Design of Mini PLC based on PIC18F452 Microcontroller using Concepts of Graceful Degradation

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***Abstract*—** Programmable logic controllers (PLCs) which are able to interact with peripherals play a key role as a controlling unit in most of the industries now a day. Main objective of this research is to design a PIC18F452 microcontroller based low cost mini PLC which is gracefully degrading to support ladder logic programming language- one of the programming languages of standard IEC61131-3. A compiler with selected features has been designed in C# language. An operating system of the microcontroller of this mini PLC has also been designed in C language. To interface programming device and mini PLC, USB to RS232 communication protocol has been used. It is easy to envision the scheme of wiring, power supply, input & output channels, microcontroller, circuits of optical isolators etc. in the mini PLC thereby providing the students a platform to understand the internal architecture of most of the PLC systems.

***Keywords*—** Mini PLC, Graceful Degradation, Redundant, Robust, Ladder Logic Compiler, Operating System

I. Introduction

Programmable Logic Controller (PLC) is a controlling device having different number of inputs/outputs (I/Os). PLC is specially designed to control a typical process or a machine. Programmable logic controllers were initially introduced to replace the conventional relay based circuits. Now these are extensively used for the implementation of systems based on logic, arithmetic, sequencing, timing, and counting [i].

According to the number of inputs/outputs, PLC market can be classified into the five groups as Fig. 1 illustrates [ii].

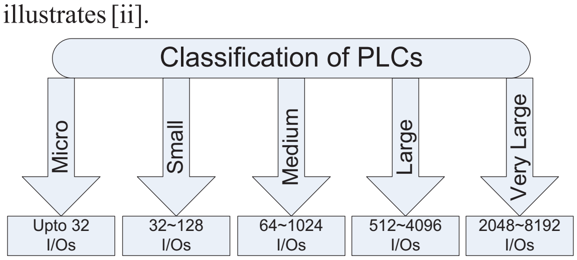

Fig. 1. PLC grouping according to I/Os.

PLCs are available in different configurations even from the same vendor. Some of the most essential & common components of a PLC are power supply, central processing unit, input/output channels, & indicator lights [iii].

Different environments of programming & debugging, addressing methods, structures of grammar etc. lead to the incompatibility and issues in use as a teaching tool at the university. International Electro-technical Commission (IEC) published the standard IEC61131-3 in 1999 which offers a uniform criterion for the manufacturers of PLCs [iv]. This standard offers the graphical and textual programming languages. Graphical programming includes ladder logic diagram, functional block diagram, & sequential function charts while text programming includes structured text & instruction list [v].

Ladder diagram is easy to understand and mostly used for programming the PLCs. It defines the instructions such as logic/Boolean and switching operations [vi]. Microsoft Visual Studio 2012 has been used to develop the ladder logic editor. On compilation of editor, it provides a text file of alphanumeric code which is sent to microcontroller of the mini PLC [vii]. The operating system of the mini PLC based on PIC18F452 microcontroller has been developed in C language [viii].

Graceful degradation/fault tolerance is the property of the system that enables it to continue functioning even in case of failure for one or more of its components. Graceful degradation occurs due to interaction of 3 aspects of system design i.e., hardware, software, and human interface between hardware & software. Graceful degradation improves the reliability of systems by increasing the robustness & redundancy [ix].

Capability of systems to resist the changes or disturbances is referred as robustness. Robust systems stablize their original configuration when subject to any change. Systems or parts of systems are designed efficiently to tackle the disturbance and noise [x].

Duplication of different functions or components of the system is termed as redundancy. It increases reliability of systems by providing backup or fail-safe capabilities. Redundant systems possess the ability to switch to other components/functions of system to exhibit the same feature in case of certain failure [xi].

Redundancy of 1st order has been incorporated in this mini PLC.

