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Implementation of PID-based Control System for Heat Exchanger in an Energy Transfer Station for Chilled Water Plant

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***Abstract*—** This paper presents the implementation of PID (Proportional-Integral-Derivative) algorithm for a heat exchanger application. A heat exchanger application is developed in line with the ISA-95 automation pyramid with temperature sensors as level-0, PLC (Programmable Logic Controller) as level-1, and HMI as level-2. The PLC system based on ControlLogix and PanelView-Plus based Human Machine Interface (HMI) has been used for level-1 and level-2, respectively. RTD based temperature transmitters have been used as level-0 sensing devices. The simulation results have been performed in MATLAB and implemented in RSLogix-5000 PLC program.

Keywords—Resistance Temperature Detector, Thermocouple, Programmable Logic Controller (PLC), Direct Digital Controller, Energy Transfer Station, Human Machine Interface, MPC, PID

Resumen— Este artículo presenta la implementación del algoritmo PID (Proporcional-Integral-Derivativo) para una aplicación de intercambiador de calor. Se desarrolla una aplicación de intercambiador de calor en línea con la pirámide de automatización ISA-95 con sensores de temperatura como nivel 0, PLC (Controlador Lógico Programable) como nivel 1 y HMI como nivel 2. El sistema de PLC basado en Control Logix y la interfaz hombre-máquina (HMI) basada en PanelView-Plus se han utilizado para el nivel 1 y el nivel 2, respectivamente. Los transmisores de temperatura basados en RTD se han utilizado como dispositivos de detección de nivel 0. Los resultados de la simulación se realizaron en MATLAB y se implementaron en el programa RSLogix-5000 PLC.

Palabras clave: Detector de temperatura de resistencia, Termopar, Controlador Lógico Programable (PLC), Controlador Digital Directo, Estación de Transferencia de Energía, Interfaz Hombre-Máquina, MPC, PID

I. Introduction

The purpose of an Energy Transfer Station (ETS) is to transfer thermal energy from one location to another. The most modern ETS stations use the indirect method of energy transfer in which a heat exchanger is used to isolate the two locations to make sure that independent pressure conditions and temperature are maintained on both sides of the systems and water is not contaminated. The main components of an ETS are as follows: the pumps, heat exchangers, pressure independent control valves (PICVs), strainers, PLC, HMI, pressure transmitters, temperature transmitters, and flowmeters along with energy meters. An ETS has two distinctive sides: primary and secondary. The primary side is connected with the chilled water supply pipeline coming from the District Cooling Plant (DCP), while the secondary side connects the building facility with ETS.

The chilled water from the DCP enters the ETS through chilled water supply pipeline and returns back to the DCP through chilled water return pipeline and heat exchanger. Temperature and pressure gauges are installed on the supply and return pipelines for visual monitoring. An energy meter is installed on the supply pipeline and return pipeline that is connected with the flowmeter and temperature sensors to measure the total energy transferred to the building. A differential pressure transmitter is installed to measure the differential pressure between the primary and secondary sides. Temperature control valves installed on the supply pipeline and return pipeline transfer the energy to the secondary side at desired temperature. Temperature gauges and pressure gauges are installed on the pipelines for local monitoring while the

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temperature transmitters are installed for remote monitoring through PLC system.

An itemized study of the thermal storage tanks (TES tanks) is performed in [1] on the Dallas Airport chilled water system to verify that the reset schedule proposed guarantees that TES tanks meet the peak load requirement in the summer season. Low Delta-T syndrome is an undesirable phenomenon that happens when the design temperature difference between the chilled water supply line and the return line is not maintained. Low Delta T syndrome results in pushing the DCP to supply the chilled water to the plant at excess flow rates in order to maintain the desired temperature in the building. As the power output is directly related to the chilled water flow, a low Delta T syndrome results in excessive water flow but does not add the power to the water circuit. As a result, the ETS runs with lower efficiency, however, if the Delta T is maintained at the desired temperature, the ETS operates efficiently. In the otherwise case, a marginal increase in the cooling requirement increases the pumping energy exponentially.

