Shatha Y. Ismail[1], Zozan Saadallah Hussain[2], Hassaan TH. H. Thabet[3], Thabit H. Thabit[4]

Northern Technical University, Technical Institute, Department of Electrical Technology, Iraq (1), (2)
Freelance Researcher, Iraq (3), Ninevah University, College of Electronics Engineering, Iraq (4)

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Using PI Controller Unit for Controlling the Water Temperature in Oil Fired Heaters by PLC Techniques

Abstract. *This paper presents the design of a Proportional-Integral (PI) controller using the Programmable Logic Controller (PLC) techniques to control the temperature of water heated by oil fired heaters that are much used in Iraq. Our laboratory work consists of hardware part: the LOGO! V6 PLC, the thermostat, the analogue output valve and the oil fired water heater with its accessories while the software part includes Function Block Diagram (FBD) programming language of our PLC. The P and I parameters are found manually and their roles are also discussed in this paper. The designed control system can serve a precise way to control physical parameters within a desired range in the laboratory. In this paper, the authors focus on how the PI controller measures the temperature of the heated water in the oil fired heater and controls the aperture of the analog valve which controls the flow rate of the oil from the tank to the furnace of the heater according to the measured temperature.*

Streszczenie. *W artykule przedstawiono projekt sterownika proporcjonalno-całkującego (PI) wykorzystującego techniki programowalnego sterownika logicznego (PLC) do kontrolowania temperatury wody podgrzewanej przez grzejniki olejowe, które są powszechnie używane w Iraku. Praca laboratoryjna składa się z części sprzętowej: LOGO! V6 PLC, termostatu, zaworu wyjścia analogowego i podgrzewacza wody wraz z akcesoriami. Część oprogramowania zawiera blok funkcyjny Diagram (FBD) język programowania naszego PLC. W tym artykule autorzy skoncentruj się na tym, jak regulator PI mierzy temperaturę podgrzanej wody w nagrzewnicy olejowej i steruje otworem zaworu analogowego, który steruje przepływem oleju ze zbiornika do paleniska nagrzewnicy zgodnie ze zmierzoną temperą. (**Wykorzystanie sterownika PI do kontroli temperatury wody podgrzewanej grzejnikiem olejowym**)*

Keywords: PI Controller, PLC, PID Tuning, FBD Language, Oil Water Heaters
Słowa kluczowe: : regulator PI, PLC, olejowe podgrzewacze wody

Introduction

In the city of Mosul/Iraq oil fired water heaters are widely used in residential sites due to their ability to produce large amounts of hot water in cold weather [1]. A control system design for the provision of water and hot water around the clock for people living in difficult times and abnormal conditions in their residential areas using solar energy as sustainable and free energy [2]. They fall in three main types [3]:

- The direct fired oil water heaters; which are used in Iraq and discussed in this paper. They are just water heaters using oil as the heat source but they are very efficient because of their high capacity of producing large amounts of hot water quickly with short recovery time; which is useful for houses with a lot of people living in them.
- The Indirect fired water heaters that are storage tanks with heating coils supplied with hot water from a boiler used to supply hot water for central heating systems.
- The Tank less coil systems; which are part of a boiler home heating system.

All the oil fired hot water heaters have high initial costs but low operating costs. They are found in cold weather climate areas where heating oil is inexpensive and high volumes of hot water are needed.

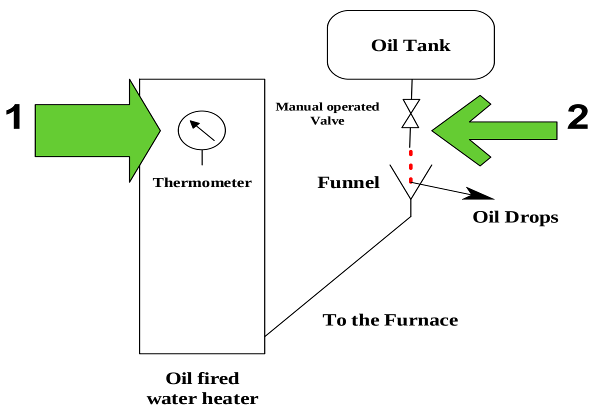

Fig.1. Primitive oil feeding system

To understand the scope of our research; it is important to know how the oil is fed to the oil fired water heaters now a days in Mosul-Iraq and how its amounts are controlled. Fig. 1 describes the primitive oil feeding system recently used in the city of Mosul.