Some of the features of the microcontroller used for the mini PLC have been described here. Microcontroller is being operated at 5V DC and at a frequency of 4 MHz by using external ceramic capacitors of value 15pF each. It has the current sink/source capability 25mA/25mA. It has three external interrupt pins with a feature of assigning a high or low priority level. It contains the timers named as: Timer0 module: 8-bit/16-bit timer/counter with 8-bit programmable prescaler; Timer1 module: 16-bit timer/counter; Timer2 module: 8-bit timer/counter with 8-bit period register (time-base for PWM); Timer3 module: 16-bit timer/counter. Two of the timers have been used as timers and one as counter in the ladder logic programming. The microcontroller has compatible 10-bit Analog-to-Digital (A/D) Converter module [xii].

The PLCs work in different phases of input scanning, logical solving, and output scanning. In input scanning, it takes the data from sensors to send it to memory of the processor of the PLC. Then processor logically solves all the problems to issue the commands to the actuators. In output scanning, actuators perform accordingly [iii].

II. METHODOLOGY

A. Design of Hardware

Figure 2 shows the complete diagram of the mini PLC. Physical size of the mini PLC is (4.25″ x 4.25″ x 4.25″). Push buttons, toggle switches, indicators, and female connectors with internal diameter of 3mm & 1mm have been shown at the top of the mini PLC. To display the status of mini PLC working, LCD (liquid crystal display) has been installed at the top of the mini PLC. A relay control board is also shown at left side of the Fig. 2. A DC motor control experiment is being tested on the mini PLC.

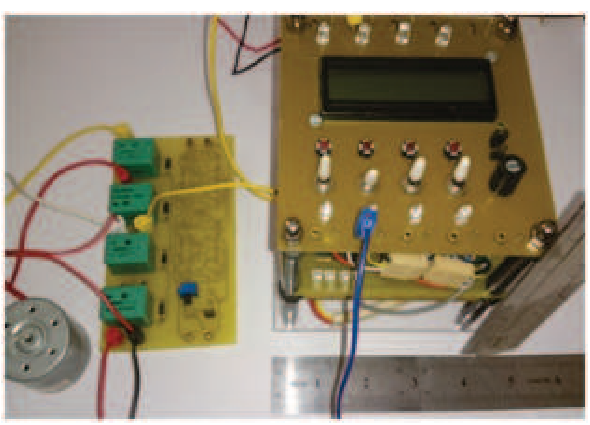

Fig. 2. Mini PLC.

System diagram of the mini PLC is shown in Fig. 3. Input module, output module, central processing unit, power supply, and programming device are shown here.

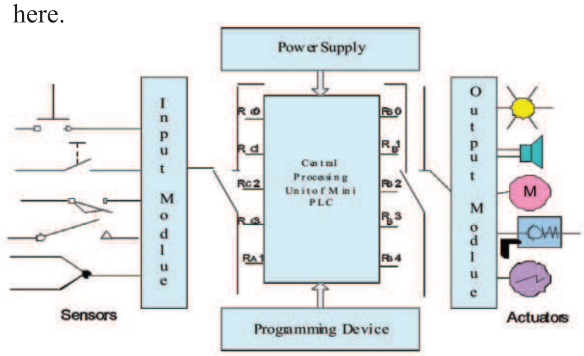

Fig. 3. Block diagram of the mini PLC.

First “4” pins of Port “C” of microcontroller are used as digital inputs, first pin of Port “A” of microcontroller is used to take analog input from the sensors and first “5” pins of Port “B” are used as digital output pins.

i) Controlling Unit

The controlling unit of the mini PLC comprises microcontroller inserted on ZIF (zero insertion force) socket, connecting pins & cables, power indicator, and crystal oscillator.

ii) I/O Section

Circuits of power section, optical isolation, input & output module, automatic power shut down system, and power feedback are shown in Fig. 4.

Fig. 4. I/O section of the mini PLC

This board has “5” I/O (out of 5, 4 are digital inputs, 1 is analog input, and 5 digital outputs) channels. I/O channels are optically isolated through optocoupler TLP523-4.

