Fault Detection and Protection of Induction Motors Using PLC

AUTHOR: Mrs.s.preetha ,Assistant Professor, Electrical and Electronics Engineering, V.S.B Engineering College,Karur

Co-authors: S.suganya, J.sudha, A.sukuna, , Electrical and Electronics ,VSB Engineering College,Karur.

mail id:sugunaarivalagan97@gmail.com

Abstract—**Protection of an induction motor (IM) against possi-ble problems, such as overvoltage, overcurrent, overload, overtem-perature, and undervoltage, occurring in the course of its opera-tion is very important, because it is used intensively in industry as an actuator. IMs can be protected using some components, such as timers, contactors, voltage, and current relays. This method is known as the classical method that is very basic and involves me-chanical dynamic parts. Computer and programmable integrated circuit (PIC) based protection methods have eliminated most of the mechanical components. However, the computer-based protection method requires an analog-to-digital conversion (ADC) card, and the PIC-based protection method does not visualize the electri-cal parameters measured. In this study, for IMs, a new protection method based on a programmable logic controller (PLC) has been introduced. In this method, all contactors, timers, relays, and the conversion card are eliminated. Moreover, the voltages, the cur-rents, the speed, and the temperature values of the motor, and the problems occurred in the system, are monitored and warning messages are shown on the computer screen. Experimental results show that the PLC-based protection method developed costs less, provides higher accuracy as well as safe and visual environment compared with the classical, the computer, and the PIC-based pro-tection systems.**

Index Terms—**Design automation, fault diagnosis, induction motor (IM) protection, programmable control.**

I. Introduction

C INDUCTION MOTORS (IMs) are used as actuators in Amany industrial processes [1]. Although IMs are reliable, they are subjected to some undesirable stresses, causing faults resulting in failure. Monitoring of an IM is a fast emerging technology for the detection of initial faults. It avoids unexpected failure of an industrial process. Monitoring techniques can be classified as the conventional and the digital techniques.

Classical monitoring techniques for three-phase IMs are gen-erally provided by some combination of mechanical and electri-cal monitoring equipment. Mechanical forms of motor sensing are also limited in ability to detect electrical faults, such as sta-tor insulation failures. In addition, the mechanical parts of the equipment can cause problems in the course of operation and can reduce the life and efficiency of a system [2].

It is well known that IM monitoring has been studied by many researchers and reviewed in a number of works [3]–[5]. Reviews about various stator faults and their causes, and detec-tion techniques, latest trends, and diagnosis methods supported by the artificial intelligence, the microprocessor, the computer, and other techniques in monitoring and protection technolo-gies have been presented. In other works, ball bearing fail-ures [6], speed ripple effect [7], air gap eccentricity [8], broken rotor bars [9], shaft speed oscillation, damaged bearings, unbal-anced voltage [10], interturn faults [11], stator winding tempera-ture [12], and microcontroller-based digital protectors [13], [14] have been recently studied subjects. In these papers, while one or two variables were considered together to protect the IMs, the variables of the motor were not considered altogether. This might cause difficulties in protection. In study [2], a computer-based protection system has been introduced. Measurements of the voltages, currents, temperatures, and speed were achieved and transferred to the computer for final protection decision. In this paper, although all the variables of the motor were con-sidered, usage of an analog-to-digital conversion (ADC) card increases the cost and the size of the system.

A programmable integrated circuit (PIC) based protection system has been introduced in [15]. The solutions of various faults of the phase currents, the phase voltages, the speed, and the winding temperatures of an IM occurring in opera-tion have been achieved with the help of the microcontroller, but these electrical parameters have not been displayed on a screen.

Nowadays, the most widely used area of programmable logic controller (PLC) is the control circuits of industrial automation systems. The PLC systems are equipped with special I/O units appropriate for direct usage in industrial automation systems [16]. The input components, such as the pressure, the level, and the temperature sensors, can be directly connected to the input. The driver components of the control circuit such as contactors and solenoid valves can directly be connected to the output. Many factories use PLC in automation processes to diminish production cost and to increase quality and reliability [16]. There are a few papers published about the control of IMs with PLC. One of them is about power factor controller for a three-phase IM that utilizes a PLC to improve the power factor and to keep its voltage-to-frequency ratio constant over the entire control range [17]. The other paper deals with monitoring control system of the induction motor driven by an inverter and controlled by a PLC providing its high accuracy in speed regulation at constant-speed–variable-load operation [16]. Despite the simplicity of the speed control method used, this system presents constant speed for changes in load torque, full torque available over a wider speed range, a very good accuracy in closed-loop speed control scheme.

