating applications because of its structure simplicity. However, its normal condition in steady state is sinusoidal cycling, and a controlled parameter will then constantly switch around a setpoint (SP). To overcome this

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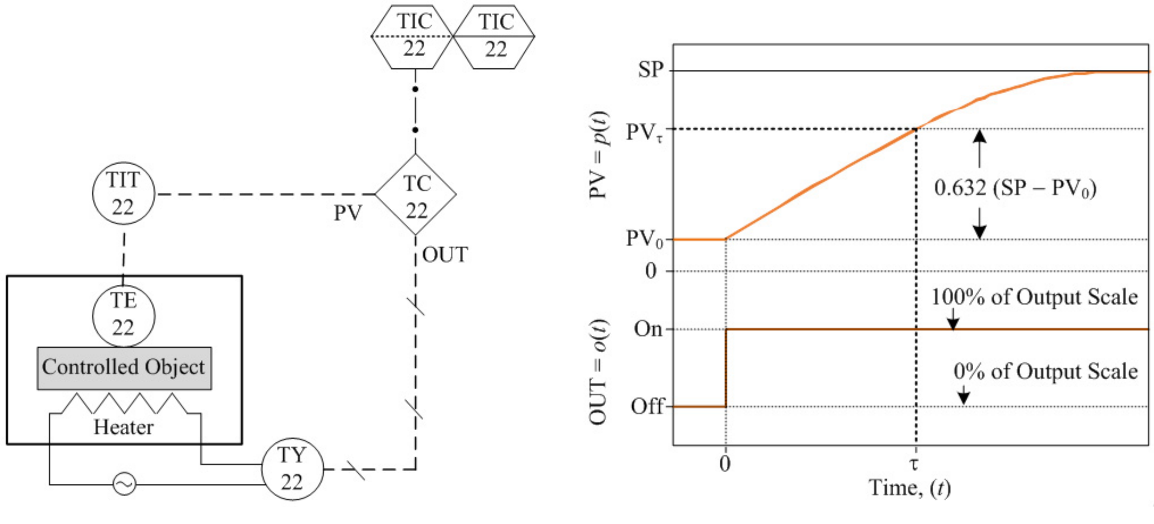
on-off control limitation, a correction method by using a programmable logic controller (PLC) has been suggested [6]. The on-off controller with additional correctors was implemented in ladder diagram of the PLC modeled S7-1200. However, in this article, the idea of utilizing the PLC for on-off control was developed in different way. This article aims to minimize energy consumption of a heater used in the PLC-based temperature control. The proposed power saving function is called 'on-off intelligent function', which was implemented in ladder diagram of the PLC modeled CompactLogix L30ER. Because industrial energy efficiency can provide environmental and financial benefits such as reducing greenhouse gas emissions and reducing energy costs to produce products and services [7-9].

The remainder of this article is organized as follows. The studied temperature control and concepts of traditional on-off action and on-off intelligent function are described in Section 2. Details of the PLC-based temperature control implementation and results of the experimental tests are presented in Section 3 and Section 4, respectively. Lastly, the conclusions and possible future work are summarized in Section 5.

2. Concept of Proposed On-Off Intelligent Function for Temperature Control.

Figure 1(a) shows a piping and instrumentation diagram (P&ID) of the interested temperature control, which is based on basic electric heating by regulating the temperature developed in the heater. A host (TIC-22), which may consist of engineering and operator workstations, is connected to the on-off controller (TC-22) not only for configuring control loop conditions and setting the desired temperature SP of a controlled object but also for monitoring control loop operations. A temperature indicator transmitter (TIT-22) coupled with a temperature sensing element (TE-22) is installed to measure the actual temperature, which is the process variable (PV) being monitored and controlled. The TC-22 performs calculations according to deviations between the desired SP and the measured PV to generate its output (OUT). Based on two-position control action, the controller OUT is in the form of an on-off signal for controlling operating statuses of a final control element (TY-22), which is a power regulator to turn on or off the heater. If the PV is less than the SP, the OUT will be 'On' (100% of output scale). Therefore, the heater is turned on by applying the '100%' power supply to increase the PV value. On the other hand, the OUT is 'Off' (0% of output scale), and the heater is turned off by applying the '0%' power supply to decrease the PV value. However, the control loop