The system shown in Fig. 1 consists of an oil fired water heater with (1) a thermometer; (2) oil tank with a manual operated valve (tap) and a funnel that receives the oil drops coming out from the tap and conveys them to the furnace of the heater. In order to operate this system efficiently; a human operator must watch the thermometer and increases or decreases the amount of oil coming from the tank by the tap according to the desired temperature decided by the operator, which means a tedious task for continuous human monitoring of the oil's rate of flow and the temperature of the water in the heater.

Literature Review of PI Controller

The PI controller [4,5] is a feedback control loop which calculates the error signal of a control system by taking the difference between the output of a system and the set point decided by the operator, it provides the following features:

1) The balancing of complexity and capability which made it the most used algorithm in process control applications.
2) Zero control error.
3) Insensitivity to interference of the measuring channel.

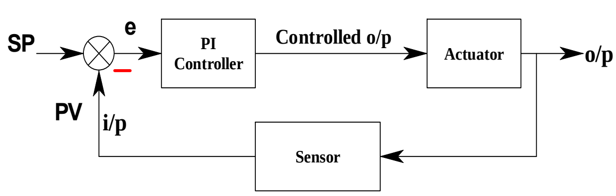

Fig.2. The closed loop control system

The only disadvantage of PI controller is its slow reaction to disturbances. Some of previous papers demonstrated on

the tuning procedures of the PI controller [6,7]; but others focused on the applications of this type of controllers [8,9].
In this paper; a PI controller is designed by using the PLC techniques to replace the above primitive system. The PI controller [9] measures an "error", the difference between the set point (*SP*) and the process value (*PV*), in each loop to control a system as shown in Fig. 2.

In order to minimize the error, each part (term) of the *PI* algorithm will have its own characteristics and roles as shown below [8]:

1. **The *P*-term:**

This part takes into account the present error only and makes an effort in proportion to how far *PV* is from *SP* at the present time. The error becomes very small as *PV* approaches *SP* but it cannot catch it; which implies that there is always an offset from *SP* in the control system that is called the steady state error (*SSE*).

Mathematically, the output of the *P*-term (controller) is given by the following equation:

(1) $$P_{term} = K_P \cdot e(t)$$

Where: K_P is the proportional gain, *e(t)* is the error at the present time "*t*".

However; a larger value of P_{term} can trigger *PV* to *SP* but the system will become unstable with oscillations and overshoots [8,9]. So; P_{term} alone is not sufficient for most control systems and is accompanied by the "I_{term}" to get the *PI* controller.

2. **The *I*-term**:

This part of the controller takes into account the history of the error from the starting of the control process to a particular point of time in that process.

Mathematically, the I_{term} can be represented by the following equation:

(2) $$I_{term} = \int_0^T Ki \cdot e(t)dt$$

Where: *Ki* is the integral gain, *T* is the total time of the controller's operation.