In [2], it is shown that the underlying causes of low delta-T syndrome can be optimized and resolved by designing a cooling plant in line with international regulations, however, the rectification of some of the causes is not practical or possible. It is suggested that proper operation and maintenance of the cooling plant results in mitigating the low delta-T syndrome. In [3], it is suggested that by using variable speed chillers and implementing load-based speed control, the DCP yields commercial benefits by consuming lower utility loads and reducing the drainage of electricity and chilled water. Conventional constant speed chillers are shown to be inefficient and not environmental-friendly. The causes of low Delta T syndrome have been studied in [4] and the control system has been identified as one of the main contributing factors. The low Delta T syndrome may occur when the control system and related sensing devices are not properly selected and sized. The control system mainly consists of PLC with HMI and related sensors such as temperature sensor, pressure sensor, differential pressure sensor, flow sensor, and energy measurement. Temperature is one of the most important parameters in an ETS and contributes to its overall efficiency. In [5], a study related to problem detection and diagnostic approach to identify the causes of low delta-T syndrome in a sophisticated HVAC system is conducted and it is observed that improper set points of the sensors, the inadequacy of control calibration, and presence of uncontrolled process load in the control system are some of the major reasons for low Delta T syndrome. In order to prevent the low delta-T syndrome for chilled water systems, a study is performed in [6] to provide an online robust control technique. In addition to the traditional control strategies, a temperature set-point reset scheme is created with the goal of offering a trustworthy temperature set-point to increase the chilled water pumps' operational reliability. In order to diagnose the faults in the chilled water circuits of the buildings that cause the low delta-T syndrome, a mathematical model is built in [7] and it is observed that the overall delta-T of the system is suggested to be lower than the delta-T of the separate coils. Under conditions where individual loads are involved, this phenomenon becomes very important.

II. Control Philosophy in an ETS Station

A. *Background*

The DCP service provider keeps the supply chilled water temperature as low as agreed upon with users. In order to maintain the differential temperature and preserve the overall energy efficiency of the DCP plant, users usually have to keep the temperature of their returned chilled water at the level specified by the DCP service provider [8]. The primary and secondary water temperatures in an ETS are expected to fluctuate depending on the ambient temperature. This control technique will keep interior temperatures at a tolerable level while lowering energy expenditures [8].

B. *Traditional Control Technique*

The representation of a typical ETS is illustrated in Figure 1. Installing partial redundancy in the ETS heat exchanger is a common approach. Installing two heat exchangers with a 75% capacity is common. The two heat exchangers operate in tandem to reach their maximum capacity, however, one of them may be shut down for maintenance while the other is active during times of low demand, preventing a disruption in service [8]. Generally, for a typical ETS, two PID loops are configured to control the district cooling return water temperature to maintain the design setpoint based on the signal from the temperature transmitters by modulating the temperature control valves. The control valves are configured in a one-third and two-third flow arrangement respectively.

The control valves are sized and constructed in line with the overall thermal loads of the consumer. Oversizing of the valves results in the reduction of their lifecycle. Control valve actuators are chosen to work well with the heat exchanger's characteristics and are sized properly to ensure the opening and closing of the valves under the system's maximum pressure differential. Using two valves connected in parallel and functioning sequentially for higher flow rates is recommended. For optimum control in most situations, the two valves are sized to effectively manage one-third and two-thirds of the overall capacity, respectively.