(a) P&ID drawing (b) Open-loop step response

FIGURE 1. Studied temperature control based on basic electric heating

cannot respond instantly due to its capacitance or thermal inertia. The higher the inertia, the longer the time that it takes to react to changes in the PV. The inertia of the studied temperature control can be determined by a thermal time constant (τ). This means that the τ can describe how fast the PV (or $p(t)$) moves in response to the change in the OUT (or $o(t)$) as shown in Figure 1(b), which is the open-loop step response of the studied control system in manual mode to the step change in the OUT. The PV and OUT are initially set at steady state with $p(t) = \text{PV}_0$ and $o(t) =$ 'Off', respectively, for time $t < 0$. The desired SP is constant for the duration of the step change experiment. At time $t = 0$, the OUT is stepped to $o(t) =$ 'On'. In case of the first-order lag control system, the process variable rising in the exponential manner can be stated as

$$p(t) = \text{SP} - [\text{SP} - \text{PV}_0]e^{-t/\tau} \tag{1}$$

After the passage of one thermal time constant, the process variable at time $t = \tau$ (PV_τ) can be given by

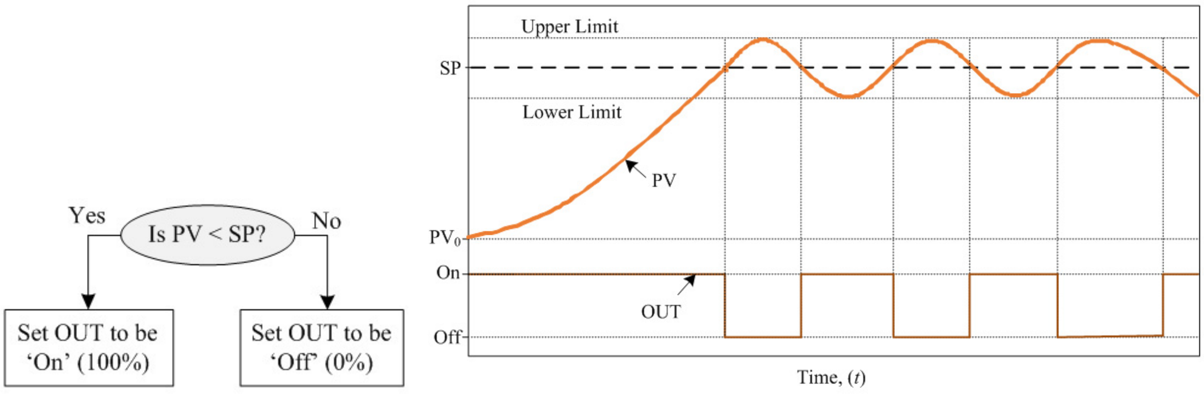
$$p(\tau) = \text{PV}_\tau = \text{SP} - [\text{SP} - \text{PV}_0]e^{-1} = \text{PV}_0 + 0.632(\text{SP} - \text{PV}_0) \tag{2}$$

The difference between the process variables at time $t = \tau$ and $t = 0$ can be written as

$$p(\tau) - p(0) = \text{PV}_\tau - \text{PV}_0 = 0.632(\text{SP} - \text{PV}_0) \tag{3}$$

