2014 11th IEEE International
Conference on Control & Automation (ICCA)
June 18-20, 2014. Taichung, Taiwan

REALIZATION OF ADAPTABLE PID CONTROLLER WITHIN AN INDUSTRIAL AUTOMATED SYSTEM

Mostafa Abdel-Geliel*, F. Qaud, H. A. Ashour**

Abstract—**this paper describes and implements an a real control technique using advanced automation technology. PID controller is one of the most controller used in industrial but it need to be adaptable in real situation in order to overcome the parameter variation and system disturbance. An adaptable PID controller based on analogical gate technique is implemented using an industrial Programmable Logic Controller (PLC) to control the temperature of a process by actuating of a three way valve. The valve distributes the hot and cooled air in order to adjust the temperature of a vessel. The system control hardware consists of first; PLC as a field controller with high sampling rates, second; Human Machine Interface (HMI) as a local operating and adjusting station, finally; SCADA software to adjust and supervise the overall system. The process parameter estimation, simulation results and practical results are obtained and compared for system validation. A comparison between conventional and the proposed adaptable one performance is introduced, showing merits and effectiveness of proposed algorithm.**

Key words: PLC, HMI, industrial automation, adaptable PID

I. INTRODUCTION

Industrial automation is the use of control systems, such as computers, to control industrial machinery and processes, replacing human operators. Automation greatly reduces the need for human sensory and mental requirements as well [1]. Although there is still a gap between most advanced automated systems and human natural capabilities; for example, no device has been invented which can match the human eye or ear for accuracy and precision in many tasks; industrial production is increasingly depending on automation. The automation cycle can be arranged as; the human operator (supervisor) gives commands to the control system, then it manipulates the command and feedback signals from sensors and produces a control signals that can be transformed into action through the actuators. Recently, programmable (digital) systems, such as industrial PC, Microcontroller and PLC, are dominated in control system implementation. The control tasks of an industrial process, using digital controller, are classified into Sequence control, Direct Digital Control (DDC) and Supervisory control. These tasks can be carried out using single control system or multi-control system. Therefore, the control system may be centralized or distributed [2].

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Temperature control plays an important role in most of real industrial system, such as steam generation, metal processing, paper production, air conditioning, etc., in order to satisfy the performance index either in transient or steady state. Most of temperature control systems are of complex nature and have multi variables. Moreover they have delay time. Hence, temperature controller should be robust and adaptable to deal with this problem efficiently. Unfortunately, most of the modern control techniques, which solve these problems, are not applied in industry due to the limitation of industrial controller either in functionality, response time or cost. Many techniques of temperature control are scattered in literature, either classical, such as PID and adaptive PID, or modern, such as Fuzzy, Adaptive Fuzzy and Model Predictive Control (MPC) as given for example [3], [4], [5] and [6]. Rare of those techniques can be implemented using PLC in low level of automation due to the time and computation constraints, but they are frequently implemented in high level (Distributed Control Level) which has a high capability of computation and processing time. Since, many of advanced control techniques are addressed by researchers, most of them are still difficult to implement specially in most of industrial system that have upto level three (field level, individual control level and group control level) of automation hieratical [7].

PID controller structure is simple and it can satisfy the requirements of many industrial processes. Therefore PID control is still the most widely used control law in most industrial loop. However, for some complex processes, such as systems with large time lag or inertia, it is difficult for the conventional PID controller to obtain better control effect. So the main objective of the work is to implement PID and adapted PID based on analogical gate in the field level (lower level of automation hierarchy) using PLC.

The proposed controller is tested and implemented for a real industrial temperature process in the field level (PLC). The process is supervised using an HMI and SCADA system. The HMI is used to monitor, tune and operate the process locally, while SCADA software is used to supervise, operate, tune identify the system remotely. The control task of the process is shared between the field level individual controller (PLC) and SCADA system. Since the main control loop requires fast scan time, the main control loop is carried out in the field level controller. While the parameter estimation and tuning process require slower scan time then they are carried out in SCADA plate form.