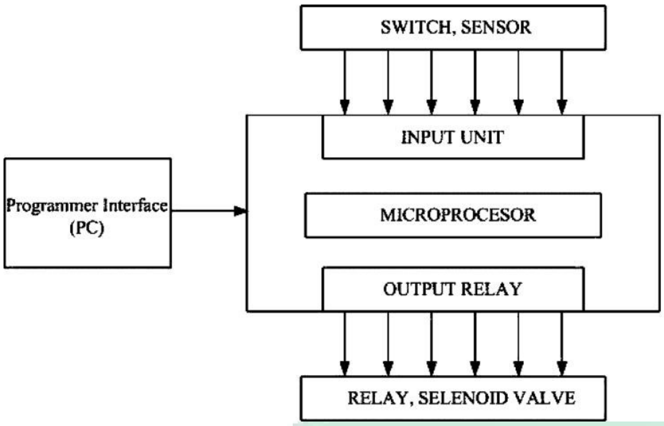

Fig. 1. Basic structure of PLC.

This paper explains a PLC-based protection and monitoring method for a three-phase induction motor. The new solutions for various faults of the phase currents, the phase voltages, the speed, and the winding temperatures of an IM occurring in op-eration have been achieved with the help of a PLC. If only a PLC is used as a protection relay for a system, it costs more. But the use of a PLC can be the right choice if it is considered in an automation system in order not to use extra microprocessor such as a PIC. This paper is organized as given next. Section II introduces the PLCs. Section III presents real-time implemen-tation details of hardware, software, and measurements of the system. Section IV expresses the experimental studies of motor fault detection and protection. The research is finally concluded in Section V.

II. PROGRAMMABLE LOGIC CONTROLLER

A PLC or a programmable controller is a small computer used for automation of real-world processes, such as control of ma-chinery on factory assembly lines. A PLC can be programmed to sense, activate, and control industrial equipment. Therefore, a PLC incorporates a number of I/O points, which allow electri-cal signals to be interfaced. Input and output components of the processes are connected to the PLC; and the control program is loaded on the PLC memory. The basic structure of the PLC is illustrated in Fig. 1.

In this study, the PLC measures the current, the voltage, the temperature, and the speed of an induction motor through ana-log inputs. In addition, it continuously monitors the inputs and activates the outputs according to the program.

Siemens PLC S7-200 module with 14 digital input/10 digital output addresses with CPU 224 sample (14*DI 24 V dc/10*DO 24 V dc) is preferred due to its easy usefulness in experimental application. The PLC programming memory used is composed of 4096 words. STEP 7—Micro/Win 32 programmer was used as the software. Statement list editor (STL) and ladder diagram (LAD) were used as programming languages. Software of the PLC was prepared on the computer and loaded on the PLC by RS 232-RS 485 PC/plan-position indicator (PPI) cable. While the program prepared is being loaded on the PLC from the computer, the most important point is the baud rate between the

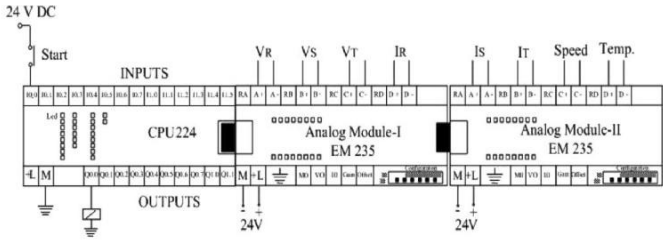

Fig. 2. Analog and digital PLC module.

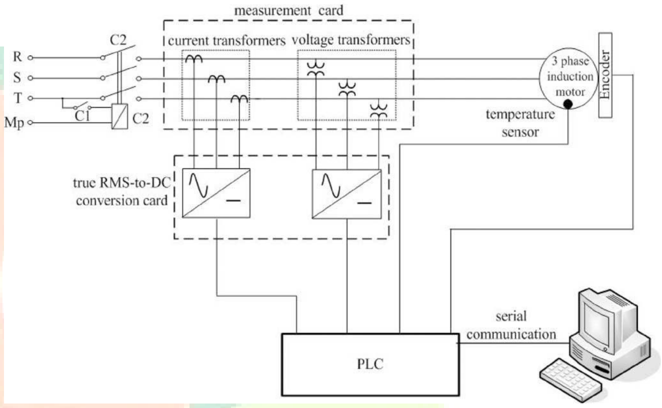

Fig. 3. Schematic diagram of the protection system.