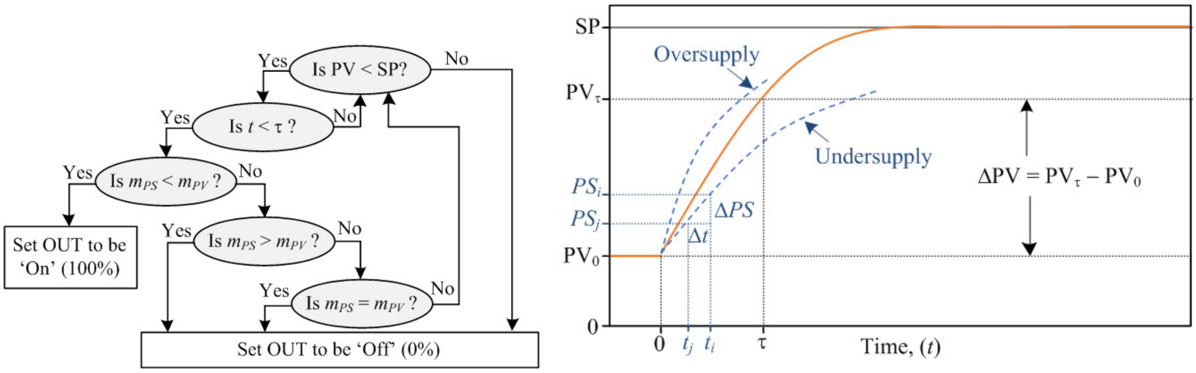
From (3), in one time constant, the PV value reaches 63.2% of its total change. It is shown that the smaller the time constant, the faster the process response.

Figures 2(a) and 2(b) display the concept and the plots of PV and OUT values against time t for running the traditional on-off control algorithm in automatic mode, respectively. The controller OUT causes changes in the measured PV to correct any deviation from the desired SP within an upper limit and a lower limit. The PV is increased by applying the 'On' OUT to the TY-22 to turn on the heater whenever it is below the target SP. If the PV rises above the SP, the 'Off' OUT will be applied to the TY-22 to turn off the heater for reducing the PV. In order to minimize the heater energy consumption for rising the PV to reach the SP during $0 < t \leq \tau$, Figures 3(a) and 3(b) illustrate the concept and the time plots of PV values for implementing the proposed on-off intelligent function. There are 3 specified cases to determine the controller OUT value to supply the power the heater; 'Undersupply' ($m_{PS} < m_{PV}$), 'Oversupply' ($m_{PS} > m_{PV}$), and 'Sufficient Supply' ($m_{PS} = m_{PV}$). The m_{PS} and m_{PV} denote the slope of the process variable being measured during $t_j < t \leq t_i$ from the closed-loop response and the slope of the process variable being measured during $0 < t \leq \tau$ from the open-loop response,



(a) Concept (b) Response

Figure 2. Concept and process response of the on-off control in automatic mode



(a) Concept (b) Response

FIGURE 3. Concept and process response of the proposed on-off intelligent function

respectively. Based on the closed-loop control scheme, the slope m_{PS} can be written as

$$m_{PS} = (PS_i - PS_j)/(t_i - t_j) = \Delta PS/\Delta t \tag{4}$$

where PS_i and PS_j are the process variables being measured at time t_i and t_j, respectively. The period of t_i is longer than that of t_j, and the difference between t_i and t_j (Δt) should be less than $\tau/10$. Based on the open-loop control scheme, the slope m_{PV} can be stated as

$$m_{PV} = (\mathrm{PV}_\tau - \mathrm{PV}_0)/(\tau - 0) = (\mathrm{PV}_\tau - \mathrm{PV}_0)/\tau \tag{5}$$

Compared with the open-loop step response, the 'Undersupply' happens when the process response of the closed-loop control is slower than the thermal time constant, whereas the 'Oversupply' happens when the process response of the closed-loop control is faster than the thermal time constant. In case of 'Sufficient Supply', the process response of the closed-loop control is the same as the thermal time constant. If the event of 'Undersupply' is detected, the proposed intelligent function, therefore, will set the controller OUT to be 'On' to fully supply the power of the heater. Otherwise, the proposed intelligent function will set the controller OUT to be 'Off' to shut off the power of the heater to reduce energy losses from the event of 'Oversupply' as well as the event of 'Sufficient Supply'.