II. PROCESS DESCRIPTION

Most of industrial applications have a temperature control loop in one or more of their processing stages. Such as steam generation in power plant and boiler, food processing, metal production and processing, air conditioning etc.. Three-way-valve is one of the actuating valves that are used in many temperature control loop to regulate a fluid temperature by mixing a fluid of high temperature (hot) with another of low temperature (cold), such as in air flow temperature control in fuel combustion subsystem in boiler [8]. controlling temperature by employing three-way valve increase the complexity of the system due to its nonlinear characteristics and dead time . Therefore, the main purpose of the proposed temperature controller unit is to present a real temperature process, as in air conditioning, by heating up a particular liquid to a desire temperature with the minimum overshoot and quickest time constant. The overview of the process is shown in Fig.3; the process consists of three-way-valve to distribute the pumped air between cooler and heater subsystem according to the required temperature, then the heated and cooled air are mixed in a vessel (reservoir) which stores the heated air at a certain temperature. The setup has industrial components that have the same range of industrial signal level and power . The three way valve is controlled by a current signal 4-20mA that is converted to a pneumatic signal (0-150psi) using current to pressure converter. An industrial programmable logic controller (PLC) is utilized to control the temperature of the process by actuating the three way valve. Depending on the output of the controller, the valve can direct the flow totally to heater or cooler, or partially to both of them. The process fluid flow operation is illustrated Fig. 1; F_t is the total flow, F_h and F_c are the flow rate of hot and cooled vessel respectively, T_{in} is the inlet temperature of the direct flow, T_h and T_c are the temperature of hot and cooled tank respectively and F_i is the input flow rate to reservoir where the total temperature (T_t) is measured.

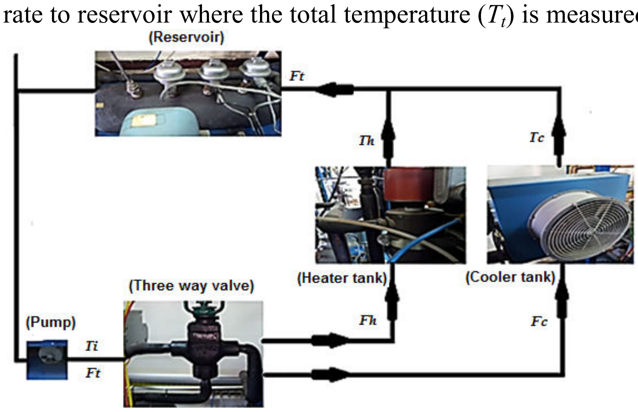


Fig. 1. The temperature process control unit

III. SYSTEM MODELING

Mathematical modeling of the process is used to simulate, validate and test the controller in addition to determine the initial parameters of the controller. Therefore an approximate model of the process is deduced. Modeling allows translating the process and its objectives into the abstract mathematical formulation [9] . Table 1 lists symbol and definition of the parameters and variables used in the given modeling equations (1)-(6).

The system dynamics is obtained through an energy balance rule applied to every element of a lumped model [10], [11].

TABLE 1: NOMENCLATURE

C_{pc}	Specific heat in the cold side, J/(kg C)
C_{ph}	Specific heat in the hot side, J/(kg C)
T_i	Inlet temperatures in the cold and hot sides, respectively, C
T_h, T_c	Outlet temperatures in the cold and hot sides, respectively, C
Q_h, Q_c	The amount of heat and cooled stem
F_c	Flow rate in the cold side, m3/s
F_h	Flow rate in the hot side, m3/s
F_t	Total pumped flow (F_i)
V_c	Volume in the cold side, m3
V_h	Volume in the hot side, m3
ρ_c	Density of the cold fluid, kg/m3
ρ_h	Density of the hot fluid, kg/m3
m	Mass of water Kg/liter
$T_{sth,}, T_{stc}$	The saturated temperature of the steam in the coil.