PLC and the computer. The baud rate must be appropriate to switch setup on the bound cable in manual [18].

An analog module is primarily required for processing analog signals. Analog modules usually work in accordance with 8 or 12 bit systems. One or more than one analog sensors can be connected to the analog module in accordance with their types. For example, electromagnetic (EM) 235 module works with 12-bit system and four analog sensors can be connected to its input. The analog module inputs are expressed as A, B, C, and D. Each channel has the capacity of processing data as Word. Analog data are processed first, and then, they are transformed into digital data. The signals of analog measurement cannot directly be read by a PLC. The PLC senses only logic signals. An analog module is needed for sensing of analog signals by a PLC. The phase currents and the voltages, the temperature, and the speed of motor values were measured with the analog module. Therefore, two analog modules were used in this study. In Fig. 2, connection scheme containing circuit elements of a PLC is illustrated.

III. CONTROL SYSTEM OF INDUCTION MOTOR

In Fig. 3, a block diagram of the protection system is il-lustrated. It consists of the measurement of the current, the voltage, the rotor speed, and the winding temperature. The pro-tection system proposed can be analyzed in three categories as the hardware, the instrumentation, and the software. The tasks of these categories are explained in the following sections.

Fig. 4. General view of the proposed system implemented.

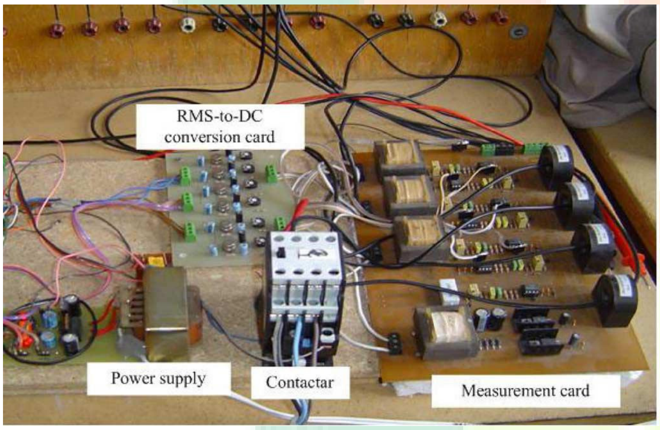

Fig. 5. View of the measurement card and the true rms-to-dc conversion card.

A. Hardware

The protection system used in this study consists of a 1.5 kW/2800 r/min three-phase IM, three voltage transformers with transformation ratio of 220/5 V, three current transformers with current ratio of 1000:1, a temperature sensor with trans-formation ratio of 10 mV for each 1 ˚C increasing temperature, and an incremental encoder with 360 pulse per revolution used for measuring the rotor speed, a true rms to dc conversion card, a Siemens CPU 224, and S7 200 series PLC. A photograph of the proposed system is demonstrated in Fig. 4.

B. Instrumentation

The currents and the voltages of the motor in the protection system were measured using the measurement card available in the laboratory including three current transformers and three voltage transformers, as shown in Fig. 5. This card includes an amplifier with opamps, a gain potentiometer, and a filter circuit used to change the current value. The outputs of the mea-surement card were applied to the input port of true rms-to-dc conversion card, as illustrated in Fig. 5. The AD536A integrated circuit was used for the true rms-to-dc conversion. The AD536A

Fig. 6. Connection of the incremental encoder to motor shaft.

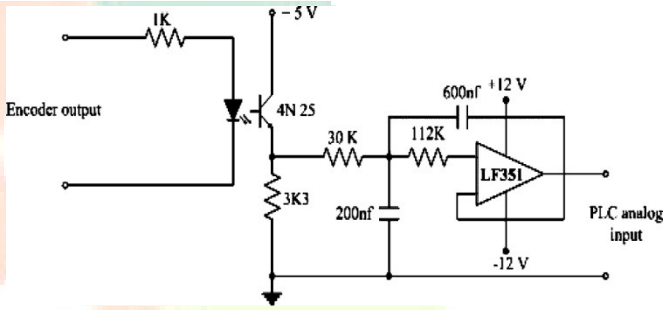

Fig. 7. PWM to dc voltage conversion circuit.

is a complete monolithic integrated circuit that performs true rms-to-dc conversion. It offers a good performance that is com-parable or superior to that of hybrid or modular units that cost more. The AD536A directly computes the true rms value of any complex input waveform containing ac and dc components [19]. Potentiometers and filter circuit, shown in Fig. 5, were used on the true rms-to-dc conversion card for changing the current and the voltage values. Converted current and voltage values were then transferred to the PLC analog module through the true rms-to-dc conversion card.