3. **Implementation of PLC-Based Temperature Control.** To verify the performance of the proposed on-off intelligent function in terms of energy saving, the studied control system as shown in the P&ID of Figure 1(a) was implemented. Figure 4 shows an overall architecture of the implemented temperature control. At the control level, the PLC modeled CompactLogix L30ER is used as the controller TC-22, which is communicated to the engineering and operator workstations (TIC-22) through Ethernet connections. At the field level, the temperature of a cup filled with water of 300 ml in range of 0-100°C is defined as the PV, which is measured by utilizing the temperature transmitter modeled Rosemount 644. The measured PV in range of HART 4-20 mA is sent to an analog input module modeled 1769-IF4 of the PLC. The controller OUT in range of 4-20 mA is sent from an analog output module modeled 1769-OF4 of the PLC to the power regulator (TY-22) modeled Sangi SCR-1A030. The power supply values of the 1300w heater are 0 and 220 V$_{\mathrm{AC}}$/50 Hz when receiving the 4 mA ('Off') and 20 mA ('On'), respectively. In addition, electrical power consumed by the heater is measured in watt-hour (Wh) by using a power meter modeled PowerLogic PM5300, which employs the current transformer modeled METSECT5CC004 as a current sensing element. The power meter output is sent to the Modbus RTU module modeled MVI69L-MBS of the PLC to monitor the amount of heater power consumption. Figures 5 and 6 illustrate the flowcharts for PLC ladder diagram programming by using Studio 5000 software to operate the automatic temperature