The outlet temperature of hot and cooled side can be given by:

$$\frac{dT_h(t)}{dt} = \frac{F_h(t)}{v_h}(T_i(t) - T_h(t) + \frac{Q_h}{\rho_h C_{ph} v_h} \quad (1)$$

$$\frac{dT_c(t)}{dt} = \frac{F_c(t)}{v_c}(T_i(t) - T_c(t) + \frac{Q_c}{\rho_c C_{pc} v_c} \quad (2)$$

Furthermore, the amount of heat and cooled flow$F_h$and$F_c$respectively can be given by the following transfer rate equation:

$$\left.\begin{aligned} F_h(t) &= \delta F_t \\ F_c(t) &= (1-\delta) F_t \end{aligned}\right\} \quad (3)$$

Where $\delta \in [0,1]$ is the valve opening ration and the amount of heat supply and removed are given by :

$$\left.\begin{aligned} Q_h &= mC_{ph}(T_{sth} - T_i) \\ Q_c &= mC_{pc}(T_{stc} - T_i) \end{aligned}\right\} \quad (4)$$

Then the total temperature in reservoir can be given by:

$$\frac{dT_t(t)}{dt} = \frac{F_h}{v} T_h(t) + \frac{F_c}{v} T_c(t) - \frac{(F_h + F_c)}{v} T_t(t) \quad (5)$$

The relation between valve control signal (*u(t))* and valve opening δ is given by

$$\delta(t) = g(u(t - t_d)) \quad (6)$$

where g is a nonlinear function with time lag (t_d). The function g contains all valve coefficient and dynamics.

IV. PARAMETER ESTIMATION

Not all the model parameters are known. Unknown parameters like flow rate (F_t), valve coefficient (C_v), specific heat and in both hot and cold side, etc. Some of the unknown parameters are estimated using parameter estimation .

In parameter estimation, the values of the unknown parameters of a parameterized model structure are estimated. Recursive Least Square (RLS) [12] method is one of the most common parameter estimation techniques.. The process output can be represented by [12]:

$$y(k) = \theta^T \phi(k) + \xi(k) \quad (7)$$

where y(k) is the scalar output of the system; θ^T is the true parameter vector of the system of size N × 1; $\phi(k)$ is the input vector of size N × 1; and $\xi(k)$ is system noise.

The basis for the identification procedure is experimental planning, where process experiments are designed and conducted so that a suitable data is obtained by applying variable control signal to the three way control valve and measuring the corresponding temperature in reservoir as shown in Fig.2 and Fig.3.

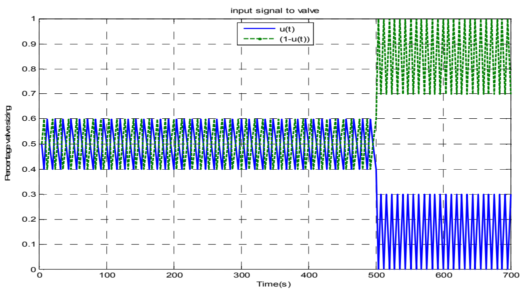


Fig. 2. Input signals for three way control valve

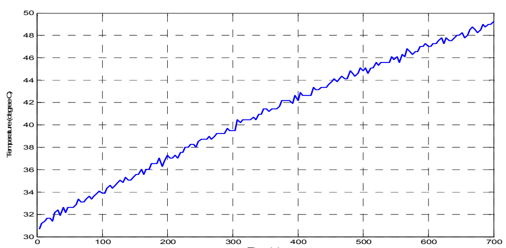


Fig. 3. Measured temperatures

The estimated parameter is given by:

$$\hat{\theta} = [\phi^T\phi]^{-1}\phi^T y \qquad (8)$$

The known parameters and the estimated parameter, which are used in simulation, are listed Table 2.

TABLE 2: PHYSICAL DATA USED IN SIMULATION

Constant	value	units
V_h	3.5×10^{-3}	m^3
V_c	1.5×10^{-3}	m^3
V_t	8.5×10^{-3}	m^3
ρ	1000	kg/m^3
c_p	0.00491	$J/(kg\,C)$
F_t	2×10^{-5}	m^3/s
m_h	3.5	kg
m_c	1.5	kg
T_{sth}	100	°C
T_{stc}	15	°C

V. PROPOSED ADAPTABLE PID CONTROLLER

Since obtaining an accurate mathematical model is so difficult in addition to parameter uncertainties and disturbance, adapted PID controller is preferred. The adaptation of PID is carried out using analogical gate [14]. Analogical gates are a method of describing multi-valued logical statements. The scope of operation of binary logic based systems to true multi-valued logic-based systems is widened based on analogical gate. Furthermore, the design and implementation of these gates for practical physical systems have proven to be efficient and simple [13] and [14]. Analogical gates are of two kinds; symmetric and asymmetric. Symmetric gates perform commutative operations similar to their logical counter parts OR, AND and XOR. Asymmetric gates perform competence operations [15].