To measure the speed of the motor, an incremental encoder was connected to motor shaft, as depicted in Fig. 6. The in-cremental encoder with 360 pulses per revolution was used for measuring the rotor speed [20]. The encoder output with pulsewidth modulation (PWM) is converted to dc voltage value using conversion circuit given in Fig. 7.

The temperature of the motor was measured with an LM-35 sensor placed between the coils. The LM-35 sensor is a linear component that can produce 10 mV voltages per 1 ˚C [21]. The temperature signal was magnified and transferred to PLC analog module. On the nameplate of the motor, maximum ambient temperature was given as 40 ˚C. Over this value, the motor is stopped by the PLC.

C. Developed Software

In order to achieve the protection of the IM easily, a PLC program was developed in Microwin using LAD programming method. The PLC system provides a design environment in the

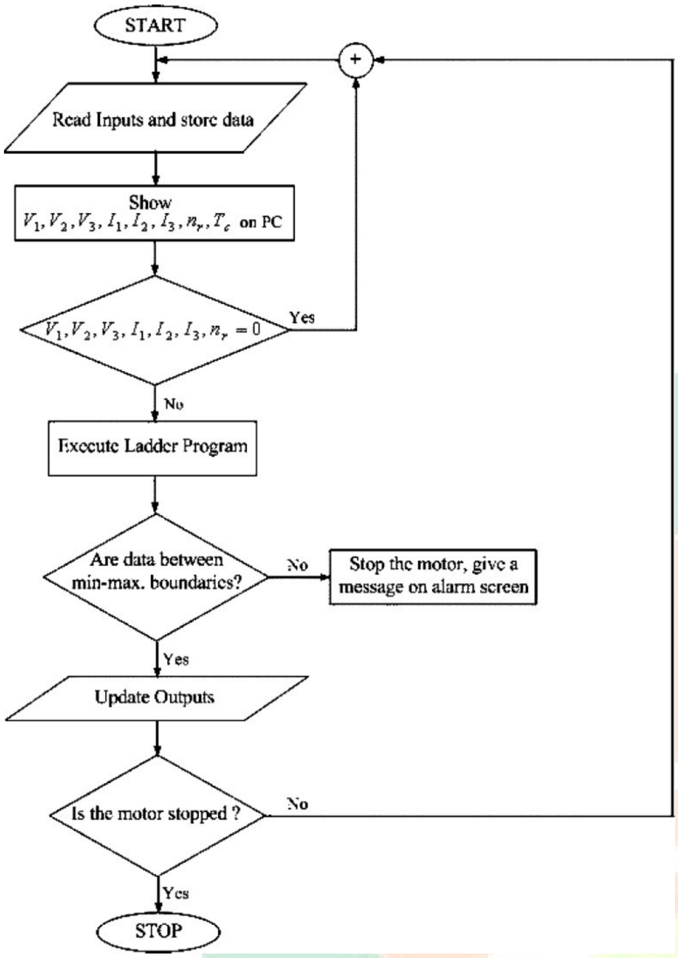

Fig. 8. Flowchart of the software developed.

form of software tools running on a host computer terminal that allows LADs to be developed, verified, tested, and diagnosed. First, the high-level program is written in LADs. The LAD is then converted to binary instruction codes, so that they can be stored in RAM or erasable programmable read-only memory (EPROM). Each successive instruction is decoded and executed by the CPU. The function of the CPU is to control the operation of memory and I/O components and to process data according to the program. Each input and output connection point on a PLC has an address used to identify the I/O bit. Flowchart of the program is given in Fig. 8. The software processes and displays the data achieved from the PLC output easily. These data are three phase voltages (V_1 , V_2 , V_3), three phase currents (I_1 , I_2 , I_3), speed (n_r), and temperature (T_C) of the IM, as shown in Fig. 3.

The motor variables and their descriptions are given in Table I.

Total length of PLC software is about 500 lines. Execution time of the PLC is about 0.37 μs for each Boolean instruction. Therefore, the PLC software developed is scanned at every 185 μs. Detection of the possible faults was also achieved about 5000 times in 1 s through the related sensors. According to the control procedure, the data are first read and then calculated.