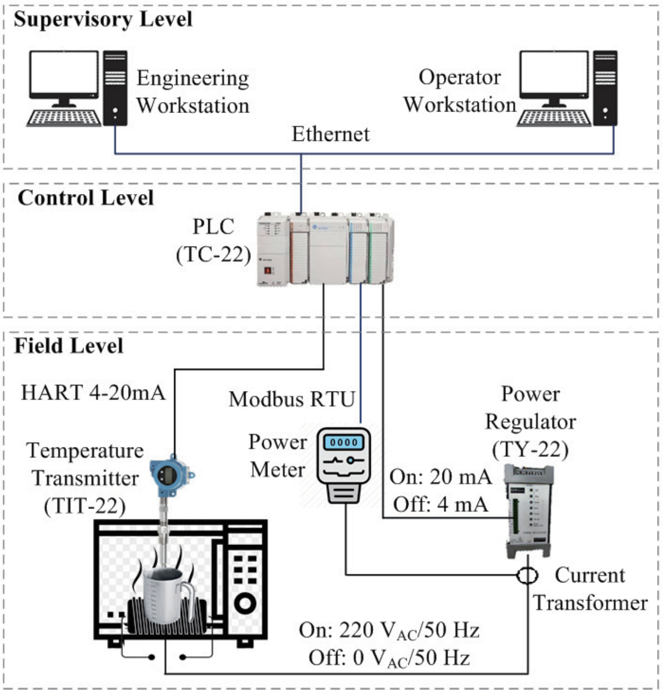


FIGURE 4. Overall architecture of the implemented temperature control

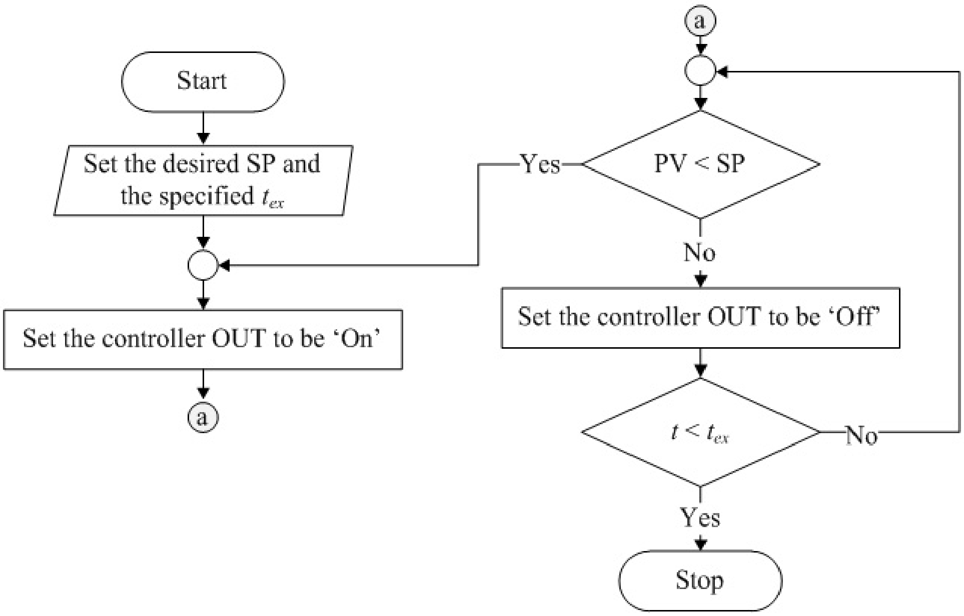


FIGURE 5. Flowchart for PLC programming when using the on-off control action

control based on the concepts in Figures 2(a) and 3(a), respectively. The default value of the controller OUT is set to be 'On', and the time period for experiment (t_{ex}) is set to be 30 min. From Figure 5, the PLC ladder diagram created for temperature control based on the traditional on-off action will set the OUT to be 'Off' in case of 'PV = SP' or 'PV > SP'. From Figure 6, the PLC ladder diagram created for temperature control based on the proposed on-off intelligent function to reduce energy consumption will set the OUT to be 'On' in case of '$m_{PS} < m_{PV}$' only. On the contrary, the OUT will be 'Off' in case of '$m_{PS} = m_{PV}$' or '$m_{PS} > m_{PV}$'. Figures 7(a) and 7(b) show the partial IEC 61131-3-based ladder diagrams in accordance with operating processes in the flowcharts of Figures 5 and 6, respectively, in the 'Run' mode.