In adaptable PID controller, two gates are employed OR and Invoke gates. Furthermore, another analogical XOR gate is employed for anti-reset windup [16].

A. *Analogical-OR*

In the analogical-OR gate, both inputs contribute to the output in relation to their magnitudes and in the absence of one input; the output linearly tracks the other. The used formulation for the analogical OR-gate [14] is:

$$z = x \oplus y = x\xi(y,x) + y\xi(x,y) \qquad (9)$$

Where $\xi(x,y) = e^{-\left(\frac{ax^2+bxy}{x^2+y^2}\right)}$ *and* $x, y \in R$

The parameter a and b is taken as $a = 1.02889$, $b = 0.3574$.

B. *Analogical-Invoke*

The invoke gate is characterized such that as the x-input grows, the share of the y-input to the output increases. The absence of the x-input inhibits the output. In the absence of the y-input, the x-input is linearly passed to the output. The used formulation or Invoke gate is [15]:

$$z = x \wedge y = x\xi_1(y,x) + y[1-\xi_2(x,y)] \qquad (10)$$

$$\left.\begin{aligned} \xi_1(x,y) &= e^{-\left(\frac{a_1x^2+b_1xy}{x^2+y^2}\right)} \\ \xi_2(x,y) &= e^{-\left(\frac{a_2x^2+b_2xy}{x^2+y^2}\right)} \quad and \quad x, y \in R \end{aligned}\right\} \qquad (11)$$

The corresponding parameters are given as:
a_1=1.4749267, b_1=0.9280491, a_2=2.6317713 and b_2=-0.2287955.

C. *Analogical-XOR*

It is a symmetric gate, the output is identically zero if both inputs are equal in magnitude and if one input is zero, the output is equal to the present non-vanishing input. The used formulation for XOR gate is

$$z = x \mathbin{¤} y = \operatorname{sgn}(x+y)\left\| |x| \oplus -|y| \right\| \qquad (12)$$

D. *Adaptable PID controller design and simulation*

The philosophy of adapted PID controller based on analogical gate does not depend on the changing of PID controller parameters but it depends on changing the share of each controller term on the total control action. As shown in

Fig.4, output control command of adaptable PID, "U_{pid}", is given by analogical gates tuning proportional part "U_p", integral part "U_i" and derivative part "U_d" as in equations (13) and (14). Two analogical gates will be used sequentially. The first gate is selected to be asymmetric and the second gate is symmetric. Analogical –INVK will be followed by analogical –OR as:-

$$\left.\begin{aligned} U_p &= K_p e(t) \\ U_i &= K_i \int_0^t e(\tau)\,d\tau \\ U_d &= K_d \frac{d}{dt} e(t) \end{aligned}\right\} \qquad (13)$$

$$\left.\begin{aligned} U_{pi} &= U_p \wedge U_i \\ U_{pd} &= U_p \wedge U_d \\ U_{pid} &= U_{pi} \oplus U_{pd} \end{aligned}\right\} \qquad (14)$$

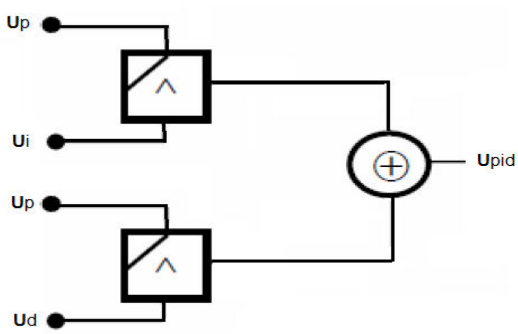


Fig. 4. PID tuning network

Since the controller has an integral term and the control signal is limited (4-20mA), the response may oscillate and settling time will increase when the control-input is saturated before the error vanishes. This phenomenon is called reset-windup. To overcome this limitation, Anti-Reset Wind-up strategy is required. An Anti-Reset Windup strategy is as follows [16]:

- When command-saturation occurs, first the magnitude of the I-gain is reduced.
- As the difference between the saturated u and the unsaturated command uo further increases, the sign of the I-gain is made negative together with a further decrease of the magnitude.