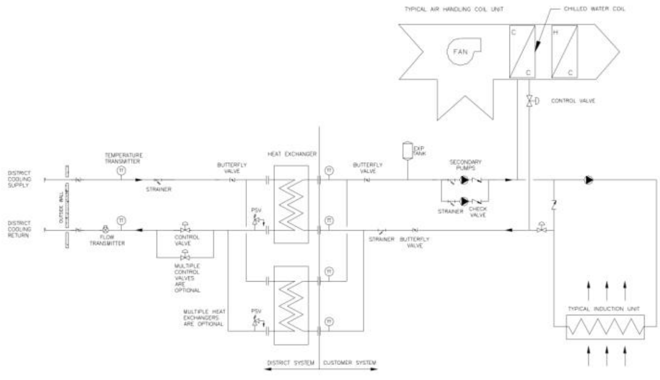

Figure 1 Typical ETS control system

III. Control of an ETS System based on the PID Technique

A. *Control System Block Diagram*

The block diagram of an ETS System is shown in Figure 2. The Plant block represents the heat exchanger. Based on the temperature setpoint, the controller compares the temperature signal from the temperature sensor and manipulates the output to the actuator to control the flow rate of the chilled water in the chilled water return pipeline by controlling the opening of

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the control valve. The control valve is fitted with an electric actuator to control the position of the butterfly valve assembly.

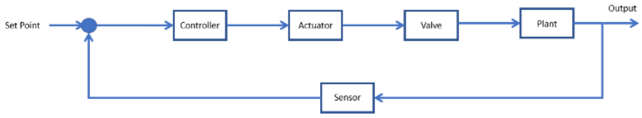


Figure 2 Block diagram of the ETS system

B. *Derivation of Transfer Function*

In order to implement and analyze the PID control loop, the transfer function of the temperature sensor, valve and actuator, and plant have been calculated.

Two independent constraints precisely and steadily regulate the capacity of a heat exchanger. The first restriction is based on how well the valve's flow characteristic matches the coil's or heat exchanger's performance characteristics. The second constraint, which is much more important, determines what proportion of the heat exchanger's design capacity will be uncontrollable. The relationship between capacity and flow rate for a heat exchanger is essentially logarithmic. This curve's precise shape depends on the design of heat fluid process parameters, and the media's temperature exchanger, face velocity, process parameters of the fluid, and the temperature of the media. The relationship between the degrees of disc rotation and heat exchanger capacity will be largely linear when a heat exchanger performance characteristic is combined with an equal percentage valve flow characteristic. The relationship between design flow rate and design capacity in percentage is given in figure 3.

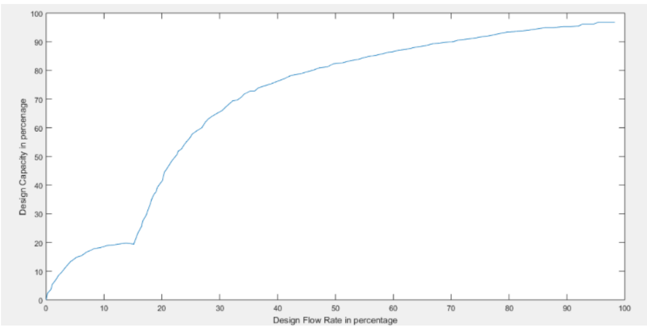
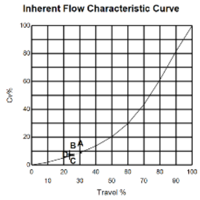


Figure 3 Performance Characteristics of a heat exchanger for water at 10 Deg C

The ability of a valve to proportionally control a heat exchanger's capacity is crucial when choosing a valve. When a valve is first opened, there is always some flow that can't be controlled. When a globe valve is involved, it happens when the plug is first lifted off the seat. When the disc first clears the seat material in a butterfly valve, this uncontrollable flow happens. This rotates between 10° and 20°, depending on the size of the valve. In order to size the control valve for this application, the butterfly valve has been sized to ensure that there are enough pressure drops to offer strong control authority and the pressure drop across the control valve is at least equal to the total pressure drop across the heat exchanger, flow meter, and related piping and machinery. Around 50% of the total system differential pressure (DP) has been applied to the pressure drop through the control valve. Figure 4 provides the sizing calculation of the valve. The valve has been sized based on four conditions and pressure recovery factor, sizing coefficient and valve diameter have been calculated accordingly.