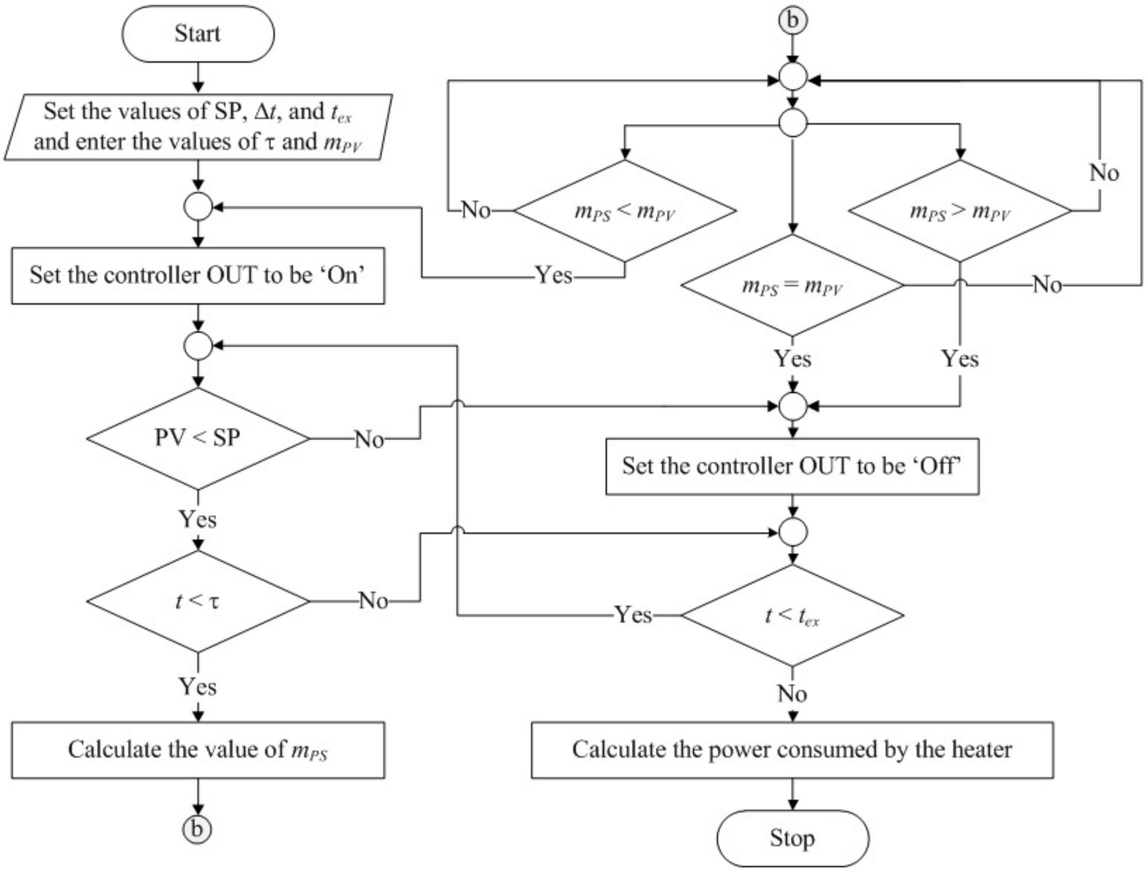
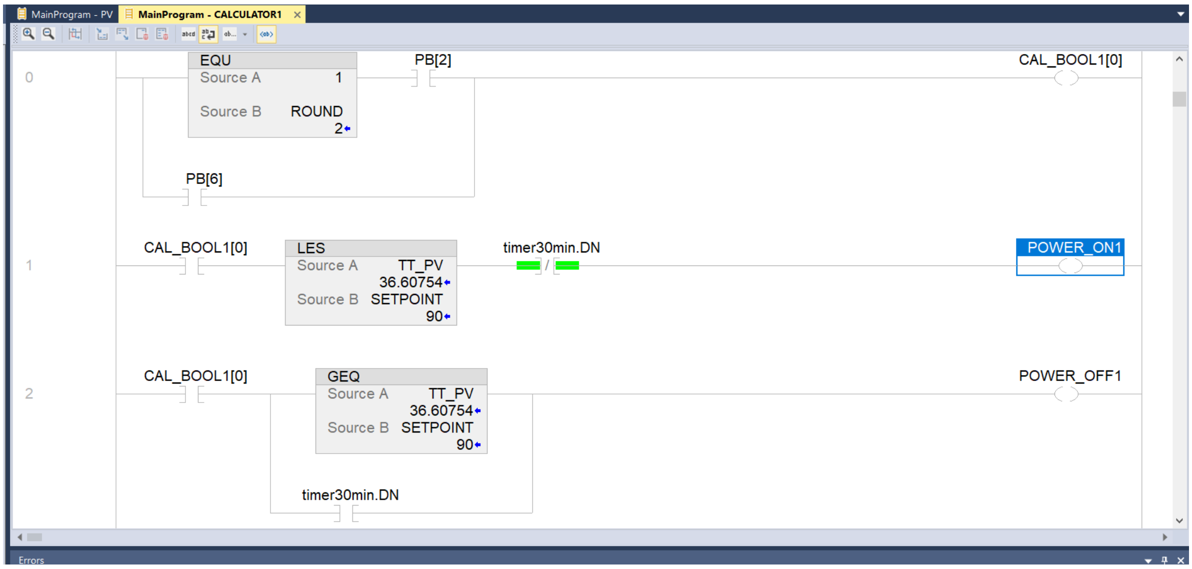
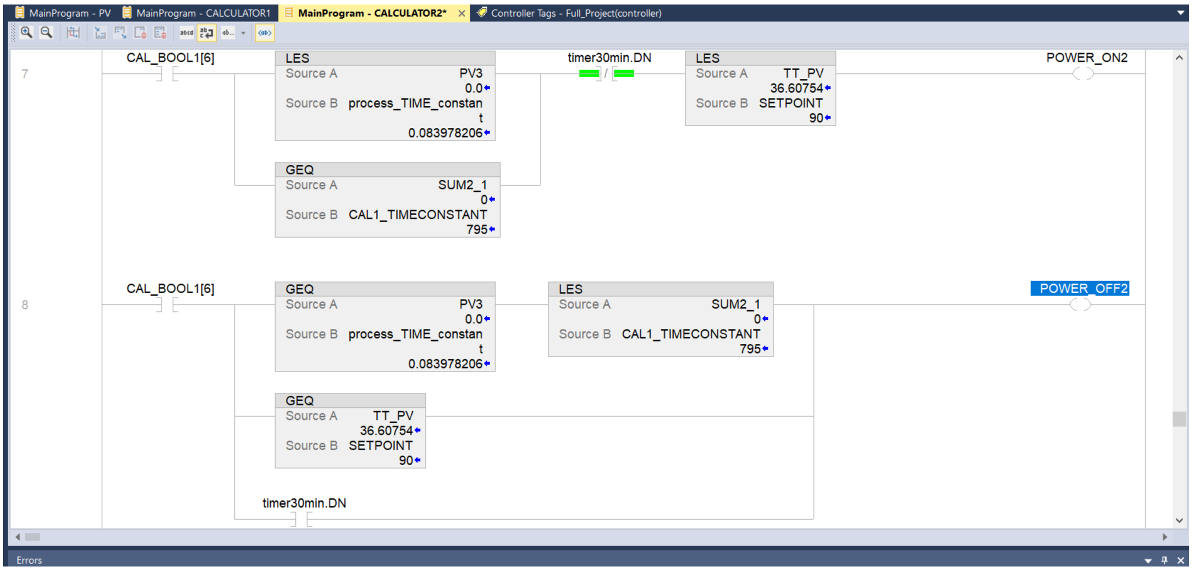