The above strategy is implemented using a single analogical XOR-gate as follows:

$$K_i = K_{oi}[\,(u-u_o)/u_o)\ \text{¤}(u/u_o)] \qquad (15)$$

where, K_i and K_{oi} are the actual and the initial I-gains respectively. The unsaturated and saturated control commands are u_o and u respectively. The overall block diagram of the system with the proposed controller is shown in Fig. 5. The tuning network perform the adaptation as illustrated in Fig. 4 and equations (13) and (14). The Anti-rest windup network is designed as in equation (15).

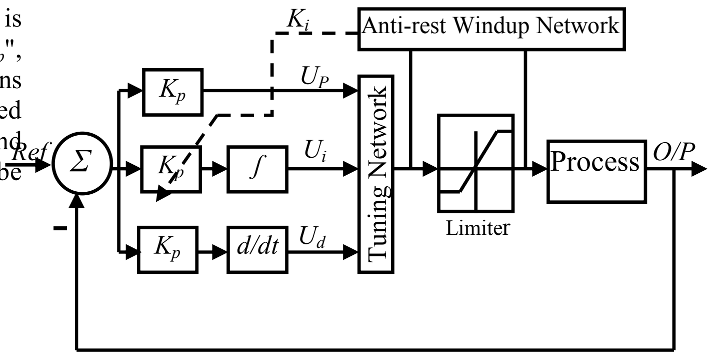


Fig. 5. Block diagram of process with adaptable PID and Anti-rest Windup network

VI. SIMULATION RESULTS

The setup is simulated with the designed controller in order to validate the controller performance and check the robustness of its behavior especially for uncertain parameters and disturbances. Moreover, it helps in determining the best initial condition of the controller parameters.

A. PID controller design and simulation

PID controller is Proportion - Integral- and Differential controller. These combinations may meet different requirements of control [17]. PID manipulates the error (*e(t)*) between the reference temperature (T_r) and the actual output value (T_t). The error value (e) is given by:

$$e(t) = T_r(t) - T_t(t) \qquad (16)$$

The control signal is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \qquad (17)$$

where K_p is proportional gain; K_i *is* integral gain; K_d *is* derivative gain.

The control signal is proportional to valve opening δ, which determines the hot and cold flow as in equation (3). For the given proposed system, the coefficient are taken as proportional coefficient K_p= 2, integral coefficients K_i=0.25 and differential coefficient K_d= 0.10. The system simulation response is shown in Fig. 6. It is clear that the system response is relatively slow and has steady state error for a step input equivalent to 50°c and initial temperature 30°C.

B. Adapted PID controller simulation

Using a conventional PID controller cannot meet the required performance due to the uncertainties of system parameters and disturbances. Therefore adaptable PID is employed. The system response using adapted PID employing Anti-Reset Windup is shown in Fig. 5; using the same PID parameters as in previous one. By comparing the two responses Fig. 6 and Fig.7, it is clear that the adapted PID response is faster and has zero steady state error. Table 3 summarizes the comparison between the response of PID controller and adaptable PID controller.