TABLE I
MOTOR ELECTRICAL VARIABLES ACHIEVED ON THE COMPUTER

Variables	Symbol	Input	Unit
Voltage of phase 1	V_1	Analog Module-I input A	Volt
Voltage of phase 2	V_2	Analog Module-I input B	Volt
Voltage of phase 3	V_3	Analog Module-I input C	Volt
Current of phase 1	I_1	Analog Module-I input D	Ampere
Current of phase 2	I_2	Analog Module-II input A	Ampere
Current of phase 3	I_3	Analog Module-II input B	Ampere
Speed	n_r	Analog Module-II input C	rpm
Winding temperature	T_C	Analog Module-II input D	Degree

The motor transient time is defined as 100 ms that is controlled continuously by the program. If the transient time is more than the defined time, the program goes to the control procedure, and the motor is stopped by sending a signal from the PLC to the control circuit of the motor. At the end of the procedure, the results are displayed on the screen. The information given on the screen is renewed at every 200 ms while the program is running continuously. Transient and renew times in the software can be changed depending on the load and the power of the motor.

The software then directly displays the phase voltages, the phase currents, the rotor speed, and the motor temperature on computer without any human interaction. After having all these data, they are controlled considering their tolerance values. The program continues to run since these data are in the defined boundaries. If there is no value read, the program recontinues to read and calculate the signals until reading new voltages, cur-rents, speed, and temperature (V_1 , V_2 , V_3 , I_1 , I_2 , I_3 , n_r , and T_c). If any fault occurs, the program compares the three phase volt-ages, the three phase currents, the speed, and the temperature with their nominal values, and the motor is then stopped by send-ing a signal from the PLC to the control circuit of the motor, and the error description messages are shown on the screen. When an undefined fault occurs, the motor stops without giving any description. In this case, the fault can be described and found by the operator. In addition, the database file gives all the history of problems that occurred. The motor can be started again if the error is removed on the motor. The motor cannot be restarted if the motor still sends an error signal when the reset button is not active.

IV. EXPERIMENTS ON MOTOR FAULT DETECTION AND PROTECTION

The computer interface program has been written using pack-age SCADA software known as Winlog. The communication is achieved according to “Modbus” protocol between the PLC and a computer. This protocol is defined as follows.

Channel: 1
Configuration: Modbus RTU
Port: COM1
Baud rate: 19200
Stop bit: 1
Data bit: 8
Time out (ms): 1000
Query pause (ms): 20