Finally, the *PI* controller output becomes:

(3) $$u = K_P \cdot e(t) + \int_0^T Ki \cdot e(t)dt$$

From practical aspect; the performance of the *PI* controller can be analyzed by the following response parameters of this controller [9] as described in Fig. 3:

A. The rising time.
B. The peak time.
C. The settling time.
D. The steady state error (*SSE*).
E. The overshoot.

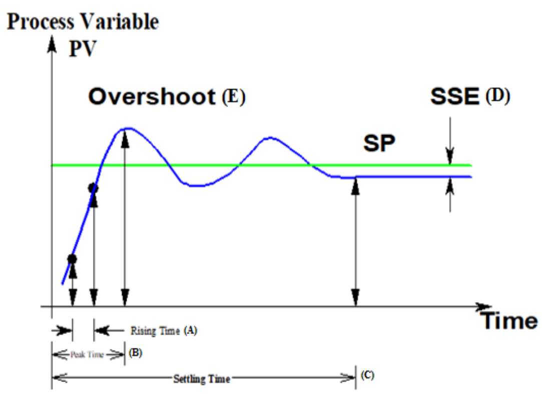

Fig.3. Parameters of PI Controller

When designing a *PI* controller system; the designer must try to achieve the following properties [10]:

1) Reduce or omit the SSE.
2) Reduce the overshoots (if any).
3) Small settling time.
4) No oscillation (damping of oscillation is preferred).

Hardware Task

Fig. 4 expounds the complete parts of the implemented water heating system that consists of:

1) The oil fired water heater tank with capacity (260 L) accompanied with its analog thermometer of a temperature range (30-90 °C).
2) The oil tank with capacity (40 L).
3) The *PLC* LOGO! *V6* (*DC/DC*/Relay); 8 digital inputs; 4 analog inputs; 4 relay (digital) outputs and the expansion module for analog outputs with 2 analog outputs.
4) The analog valve which is operated by a servo motor (0 *VDC* completely closed (0°) and 10 *VDC* fully opened (180°)).
5) The analog thermostat with temperature range (0-100 °C).

When starting the heating process; the analog thermostat measures the temperature of the heated water and sends it to the analog input of the *PLC* (red dashed line), which will process it and send the result to the analog valve that is operated by a servo motor (its range of rotation is from *0° to 180°*) via the expansion analog output module (red dashed line) to decide the size of its aperture in order to control flow rate of the oil to the furnace.

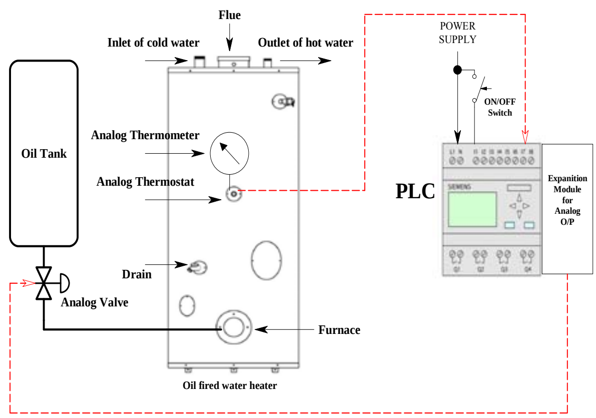

Fig.4. The suggested PLC based control system

Software Design

In this part of the research; the authors split the design procedure into two parts. The first part describes the design and the tuning method of the *PI* controller used in this task, the second part discusses the scaling concepts of the input and the output analog values.

A. Designing and tuning the *PI* controller

The *PI* controller is the most important type of the *PID* controller types and the most often used [9,10], its algorithm is simple and easy to be understood and implemented practically.

Equation (4) shows the relation between the *P* and *I* parameters; the error and the output of the *PI* controller [10]:

(4) $$u(t) = K_c \cdot e(t) + \frac{Kc}{Ti}\int_0^t e(t)dt$$

were: $u(t)$ - Output of the *PI* controller in time domain, $e(t)$ - The error signal ($e= SP-PV$), K_c - The controller gain (tunable), Ti – The integral time (tunable).

The Ziegler-Nichols open-loop tuning method [9,10] is implemented in this paper to calculate the values of K_c and T_i by placing the controller in the manual mode, applying the bump (step) test and finally making calculations [11,12] as shown in the trend view of Fig.5.