FIGURE 6. Flowchart for PLC programming when using the on-off intelligent function

4. **Experimental Test Results.** A step test of the implemented control system of Figure 4 in open-loop scheme was performed to determine its thermal time constant (τ), which is approximately equal to 625 s (for SP = 80°C) or 749 s (for SP = 90°C) when setting $\mathrm{PV}_0 = 25$°C. Therefore, the slopes $m_{PV} = 0.09591$°C/s and $m_{PV} = 0.08914$°C/s for the desired SP of 80°C and 90°C, respectively, can be obtained. For experimental test setup, $t_{ex} = 30$ min, $\Delta t = 1$ s, and $t_{ex} = 30$ min were chosen. Figures 8(a) and 8(b) show the experimental results of the implemented PLC-based temperature control by utilizing the traditional on-off algorithm and the proposed on-off intelligent function, respectively, in case of SP = 80%. It is seen that the measured PV curves of both Figures 8(a) and 8(b) are similar, but the on-off switching frequency of the controller OUT in Figure 8(b) during $0 < t < \tau$ is higher than that of the controller OUT in Figure 8(a). To demonstrate how the proposed on-off intelligent function can save electrical energy, the tests of the intelligent function-based temperature control were repeated 5 times in the same conditions for SP = 80% and SP = 90%. The calculated values of power consumption from experiments when setting SP = 80% and SP = 90% are summarized in Tables 1 and 2, respectively, where $\mathrm{P_{B80}}$ and $\mathrm{P_{B90}}$ are the powers consumed by the heater from using the basic on-off control algorithm in the event of SP = 80% and SP = 90%, respectively. The $\mathrm{P}_{\mathrm{I}80k}$ and $\mathrm{P}_{\mathrm{I}90k}$ denote the powers consumed by the heater from using the proposed on-off intelligent function in the event of SP = 80% and SP = 90%, respectively, and k $(= 1, 2, 3, 4, 5)$ is the experiment number. The average powers consumed by the heater in case of using the proposed function are less than the powers consumed by the heater in case of using the traditional on-off control action. It is apparent that the proposed on-off intelligent function can minimize the electrical power for the studied temperature control by 4.57%-6.65%.