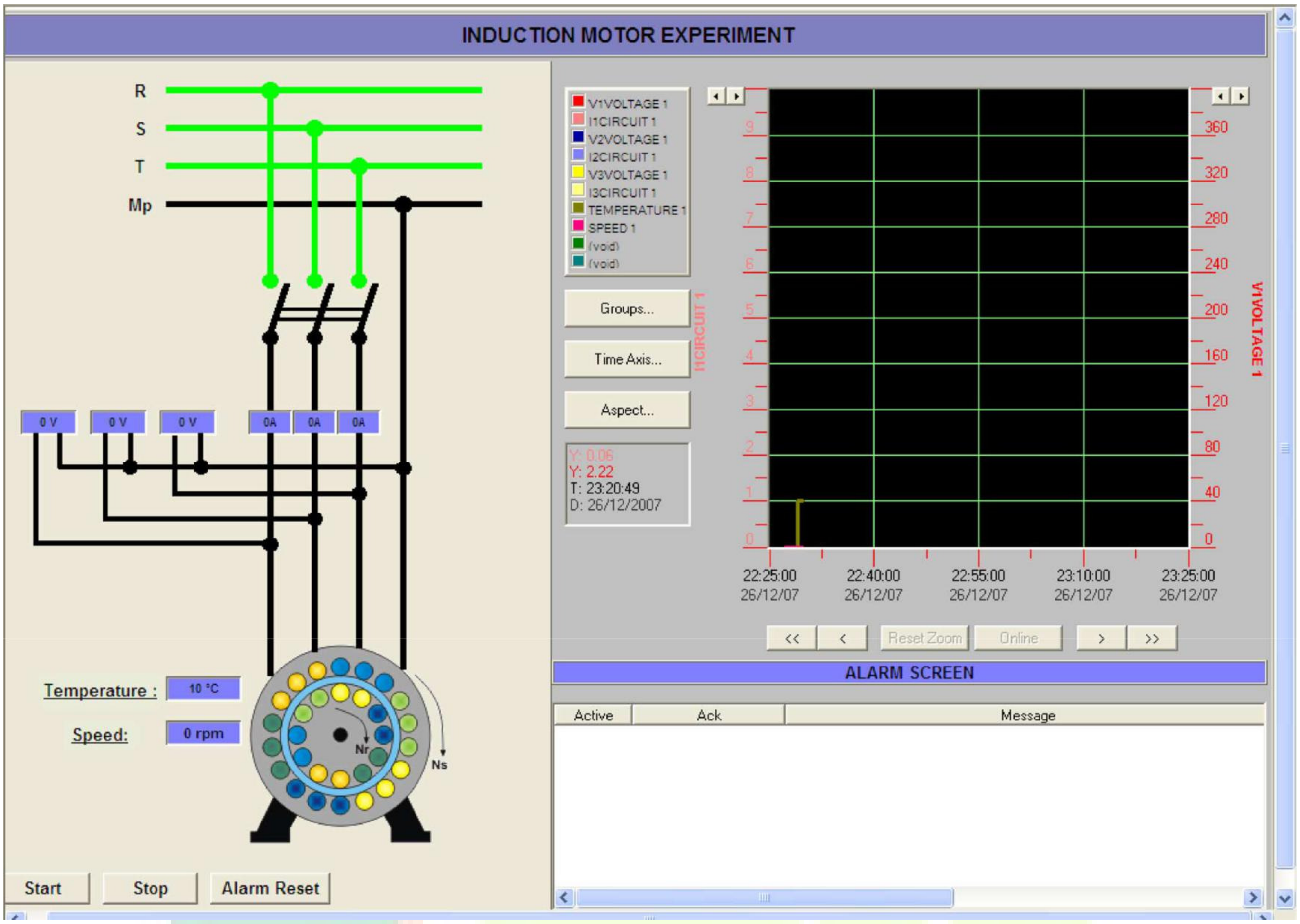

Fig. 9. Screenshot of starting page.

The software menu developed for the motor protection is given in Fig. 9. To detect the faults and to protect the motor, the software developed was used throughout experiments.

The menu of the program consists of six buttons as start, stop, alarm and reset, groups, time axis, and aspect.

1) Start is used to start the motor.
2) Stop is used to stop the motor.
3) Alarm and reset is used to stop the motor at any failure. Even if the failure condition turns to normal, the motor will

not start again automatically. To start the motor, first the reset icon and then the start icon must be clicked on.

Group is used to constitute individual graphical group. For example, if the user wants to see three phase graphic, only the groups are seen on computer as graphic by means of group.

4) Time axis is used to adjust time division. Therefore, time range is adjusted as given in Fig. 10.
5) Aspect is used to set line thickness.

Graphic forms of the voltages and the currents are also il-lustrated in this menu. Moreover, eight different motor status buttons representing three phase currents and voltages are given in this screenshot. Motor variables, the three phase voltages, the three phase currents, the temperature, and the speed are also displayed on this screen.

If the induction motor is required to be run, minimum and maximum values of the voltage, the current, the temperature,

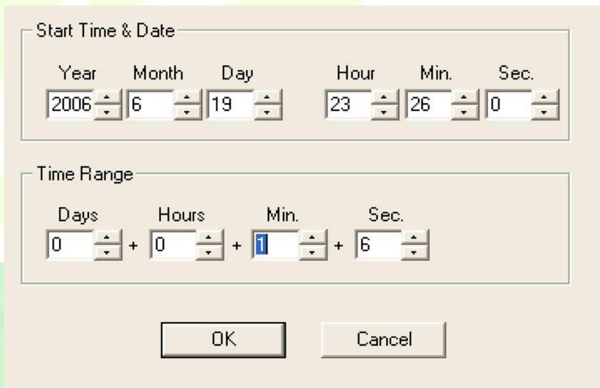

Fig. 10. Display of time range.

and the speed have to be entered from the keyboard first. After entering all values, the motor is then ready for starting. When the motor icon is clicked on, the menu shown in Fig. 11 is displayed on the screen. The optional waveforms of the currents and the voltages can be seen on the oscilloscope. These obtained data are then analyzed on the computer using the software developed. In addition, the computer screen is refreshed at every 200 ms.

The motor protection settings are based on rule-based con-trol methodology to detect the fault and to protect the motor.