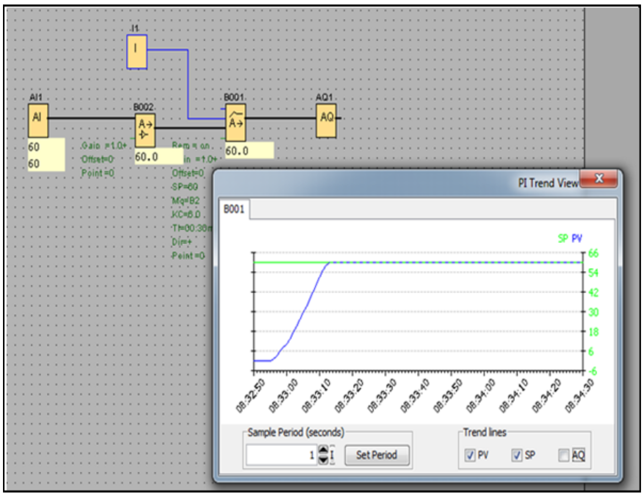

Fig.5. Featured simulated operation of our tuned PI controller

The selected values of the tuned parameters in the design of our *PI* controller according to The Ziegler-Nichols open-loop tuning method are: $KC = 0.5$ and $T_i = 30$ seconds.

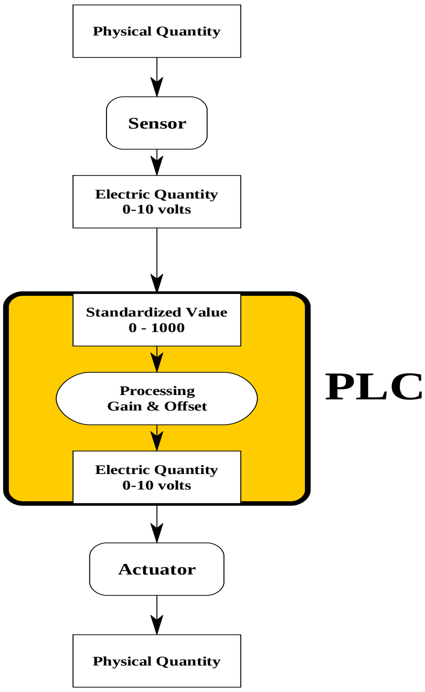

Fig.6. Processing analog quantities by PLC

B. Scaling the analog signals

Sensors are used to measure or sense physical phenomena such as temperature, pressure, liquid flow rate, speed and many others. They transduce the physical quantities (°*C*, *Bar*, *RPM*) into electrical quantities (*0 -10 VDC or 0 – 20mA*) in order to be read by computers or controllers such as (*PLCs*) by processing and converting them into a standardized value of certain ranges, the *PLC* used in this paper has a range of (2^{10}*bit*) resolution [13], this value is applied in the circuit program on the input port of the analog function. To adapt the standardized value to the application; the gain and the offset are considered by the *PLC* to calculate the analog value which is evaluated by the analog amplifier function and stored in the memory of the *PLC*. The stored analog value, when needed, can be converted back into an electrical value (current or voltage) to control an actuator, which converts the analog output voltage into a physical quantity. Fig.6 illustrates this order of events.

Therefore, for this case, (Fig. 7) describes the linear relation between the analog values and the standardized values (resolution) of the *PLC*, also the equation of a straight line of this relation is shown mathematically as below:

(5) $$A_y = mA_x + c$$

where: *Ay* – The physical quantity, *Ax* – The resolution of the standardized values *(sv), m* – Gain, *C* – Offset

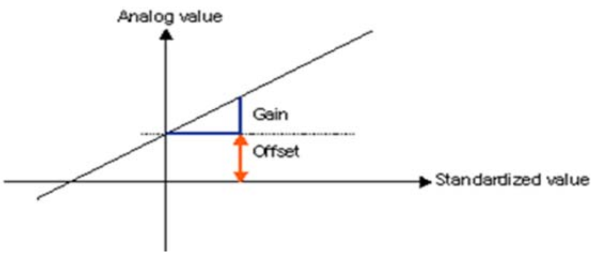

Fig.7. Relationship between Analog Values and Standard Values

1) Scaling of analog input in our case

As shown in (Fig.8); the relation between the input temperature and the output voltage of the sensor is *(0.1V/ °C)*.