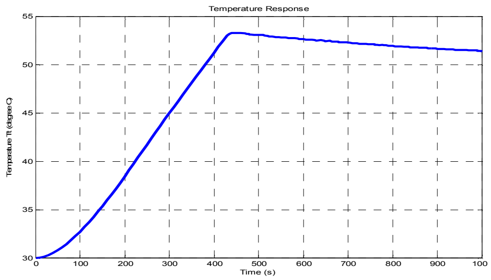


Fig. 6. Simulation result for PID controller

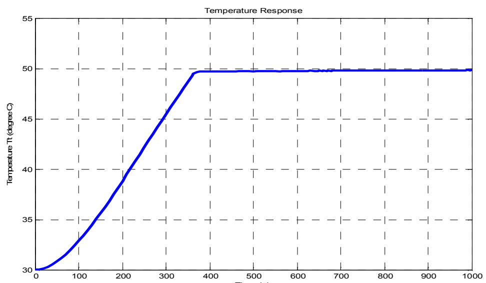


Fig. 7. Simulation result of adaptable PID controller

TABLE 3:COMPARISON BETWEEN PID AND ADAPTABLE PID CONTROLLER

	Rise time (s)	*Settling time (s)*	*Overshoot %*	E_{ss}	*Temperature set*
PID	370	Over 1000	2.5%	2°C	30°-50°C
Adaptable PID	360	360	0%	0.3°C	30°-50°C

VII. PRACTICAL REALIZATION

The proposed controller, illustrated in the previous section, is implemented using a complete automation solution system deducted by delta commercial company [9] as depicted in Fig. 8. In this application, the selected configuration of the process consists of Delta DVP-20 EX PLC. The controller is supervised via Delta HMI, DOP-A type, controller as a master in addition to SCADA software (InduSoft) within PC as shown in Fig. 8.

A. *Hardware Configuration*

The control function of the process is carried out by Delta DVP PLC [18] to control the temperature of a process by actuating of three way valves as shown in Fig. 8. The valve distributes the hot and cooled air in order to adjust the temperature of a vessel. The HMI, here, is taken as the master controller for PLC. The HMI has two ports, COM1 and COM2. COM1 utilizes two standards, either RS232 or RS485 according to the communication protocols Point to Point Interface (PPI) or Multi Point Interface (MPI). COM2 utilizes RS458 standard [19]. The InduSoft SCAD plate form (PC) is used to supervise the operation of HMI and PLC in addition to use the on-line data in order to identify and adapt the system parameter in addition to system diagnosis. The SCADA platform is connected to PLC through RS 232 serial communication.

B. *Software configuration*

Delta PLC is programmed using WPLSOFT software to program the control function. The main control function in temperature controller is PID and adaptable PID as shown in Fig. 9. The HMI is programmed using ScreenEditor software available from Delta automation and used for defining set point, controlling algorithm, processing data and constrain. InduSoft SCADA software in PC is used on-line to estimate the system parameter either for model identification or diagnosis and supervise overall system.

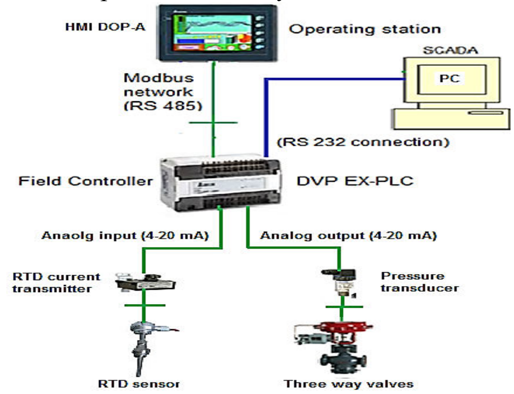


Fig. 8. The suggested automation solution

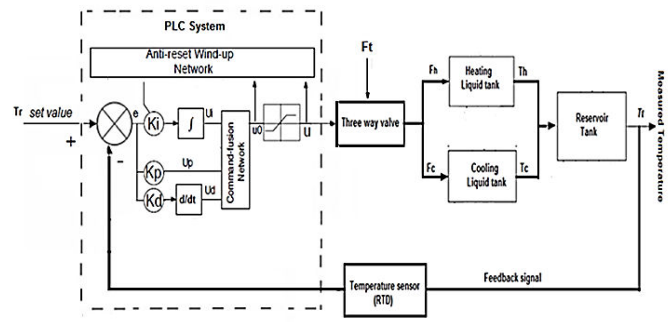
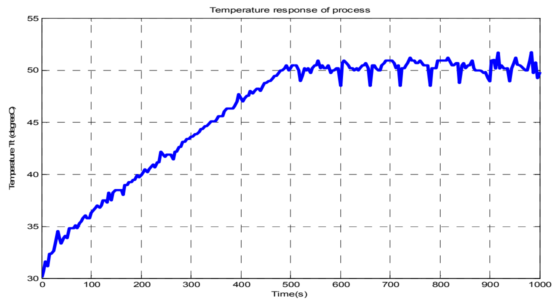