Initially, ladder logic code is developed in ladder logic editor and after compilation the result is sent to the microcontroller. The microcontroller will read the data and solve for the required output to send to the actuators at the output module of the mini PLC. Working of mini PLC is explained in Fig. 5.

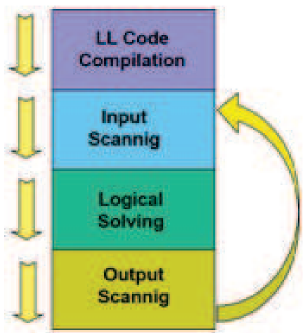

Fig. 5. Working of the mini PLC

iii) Power Source & its Feedback System

Power supply of 5V DC & 24V DC is used for microcontroller & I/O module respectively. Microcontroller is optically isolated from the transducers making both the power sources independent of each other.

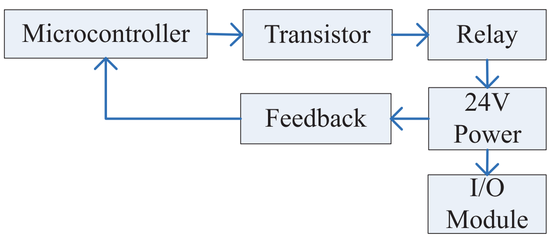

Fig. 6. Power source with feedback.

To avoid the manual troubleshooting in case of power failure of 24V DC power supply of transducers, a power feedback system has been developed. In this system, microcontroller is capable to automatically troubleshoot and take the corresponding action.

iv) Gracefully Degrading Design

Graceful degradation has been implemented in context of redundancy & robustness to improve the reliability of the system.

a. Redundancy of Zener diodes

Zener diodes work as zener in reverse bias and are used to regulate the voltage values [xiii]. Zener diodes have been duplicated at I/O module.

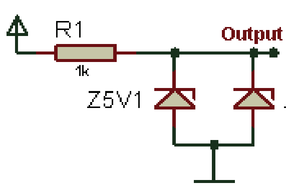

Fig. 7. Redundancy of zener diodes.

These zener diodes are used to provide constant values of 5V and 24V at different nodes of the circuits of mini PLC. In case of open circuit failure of one zener, the other zener will be conducting, providing constant voltage where required.

b. Redundancy of optical isolators

Like Zener diodes, optical isolators have also been duplicated in the mini PLC. It has been tested through switches and shows that signal will adopt the alternative path in case of open circuit failure of one IR LED of optical isolator. Fig. 8 shows redundancy of IR LEDs.

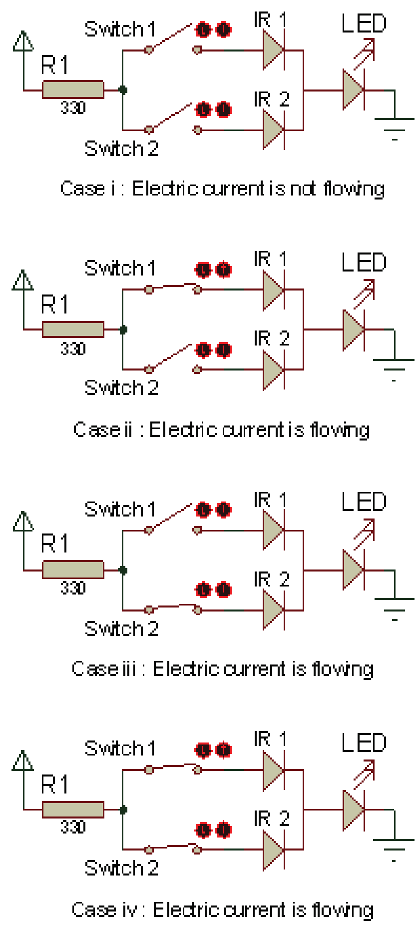

Fig. 8. Redundancy of IR LEDs.

Figure 9 shows overall working of optoisolator being redundant. IR LEDs will work fine when redundant but phototransistor will be fail-safe. Phototransistor/s of the corresponding IR LED/s will be in saturation or in cutoff mode.