Item Description	8", CL 150, Lug			
SERVICE AND SIZING	Cond1	Cond2	Cond3	Cond4
Process Fluid Name	Water			
Inlet Pressure (bar[g])	1	2	2	2
Outlet Pressure (bar[g])	0.5	1.24	1.24	1.24
Liquid Flow (gpm (US))	675	673.571	673.571	673.571
Vapour Pressure (bar[g])	-1.01	-1.01	-1.01	-1.01
Specific Gravity	1	1	1	1
Temperature (°C)	4	4	4	4
Pressure Recovery Factor, FL	0.866	0.862	0.862	0.862
Valve Style Modifier Factor, Fd	0.381	0.363	0.363	0.363
Combined Recovery Factor, FLP	0.862	0.859	0.859	0.859
Piping Correction Factor, Fp	0.998	0.999	0.999	0.999
Critical Pressure Ratio Factor, Ff	0.959	0.959	0.959	0.959
Valve Diameter, d (in)	8"	8"	8"	8"
Inlet Pipe Diameter , D1 (in)	10.75	10.75	10.75	10.75
Outlet Pipe Diameter, D2 (in)	10.75	10.75	10.75	10.75
Cavitation Index, Kc	0.249	0.252	0.252	0.252
Dynamic Torque	188	222	222	222
Sizing Coefficient, Cv	251	203	203	203
Pressure Drop (bar)	0.5	0.76	0.76	0.76
dP Choked (bar)	1.5	2.2276	2.2276	2.2276
Noise Calculation				
Valve Type	Butterfly	Butterfly	Butterfly	Butterfly
Downstream Pipe Size (in)	10	10	10	10
Downstream Pipe Schedule	STD	STD	STD	STD
Valve SPL (dBA)	55	56	56	56
Velocity				
Inlet Velocity (ft/s)	2.757	2.752	2.752	2.752
Outlet Pipe Velocity (ft/s)	2.757	2.752	2.752	2.752
Valve Velocity (ft/s)	4.308	4.299	4.299	4.299

Valve Series :	Series 41
Valve Size:	8"
Rated Cv:	2800
Flow Char:	Equal Percentage



% Opening, Calculated Cv
A - (30.4,251)
B - (25.8,203)
C - (25.8,203)
D - (25.8,203)

Travel (%)	10	20	30	40	50	60	70	80	90	100
Cv	58.5	145	245.5	385.6	570.5	835	1219	1718	2287	2800

Figure 4: Sizing calculation of the butterfly valve

The actuator for the valve has been sized for the valve and the sizing calculation is given in Figure 5 and the Maximum Allowable Stem Torque (MAST) to which the quarter-turn valve stem can be subjected during operation without mechanical failure is calculated to be 5544 lbs.-in.

Item Description	8", CL 150, Lug, Electrical
ACTUATOR SIZING	
Valve Size (in)	8
Media	Water
Temperature (°C)	20
Maximum Inlet Pressure (bar[g])	2
Maximum Pressure Drop (bar)	0.76
Shut off Pressure (bar[g])	8
MAST (lbs-in)	5544
Basic Torque (lbs-in)	1414
Safety Factor	1
Torque with Safety factor	1414
Actuator Type	Electrical
Available Supply Voltage	120 VAC
Manual Override	No
Avail. Actuator Torque (lbs-in)	2000

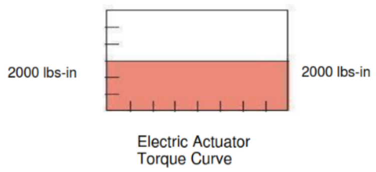


Figure 5: Sizing calculation of the actuator for butterfly valve

The block diagram of a control valve is shown in Figure 6. The gain of the control valve is the steady state change in the output of the control valve with respect to the input.