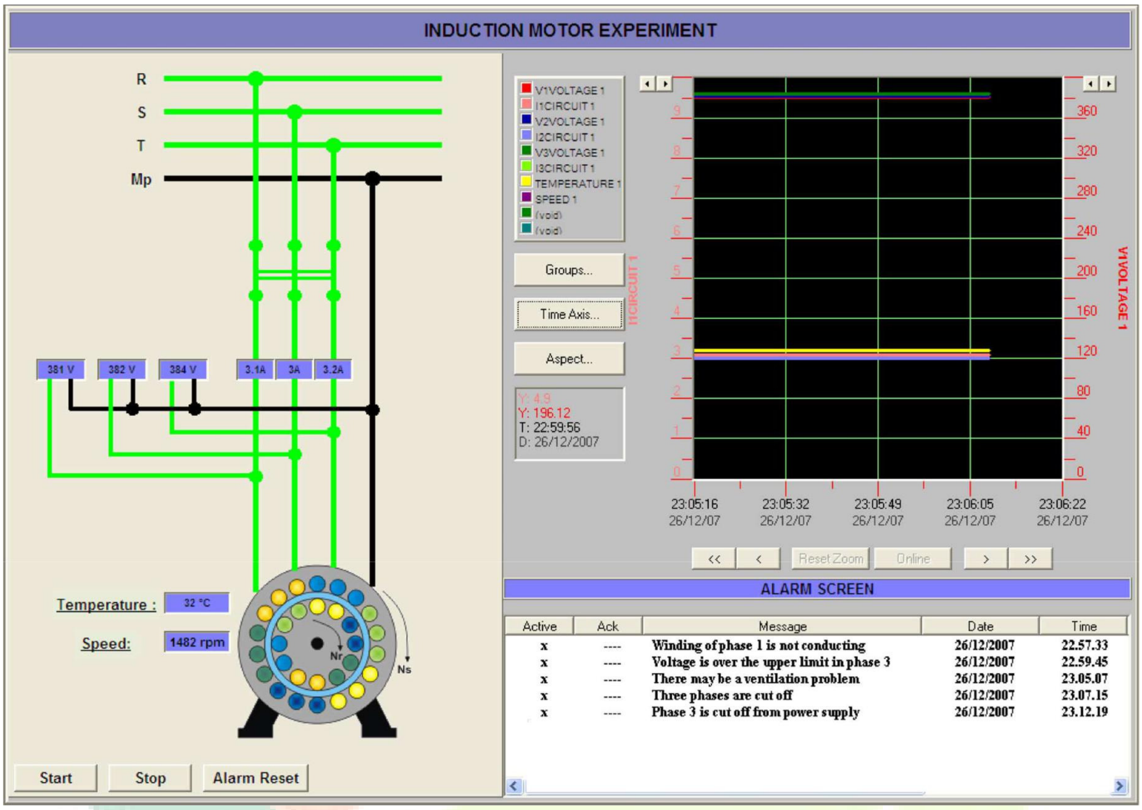

Fig. 11. Screenshot of program page.