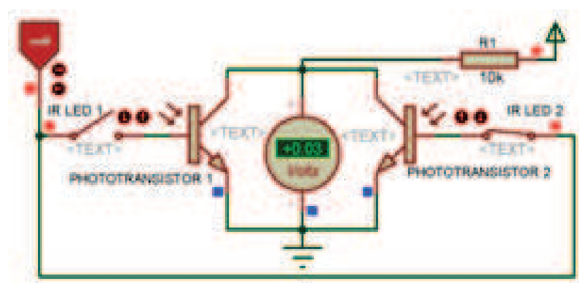

Fig. 9. Redundancy of optoisolator.

c. Robustness

The leads of the components like transistors, zener diodes etc. have been used as long as it possible to save the components from thermal effects. The long leads increase the metallic area of the components thereby increasing the heat sinking capability. A lot of electronic components exist e.g. BJTs in plastic package which are heat sensitive but there is no space/option to attach heat sinks on them. Components used in metal packages also provide robustness to the system.

In the circuit of mini PLC, relay has been used to switch ON/OFF the power of sensors and actuators. The coil of relay is made fail-safe using the circuit of back EMF (electro motive force) eliminator. Applying the fuse is common to most of the circuits. Referring to Fig. 10, a capacitor C_4 is used to avoid voltage fluctuations and zener diode D_3 is used to regulate the voltage at the coil terminal. If LEDs D_{24}, D_{25} will glow, it indicates the successful operation and switching ON the power of sensors and actuators.

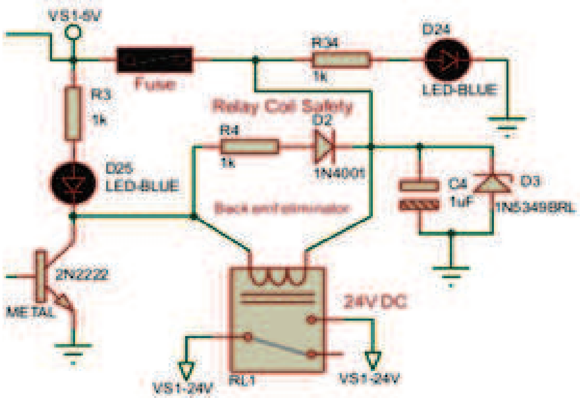

Fig. 10. Robust circuit for relay.

Fans and heat sinks are also used to avoid the components from thermal effects. A small fan of 5V DC has been incorporated to provide cooling to the electronic components of the mini PLC. It is located near the voltage regulator of power supply circuit. Voltage regulators are continuously performing the functions of input & output load regulations, therefore they may heat up due to increase of load current.

B. Design of software

To interface the mini PLC hardware, a software platform is required. This software allows editing and compiling ladder logic programming. Microsoft Visual Studio 2012 has been used to develop the graphical user interface for ladder logic editing.

i) Ladder logic editor

Using Microsoft Visual Studio 2012, the ladder logic editor has been developed in C# language. Fig. 11 shows the main window of the software. It contains the symbols of NO (normally open), NC (normally closed), branches, wire, timers, counters, analog input. All these symbols are given at the left side of the ladder logic editor.

Compiled output of alphanumeric code can be visualized at the right side of Fig. 11. User can also write comments/working of ladder logic code in the window of compiled output.

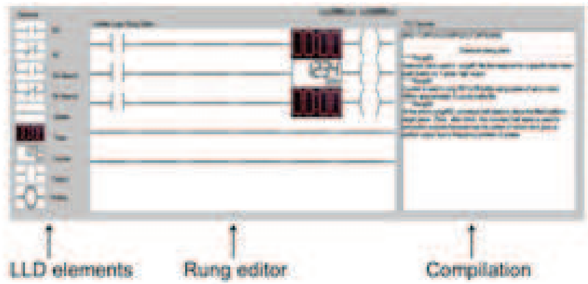

Fig. 11. Ladder logic editor.

ii) Ladder logic simulator

It is illustrated in Fig. 12, simulation of ladder logic compiler. The simulation has been prepared in Proteus v7.8 [xiv] with the hex file loaded into the microcontroller of the mini PLC.