Figure 6: The block diagram of the valve with the actuator

The transfer function of the butterfly valve has been calculated as below:

$$Transferfunction = Kv/(\tau_v s + 1)$$

Kv= Valve Gain

τ_v= Time Constant of the valve Actuator

For this experiment, a butterfly valve from Bray has been considered fitted with an electric actuator to perform the modulating action. The actuator is fitted with a solid-state speed control module with 120 seconds of valve opening/closure time. The actuator has electronic proportional control with a servo amplifier capable of accepting 4 to 20 mA valve modulation. The valve Gain calculated for this experiment is 6.7 GPM / % Control Output and the time constant τ_v is 2 minutes. The transfer function of the valve has been calculated as below:

$$Transferfunction = 6.7/(2s + 1)$$

Transfer Function of the Temperature Sensor

The transfer function of an RTD sensor is governed by the following equation:

$$Rt = Ro(1 + \alpha \Delta T)$$

Where Rt is the resistance of the RTD sensor measured as a function of the process temperature. Ro is the resistance of the RTD sensor at 0°C which is 100 Ω in the case of Pt-100 sensor. α is the temperature coefficient while ΔT is the difference in temperature. The transfer function of the RTD sensor as calculated for this experience is below:

$$Transferfunction = 1/(0.1s + 1)$$

The transfer function of the heat exchanger has been estimated based on the historical data collected from an ETS station and is given as below:

$$\text{Transfer function} = \frac{70e^{-2s}}{20s + 1}$$

The total transfer function would be as below:

$$Transfer\ function = \frac{63.47}{40s^2 + 22s + 1}$$

C. *Tuning of the PID controller*

It was observed that process value (PV) and the setpoint value (SP) differ significantly in the temperature control process. The PV begins at 0°C of this temperature feedback loop and advances toward the SP value of 4°C, over time, the variation between the high and low manipulated value (MV) reduced and stabilized. It was noted that the values used for each of the P, I, and D parameters affect how the MV behaves.

While tuning the PID loop, it was noted that the process value changes slowly during the summer season, hence, the PID loop tuning was started with greater gains and lower resets, between 3 and 6, and 0.02 and 0.4, respectively. As a result of setting the gains, it was noted that the process variable moves slowly and the gain parameter was changed, and the outcome was tracked until the stable process was achieved. The same activity was repeated for the second parameter for the sable process achievement.

Figure 7 and figure 8 show the step response and reference tracking of the ETS plant respectively.

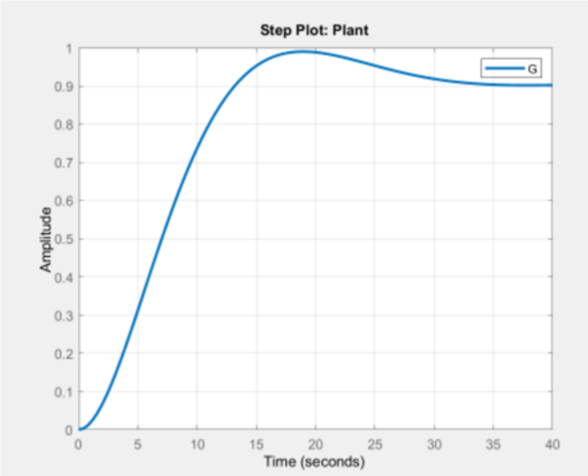


Figure 7: Step response of the ETS plant

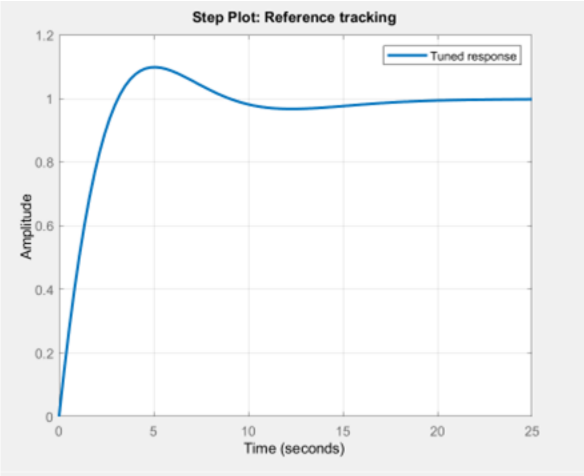


Figure 8: Tuned Response of the ETS plant.