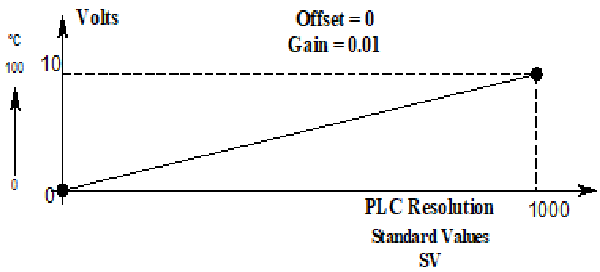

Fig.8. Relationship between input analog values and standard values

By applying equation (5); the offset is (0) and the gain is (0.01) as shown. For calculating multi values of the input temperature, the following results are achieved as described in (table 1).

Table 1.The input results

C°	V	PV
0	0.0	0
30	3.0	300
43	4.3	430
68	6.8	680
91	9.1	910
100	10.0	1000

2) Scaling of Analog Output

The analog output values of the *PLC* are (0-10) volts that are converted to (0°-180°) by the actuator as shown in Fig.9.

Also by applying equation (5); the offset is (0) and the gain is (0.18) as shown in Fig.9 for multi values of the output voltage, the following results are achieved as described in (table 2). The relation between the output voltage and the degrees of rotation of the actuator is (18°/V).

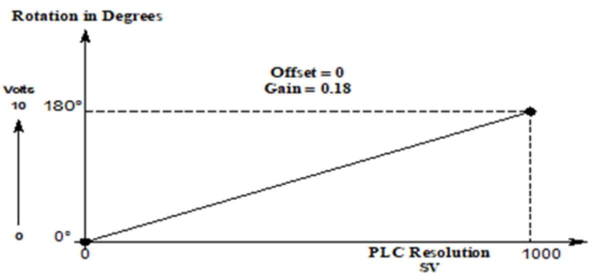

Fig.9. Relationship between output analog values and standard values

Table 2. The output results

PV	V	°
0	0.0	0
200	2.0	36
500	5.0	90
700	7.0	126
900	9.0	162
1000	10.0	180

Description of the Program

Fig.10 shows the complete *FBD* program of the control system. It consists of the analog input that receives the temperature of the heated water from the thermostat as a voltage, which is processed in the analog amplifier and conveyed to the *PI* controller that makes the decision and sends it to the output port to be transmitted to the actuator in order to control the flow rate of the oil.