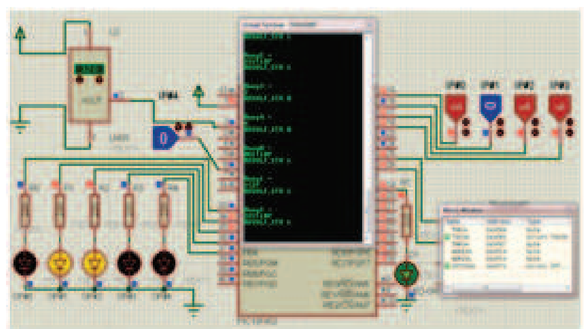

Fig. 12. Ladder logic simulator.

C. Operating the mini PLC

Check to ensure that all the wires and connections are in proper order. After receiving a signal of power feedback circuit, microcontroller of the mini PLC would power up the circuits of input/output module. Build code in the ladder logic editor using required number of rungs. Perform the compilation of ladder logic code. Now send the alphanumeric code produced to the microcontroller of mini PLC developed.

After receiving alphanumeric code, safety conditions would be checked by the mini PLC. Now mini PLC shall wait for the inputs from different sensors according to ladder logic code. All the functions would be performed through output modules after logical solving by the microcontroller.

III. EXPERIMENTATIONS

Different experiments performed on the mini PLC designed are given here.

A. Handling the graceful degradation for the increased *voltage signal at inputs and outputs of the mini PLC*

Purpose of this experiment is to gracefully degrade the exceeded voltage at inputs & outputs of mini PLC by using circuits of zener diode. Zener diode operates in the reverse bias mode & starts to conduct at nominal value of voltage as shown in Fig. 13.

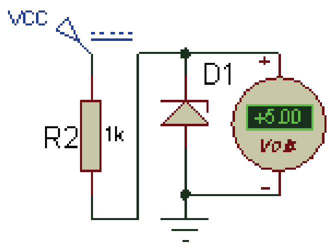

Fig. 13. Handling the graceful degradation.

B. Switching off input signal at infrared LED of optoisolators in case of exceeded voltage at the input of mini PLC

This circuit has been made by using voltage comparator along with AND gate logic IC. Voltage signal of the value 8V has been fixed as a reference voltage by using combination of resistors at inputs. The signal is then fed at negative terminal of gates of voltage comparator IC. All positive terminals of each gate of voltage comparator IC are fixed with values of "8.1V", "8.3V", "8.5V", & "8.7V".

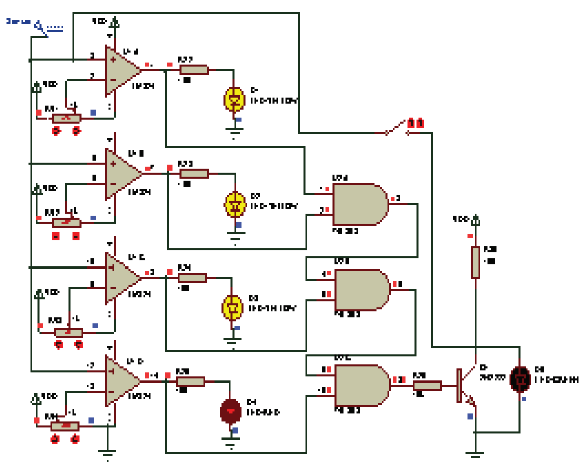

Fig. 14. Automatic power shut down circuit

When input voltage will exceed 24V, the 8V signal will start to increase and at the value of 8.1V, 1st yellow LED will start to glow. At 8.3V, the 2nd LED will start to glow and so on. All "4" outputs received due to increased voltage level will be given as inputs to AND gate. The output will become high when all inputs are high. High signal will switch the transistor into saturation mode giving zero volts at the input module.