Controller Parameters

	Tuned
Kp	7.4369
Ki	0.99273
Kd	13.9282
Tf	n/a

Performance and Robustness

	Tuned
Rise time	2.29 seconds
Settling time	15.8 seconds
Overshoot	9.85 %
Peak	1.1
Gain margin	Inf dB @ NaN rad/s
Phase margin	69.2 deg @ 0.66 rad/s
Closed-loop stability	Stable

Figure 9: Controller Parameters.

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IV. PID BASED CONTROL SYSTEM TEST SETUP

A. *PLC based Control System Setup*

Brick-style controller with embedded inputs and outputs based on MicroLogix 1500 series controllers from Rockwell Automation has been used for the PID loop implementation. MicroLogix series controllers come with 14 digital inputs and 8 digital outputs as embedded inputs and outputs. To implement the PID loop, the controller needs analog input and analog outputs. Hence, an analog input module and an analog output model have been considered as mentioned in figure 11 & figure 12.

Figure 10: PLC for PID loop implementation

The analog input module with part number 1769-IF4 Allen-Bradley has been considered which offers 2-channel, non-isolated, unipolar voltage/current analog input signal with 12-bit resolution and data range of 0 to 65535 bits. To interface the RTD sensor with the analog input module, the analog signals have been configured to take 4 to 20 mA current input signal as shows in Figure 6.

Figure 11: Analog input module configuration to take 4 to 20 m A input signal from the RTD sensor

The analog output module with part number 1769-OF4 Allen-Bradley has been considered which offers 2-channel, non-isolated, unipolar voltage/current analog output signal with 12-bit resolution and data range of 0 to 65535 bits. To interface the control valve with the analog output module, the analog signals have been configured to 4 to 20 mA current output signal as shown in Figure 8.

Figure 12: Analog output module configuration to send 4 to 20 m A output to control valve

B. *PID loop Implementation*

By modifying the control outputs, proportional-integral-derivative (PID) control enables the process control to precisely maintain the setpoint. All of the logic required to implement proportional/integral/derivative (PID) control is combined in a PID function block used for this experiment and the proportional-integral-derivative (PID) logic's inputs and outputs have been configured accordingly. The PID functional block used in this experiment processes the control loops to determine an error value as the difference between a desired setpoint and a measured process variable to control the physical attributes like temperature in this case. The controller functional block is used to alter the control variable in an effort to reduce the error over time. The terms utilized in the calculation are proportional (P), integral (I), and derivative (D) terms where the proportional (P) term alters the present values of the error, integral (I) term takes care of the past values of the error while based on the error's present rate of change, potential values for the error in the future are altered by the derivative (D) term. By tuning the proportional, integral and derivative terms, the process variables temperature and flow rate through the control valve are controlled.

The PID ladder used for this experiment is known as IPIDCONTROLLER function ladder and is shown in figure 13 with the arguments with the details of arguments is given in table 2.

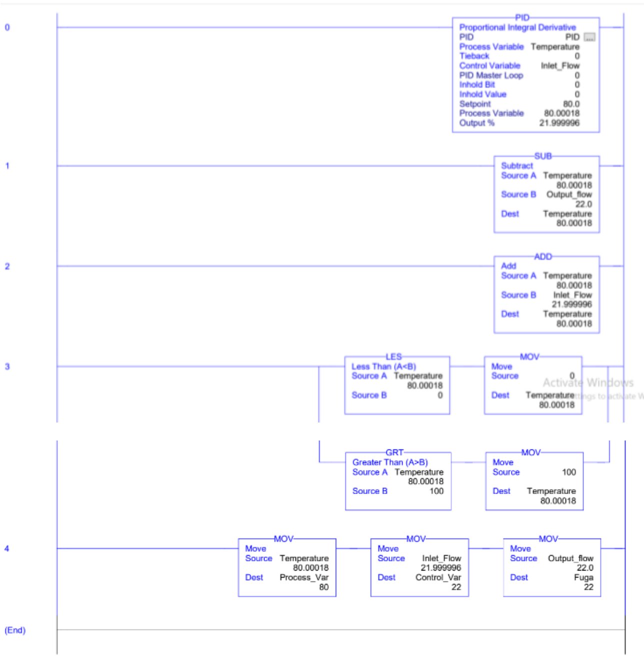

Figure 13: Ladder Logic Diagram

Parameter	Parameter Type	Data Type	Description
			Function block enable
EN	Input	BOOL	TRUE = Execute function.
			FALSE = Do not execute function. Applicable to Ladder Diagram programs.