Fig. 9. Overall block diagram of the investigated system

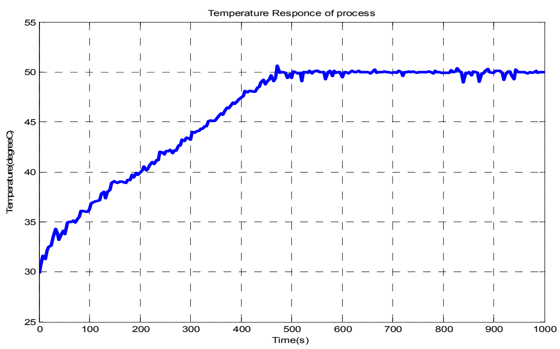
The selected parameters in the process simulation are implemented through the programming of PID controller in Delta PLC with the following parameter K_p= 2, K_i=0.25 and K_d= 0.10. The practical PID response of the process is shown in Fig. 10a for a step temperature 50°C. Using adapble PID controller based on analogical gate with initial parameters as before, the practical response is shown in Fig. 10b. A comparison between the practical results of PID and adapted PID is summarized in Table 4. It is noted that adaptable PID controller has produce faster response by 50s and reduce the steady state error (E_{SS}) by 70% than the PID controller these due to the online tuning of control command of PID controller (U_p,U_i and U_d) based on analogical gate technique that explained previously. The difference between the controller response in simulation (Fig. 6 and Fig. 7) and the real implementation is due to the neglecting of valve sizing coefficient and heating time in simulation design. However, both simulation and practical results are well correlated and insure the effectiveness of the proposed adaptable PID algorithm.

TABLE 4: COMPARISON BETWEEN PID AND ADAPTABLE PID RESPONSE

	Rise time	*Settling time*	*Ess*	Temperature set
PID	500	500	±1.5°C	30°-50°C
Adaptable PID	450	450	±0.25°C	30°-50°C



a- PID controller response



b- Adaptable PID controller response

Fig. 10. Practical results

C. *SCADA pages*

Six different pages for the graphical user interface (GUI) of the SCADA system are designed and implemented. The main screen is the navigation page of the other five screens. It should be noted that all screens are utilized within HMI and can be also navigated within PC. The initial parameters of PID and other parameters are selected in the second and third screens respectively. The trends are illustrated in the fourth and fifth screens; that give plot of the controller response and the data generated can be saved in PC for analyzing. the alarms are logged in the last screen. One of these screen is shown in Fig. 11.

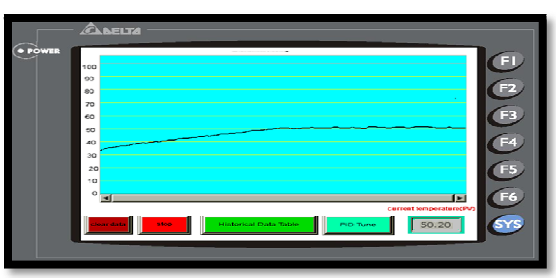


Fig. 11. SCADA GUI screen

VIII. CONCLUSION

In this paper, an adaptable PID control approach based on analogical gate has been introduced, in order to overcome uncertainty, disturbance, and/or parameter variation. Employing system model helps in adapting and diagnosis the process therefore online identification is carried out in the SCADA level. PID and adapted PID controller are implemented in the field level (PLC) of advanced automation level hierarchy. The implemented controller in PLC is supervised using SCADA and HMI units. The proposed PID gives better results than conventional PID controller. The effectiveness of the proposed control scheme has been numerically verified. The presented setup can be extended to cover other control algorithm such as Model predictive Control (MPC) and Fuzzy control to be implemented using the distributed control task between field level and the other levels of automation hierarchy.

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