C. Implementation of the ladder logic branching

In this experiment, the implementation of ladder logic branch using one branch has been shown in Fig. 15.

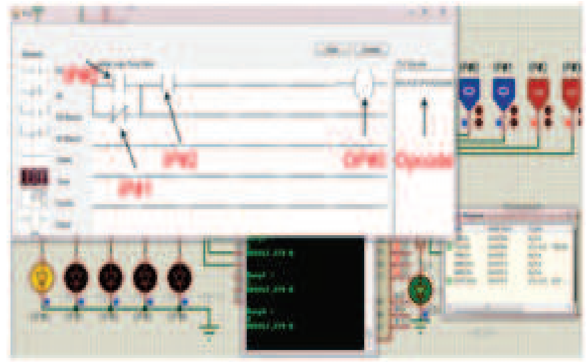

Fig. 15. Ladder logic branching.

D. Measurement of temperature using analog input channel

The experiment is designed to measure & control the temperature of room. The sensor LM-35 used here has a resolution of 10mV/ C°. Thermostat control has been implemented. Threshold value of thermostat is 25°C. Fan will be ON when temperature goes above 25°C & is shown in Fig. 16. Similarly fan will be OFF when the temperature goes below 25C°.

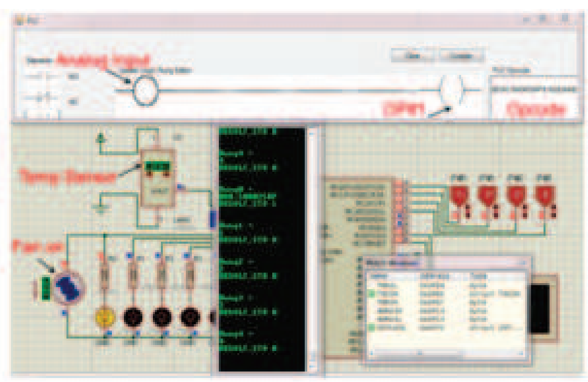

Fig. 16. Temperature control fan switched ON.

IV. Results

The property of graceful degradation offers the systems a capability to stablize on its own. PLC systems having ability of graceful degradation continue to perform rather than failing completely when faults occur in the system.

Redundancy of zener diodes and optical isolators enabled the mini PLC to remain in fail-safe mode due to open circuit failure mode. Statistical review of open circuit failure mode in Table I, shows, the probability is 0.75 for the electric signals of transducers at digital channels to flow even in case of failure.

TABLE I
STATISTICAL DATA ON REDUNDANCY

Binary Data	Cases	Best Cases	Worst Case	Redundancy order	Probability
$2^0 = 1$	2	1	1	0^{th}	0.50
$2^1 = 2$	4	3	1	1^{st}	0.75

Zener diodes are capable to bear the increased value of voltage signal and provide regulated voltage as an output. Redundancy of zener provides an alternative path to the signal in case of open circuit failure mode.

Using this mini PLC, students of the university have tested the sensors (PT-100 RTD, LM-35 temperature sensor, limit switch, proximity sensor, tilt sensor, LDR, and IR sensor etc.) and actuators (DC motor, DC servo motor, pumps, SOVs,) in different projects.

The power section with feedback circuit works successfully in circuit hardware thereby avoiding the operator effort for troubleshooting in case of power failure. When there is a failure of power, operator has to trace out where problem was occurred & will find the solution accordingly. After incorporating the circuit, the corresponding actions have been taken by microcontroller of mini PLC and if required, specific problems may be communicated to the user.

Automatic power shut down circuit successfully switched off the sensor input at the input module. When voltage signal increased to 24.5 V, 1^{st} yellow LED started to glow, 2^{nd} yellow LED started to glow at 25, 3^{rd} yellow started to glow at 25.5 V. Finally at 26 V, 4^{th} LED (red) started to glow and switch off the signal through microcontroller at input module.