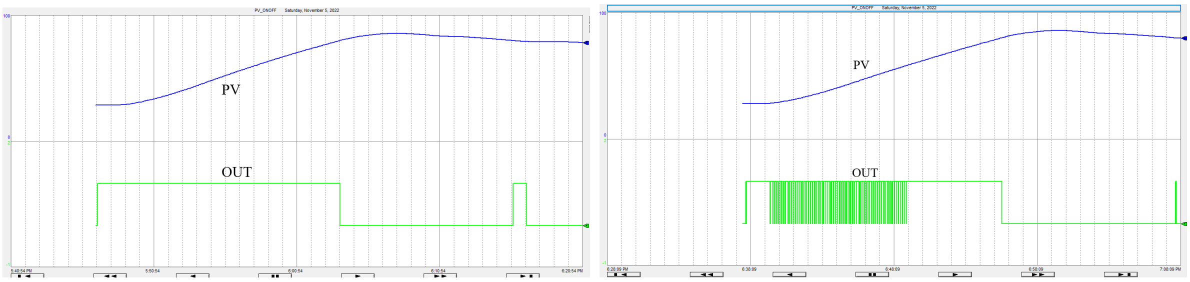


(a) Diagram based on Figure 5



(b) Diagram based on Figure 6

FIGURE 7. Partial ladder diagrams created for operating the studied temperature control



(a) Traditional on-off action (b) Proposed on-off intelligent function

FIGURE 8. Responses of the implemented temperature control for SP = 80%

TABLE 1. Power consumed by the heater for controlling the temperature at SP = 80%

Control algorithm	Power		Difference power		
	Parameter	Value (kWh)	Parameter	Value (kWh)	Value (%)
Traditional action	P_{B80}	341	P_{B80}-P_{B80}	0	0
Proposed function	P_{I801}	323	P_{B80}-P_{I801}	18	5.278
	P_{I802}	318	P_{B80}-P_{I802}	23	6.744
	P_{I803}	333	P_{B80}-P_{I803}	8	2.346
	P_{I804}	329	P_{B80}-P_{I804}	12	3.519
	P_{I805}	324	P_{B80}-P_{I805}	17	4.985
	P_{I80avg}	325.4	P_{B80}-P_{I80avg}	15.6	4.5744

TABLE 2. Power consumed by the heater for controlling the temperature at SP = 90%

Control algorithm	Power		Difference power		
	Parameter	Value (kWh)	Parameter	Value (kWh)	Value (%)
Traditional action	P_{B90}	412	P_{B90}-P_{B90}	0	0
Proposed function	P_{I901}	375	P_{B90}-P_{I901}	37	8.981
	P_{I902}	393	P_{B90}-P_{I902}	19	4.612
	P_{I903}	381	P_{B90}-P_{I903}	31	7.524
	P_{I904}	384	P_{B90}-P_{I904}	28	6.769
	P_{I905}	390	P_{B90}-P_{I905}	22	5.339
	P_{I90avg}	384.6	P_{B90}-P_{I90avg}	27.4	6.6504

5. **Conclusions.** An effective concept of on-off intelligent function to minimize electrical power consumption of temperature control based on electric heating has been presented. In order for demonstration of how the proposed concept works, engineering details for implementing the PLC-based temperature control have been described. Experimental test results of the implemented temperature control to compare the proposed on-off intelligent function with the traditional on-off control action have been demonstrated. Utilization of the proposed intelligent function in PID-based control systems to reduce their energy consumption is future work.

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