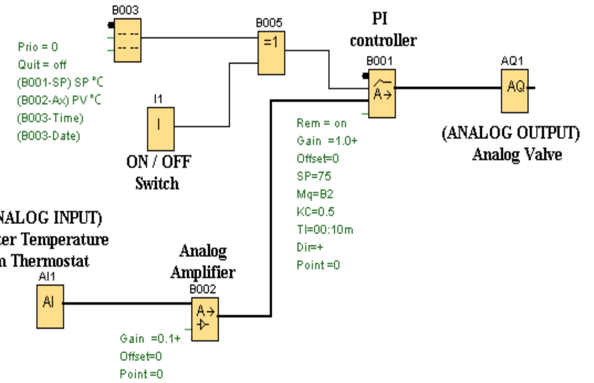

Fig.10. The complete control of PLC program

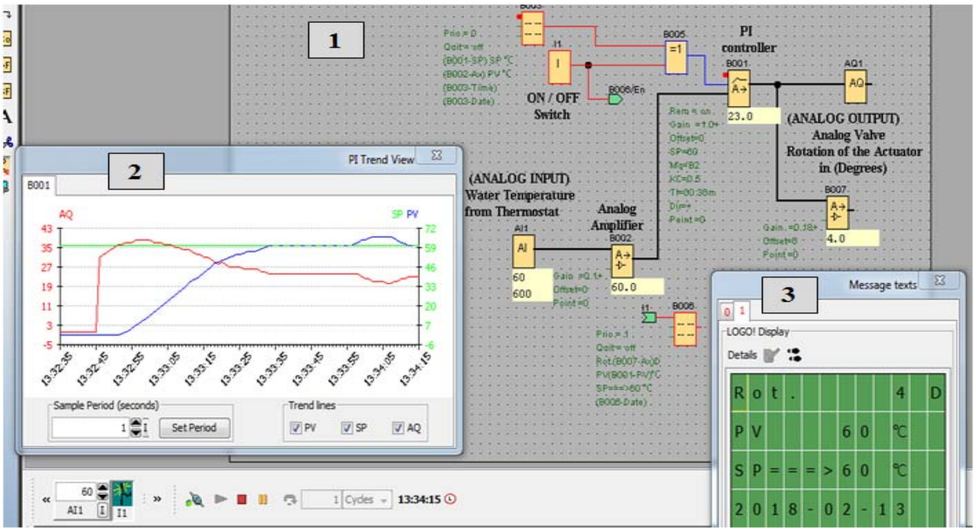

Fig.11. The simulated control process

Fig.12. The PLC control board

Results

Fig.11 describes the whole simulated control process; it consists of three parts:

1. The background part that shows the control program in the simulation mode.
2. The trend view part, which describes the behavior of each parameter of the *PI* controller; where the green line is the *SV* (Set Value) of the water's temperature of the oil fired system set by the operator via the thermostat; the blue line is the *PV* (Process Value) of the actual temperature of the water read by the thermometer of the tank which is simulated as a variable resistor at the analog input of the *PLC* and finally the red line is the analog output of the system that could be simulated by an analog valve driven by a servo motor which was not available in the laboratory during the research work, so the authors employed a voltmeter to measure the output voltage as shown in Fig.12. The trend view also explains the relation between input temperature (*PV*) and the rotation of the analog valve (0°-180°) that is an inverse relationship. It also describes the response of the system which uses the *PI* controller as shown in Fig.11.
3. The *HMI* part

This part gives the operator information about *SV*, actual PV, the output value and the date of the operation. The operator can change the *SV* from the *HMI* online and monitor the changes.

Fig.12 shows the operated system which consists of the *PLC*, the analog output module, the *HMI* or the *TD* (Text Display), the variable resistor (as an input temperature) and the voltmeter that measures the output voltage of the system, which will control the angle of rotation - the size of the aperture- of the analog valve driven by a servo motor in order to control the rate of flow of the oil from the oil tank.

Conclusion

As a conclusion, this paper tried to automate a primitive system by using *PLC* techniques with a simple and efficient program employing the featured characteristics of a tuned *PI* controller to control the temperature of the heated water in oil fired-water heaters. This method reduces the human efforts in controlling the water's temperature of this system by implementing the techniques of a *PI* controller built in a *PLC* system. The authors aim to exploit this idea commercially; but the only drawback in exploiting this system commercially is the high cost of the *PLC* system. As a future work the *PLC* may be replaced-if possible-by an Arduino controller in order to reduce the cost of the system.

Authors: *Shatha Y. Ismail, e-mail: shathayousif61@ntu.edu.iq; Zozan Saadallah Hussain, e-mail: zozan.technic@ntu.edu.iq; Hassaan TH. H. Thabet, e-mail:engineer.h.thabet@gmail.com; Thabit H. Thabit, e-mail: thabit.thabit@uoninevah.edu.iq;*

The correspondence e-mail: shathayousif61@ntu.edu.iq

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