The basic logic gates including NOT gate, OR gate, AND gate, & X-OR gate have been tested on this mini PLC. Operating system & hardware showed the successful results.

The slope equation i.e., $y=mx+c$ has been programmed into the microcontroller of mini PLC. A threshold value is required to get high or low output accordingly e.g. a threshold value of 25°C has been shown in Fig. 17.

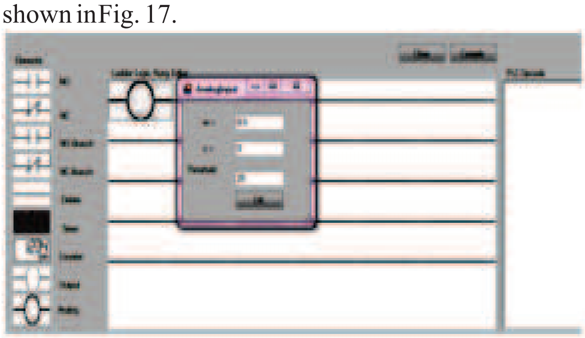

Fig. 17. Analog input editing.

Operator would enter the values of parameters into this equation to obtain the required output.

The results of temperature measurement using LM-35 temperature sensor have been shown in Fig. 18.

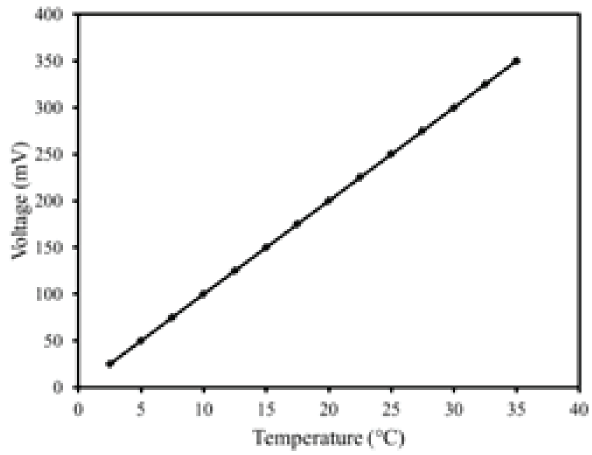

Fig. 18. Temperature Vs Voltage plot of thermostat.

V. CONCLUSIONS

It has been observed that the mini PLC gracefully degrades the electrical noise in such a way that it remained functional even when voltage signal was increased from 24V~26V DC at the input/output of the mini PLC.

Graceful degradation enhanced the reliability of the mini PLC by implementing redundant and robust circuits. Redundancy of optical isolators and zener diodes in the mini PLC provided the alternative path to the electrical signals in case of open circuit failure mode. Probability of biasing the digital electric signals is 0.75 by means of redundancy of 1^{st} order. Without redundancy, probability is 0.50 to bias the digital electric signals. Robust circuit of relay is able to oppose the voltage over flow & fluctuations due to zener & capacitor circuitry respectively.

Power feedback system provided a capability to the mini PLC to automatically troubleshoot the possible faults in case of power failure. Voltage signals of 5V, 12V, and 24V were successfully sent to corresponding electronic components and also checked through power feedback system.

Students are using this mini PLC at Department of Mechatronics Engineering UET Taxila, Sub-campus Chakwal in "Robotics and Automation Lab". During and after the practice they found it useful due to user friendly ladder logic editor, low cost hardware, and easy troubleshooting.

Short circuit failure mode for the said electronic components may be considered in future study. Using the same schematic & programming approach, input and output channels can be increased. If we have a team of engineers, a PLC can be developed to present to industry locally meeting the requirements. The successful team effort having well defined goals may lead Pakistan to become a gracefully degrading PLC manufacturer.

Availability of persons for installation/ maintenance/ troubleshooting/ repairing within Pakistan may provide ease to the industries. This mini PLC being low cost provides the greater productivity and avoids the shipping charges.

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