TABLE II
MOTOR ELECTRICAL VARIABLES ACHIEVED ON THE COMPUTER

Types of Faults	I_1	I_2	I_3	V_1	V_2	V_3	n_r	T_C
Motor is stopped or three phases are not present	<	<	<	<	<	<	<	*
Winding of phase 1 is not conducting	0	≥ N	≥ N	N	N	N	≤ N	*
Winding of phase 2 is not conducting	≥ N	0	≥ N	N	N	N	≤ N	*
Winding of phase 3 is not conducting	≥ N	≥ N	0	N	N	N	≤ N	*
Winding of all phases are not conducting	0	0	0	N	N	N	≤ N	*
Phase 1 is cut off from supply	0	≥ N	≥ N	<	≤ N	≤ N	N	*
Phase 2 is cut off from supply	≥ N	0	≥ N	N	<	N	≤ N	*
Phase 3 is cut off from supply	≥ N	≥ N	0	N	N	<	≤ N	*
There may be a short circuit in phase 1	>	≤ N	≤ N	*	*	*	<	*
There may be a short circuit in phase 2	≤ N	>	≤ N	*	*	*	<	*
There may be a short circuit in phase 3	≤ N	≤ N	>	*	*	*	<	*
Voltage is over the upper limit in phase 1	≥ N	≥ N	≥ N	>	N	N	N	*
Voltage is over the upper limit in phase 2	≥ N	≥ N	≥ N	N	>	N	N	*
Voltage is over the upper limit in phase 3	≥ N	≥ N	≥ N	N	N	>	N	*
Voltage is over the upper limit in phases 1 and 2	≥ N	≥ N	≥ N	>	>	N	N	*
Voltage is over the upper limit in phases 1 and 3	≥ N	≥ N	≥ N	>	N	>	N	*
Voltage is over the upper limit in phases 2 and 3	≥ N	≥ N	≥ N	N	>	>	N	*
Voltage is over the upper limit in phases 1, 2 and 3	≥ N	≥ N	≥ N	>	>	>	N	*
Voltage is below the lower limit in phase 1	≤ N	≥ N	≥ N	<	N	N	≤ N	*
Voltage is below the lower limit in phase 2	≥ N	≤ N	≥ N	N	<	N	≤ N	*
Voltage is below the lower limit in phase 3	≥ N	≥ N	≤ N	N	N	<	≤ N	*
Voltage is below the lower limit in phases 1 and 2	≤ N	≤ N	≥ N	<	<	N	≤ N	*
Voltage is below the lower limit in phases 1 and 3	≤ N	≥ N	≤ N	<	N	<	≤ N	*
Voltage is below the lower limit in phases 2 and 3	≥ N	≤ N	≤ N	N	<	<	≤ N	*
Voltage is below the lower limit in phases 1, 2 and 3	≥ N	≥ N	≥ N	<	<	<	≤ N	*
There may be a ventilation problem with the motor	N	N	N	N	N	N	N	>
All three phases are cut off and motor is not starting	0	0	0	0<	<	<	<	*
The coil of phase 1 is cut off or there is a problem with the connection box	0	>	>	N	N	N	<	*
The coil of phase 2 is cut off or there is a problem with the connection box	>	0	>	N	N	N	<	*
The coil of phase 3 is cut off or there is a problem with the connection box	>	>	0	N	N	N	<	*

The software developed was used throughout experiments. The temperature sensor was used only for the stator current faults. The temperature of the rotor was neglected. Possible detectable faults are given in Table II [2]. In this table, the symbols <, >, ≥, and ≤, respectively, represent less, greater, greater equal, and less equal boundaries for I_1 , I_2 , I_3 , V_1 , V_2 , V_3 , n_r , and T_C . As-terisk (*) indicates none value in the table. N illustrates the normal value. In the software, all possible faults were de-scribed. The faults' date, hour, and possible names are dis-played on the alarm screen. After removing the alarm, the sys-tem is reset by pushing on the reset button. If the alarm is still active, it cannot be removed even by pushing on the reset button.

The faults of the motor are shown in Table II. There are 30 faults described. In each fault, three phase currents, three phase voltages, speed, and temperature were compared with their nominal values. If any of these faults is occurred, the motor is then stopped by sending a signal from the com-puter to the control circuit of the motor. When an undefined fault occurs, the motor stops without giving any description. In this case, the fault can be described and found by the operator.

V. CONCLUSION

In this study, a novel digital protection system for three phase IMs designed and implemented in Gazi Electrical Ma-chines and Energy Control (GEMEC) Group Laboratory at Gazi University has been introduced successfully. A 1.5 kW three-phase IM has been connected to the protection system through the measuring components, as illustrated in Fig. 5. The proposed PLC-controlled protective relay deals with the most important types of these failures, which are summarized as the phase lost, the over/undercurrent, the over/undervoltage, the unbalance of supply voltages, the overload, the unbalance of phase currents, the ground fault, and the excessive repeated starting. If any fault is observed during online operation of the motor, a warning message appears on computer and then the motor is stopped. When an undefined fault occurs, the motor stops without giving any description. In this case, the fault can be described and found by the operator. The test has been found successful in detecting the faults and in recovering them.

The results showed that a reliable PLC-based protection sys-tem including all variables of the three-phase IMs and operators have been developed. The total length of the PLC software is about 500 lines. Therefore, the PLC software developed is scanned at every 185 μs. The detection of the possible faults was also achieved about 5000 times in 1 s through the related sensors. It is expected that motor protection achieved in this study might be faster and more efficient than the classical techniques be-cause of the electronic equipment used in the experiments rather than mechanical equipment. In addition, it does not require any conversion card, and therefore, costs less than a computer-based protection method. Moreover, it provides a visual environment, which makes the system more user-friendly than a PIC-based protection method. Finally, being flexible in the range settings, considering all motor variables together, eliminating the conver-sion card, and providing a visual environment make the proposed protection system better than other PLC-based protection sys-tems studied. This proposed protection system can be applied to different ac motors by doing small modifications in both the hardware and the software. The only difficulty faced was the measurement of the encoder signal during the experimental study.

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