Process	Input	REAL	Process value, which is the value measured from the process output.
Setpoint	Input	REAL	The set point value for the process.
			Feedback signal, which is the value of the control variable applied to the process.
Feedback	Input	REAL	For example, the feedback can be IPIDCONTROLLER output.
			Operating modes of PID controller: TRUE =
Auto	Input	BOOL	Normal operation of PID. FALSE = Output tracks Feedback.
			A change in value
Initialize	Input	BOOL	(TRUE to FALSE or FALSE to TRUE) causes the controller to eliminate any proportional gain during that cycle. It also initializes AutoTune sequences.
			Gains PID for IPIDCONTROLLER.
Gains	Input	GAIN_PID	Use the GAIN_PID data type to define the parameters for the
			Gains input.
AutoTune	Input	BOOL	TRUE = Autotune. FALSE = No Autotune.
			AutoTune parameters
ATParameters	Input	AT_Param	Use AT_Param data type to define the parameters for the
			ATParameters input.
Output	Output	Real	Output value from the controller.
AbsoluteError	Output	Real	Absolute error (Process - SetPoint) from the controller.
			Warning for the AutoTune sequence. Possible values are:
			0 = No auto tune done.
			1 = In auto tune mode.
ATWarnings	Output	DINT	2 = Auto tune done.
			-1 = Error 1: Input automatically set to TRUE, no auto tune possible.
			-2 = Error 2: Auto tune error, the ATDynamSet expired.
OutGains	Output	GAIN_PID	Gains calculated from AutoTune Sequences.
			Use GAIN_PID data type to define the OutGains output.
ENO	Output	BOOL	Enable output.
			Applicable to Ladder Diagram programs.

Table 1 Arguments details of PID controller function block used for this experiment.

The PID loop is implemented using the functions mentioned in Table 1. The raw value coming from the temperature transmitter is converted to the real value for processing in the PLC system. After getting the real value, scaling is performed on the real number to perform computations on the signal, which is a current output from a sensor to make it meaningful to the operator in the control room in terms of engineering units. The output from the scalar is fed to the IPIDCONTROLLER functional ladder and PID parameters are set in HIM. The output from the PID functional ladder is scaled again to convert the variable to real number and a 4 to 20 m A output signal is generated which is sent to the actuator of the control valve.

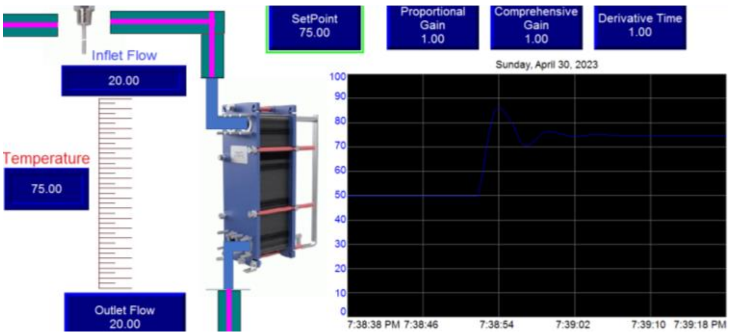

Figure 14: Functional HMI of PID loop implemented in Rockwell Automation-based PLC system

V. Conclusion

This research paper examines PID based control approach to controlling the output fluid temperature using a case study of a heat exchanger system in an ETS station. The response of individual transfer functions as well as overall transfer function against the step signal has been studied and PID control algorithm has been implemented to improve the settling time, rise time, percentage overshoot and the system stability using MATLAB. The system has been implemented using Rockwell based PLC and SCADA system. It has been concluded that PID control significantly improved the response of a heat exchanger.

ACKNOWLEDGMENT

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