Design and Implementation of PLC-Based Monitoring Control System for Induction Motor

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***Abstract*—The implementation of a monitoring and control system for the induction motor based on programmable logic controller (PLC) technology is described. Also, the implementation of the hardware and software for speed control and protection with the results obtained from tests on induction motor performance is provided. The PLC correlates the operational parameters to the speed requested by the user and monitors the system during normal operation and under trip conditions. Tests of the induction motor system driven by inverter and controlled by PLC prove a higher accuracy in speed regulation as compared to a conventional V/f control system. The efficiency of PLC control is increased at high speeds up to 95% of the synchronous speed. Thus, PLC proves themselves as a very versatile and effective tool in industrial control of electric drives.**

***Index Terms*—Computer-controlled systems, computerized monitoring, electric drives, induction motors, motion control, programmable logic controllers (PLCs), variable-frequency drives, voltage control.**

I. INTRODUCTION

SINCE technology for motion control of electric drives became available, the use of programmable logic controllers (PLCs) with power electronics in electric machines applications has been introduced in the manufacturing automation [1], [2]. This use offers advantages such as lower voltage drop when turned on and the ability to control motors and other equipment with a virtually unity power factor [3]. Many factories use PLCs in automation processes to diminish production cost and to increase quality and reliability [4]–[9]. Other applications include machine tools with improved precision computerized numerical control (CNC) due to the use of PLCs [10]. To obtain accurate industrial electric drive systems, it is necessary to use PLCs interfaced with power converters, personal computers, and other electric equipment [11]–[13]. Nevertheless, this makes the equipment more sophisticated, complex, and expensive [14], [15].

Few papers were published concerning dc machines controlled by PLCs. They report both the implementation of the fuzzy method for speed control of a dc motor/generator set using a PLC to change the armature voltage [16], and the incorporation of an adaptive controller based on the self-tuning regulator technology into an existing industrial PLC [17]. Also, other types of machines were interfaced with PLCs. Thereby, an industrial PLC was used for controlling stepper motors in a five-axis rotor position, direction and speed, reducing the number of circuit components, lowering the cost, and enhancing reliability [18]. For switched reluctance motors as a possible alternative to adjustable speed ac and dc drives, a single chip logic controller for controlling torque and speed uses a PLC to implement the digital logic coupled with a power controller [19]. Other reported application concerns a linear induction motor for passenger elevators with a PLC achieving the control of the drive system and the data acquisition [20]. To monitor power quality and identify the disturbances that disrupt production of an electric plant, two PLCs were used to determine the sensitivity of the equipment [21].

Only few papers were published in the field of induction motors with PLCs. A power factor controller for a three-phase induction motor utilizes PLC to improve the power factor and to keep its voltage to frequency ratio constant under the whole control conditions [3]. The vector control integrated circuit uses a complex programmable logic device (CPLD) and integer arithmetic for the voltage or current regulation of three-phase pulse-width modulation (PWM) inverters [22].

Many applications of induction motors require besides the motor control functionality, the handling of several specific analog and digital I/O signals, home signals, trip signals, on/off/reverse commands. In such cases, a control unit involving a PLC must be added to the system structure. This paper presents a PLC-based monitoring and control system for a three-phase induction motor. It describes the design and implementation of the configured hardware and software. The test results obtained on induction motor performance show improved efficiency and increased accuracy in variable-load constant-speed-controlled operation. Thus, the PLC correlates and controls the operational parameters to the speed set point requested by the user and monitors the induction motor system during normal operation and under trip conditions.

II. PLC AS SYSTEM CONTROLLER

A PLC is a microprocessor-based control system, designed for automation processes in industrial environments. It uses a programmable memory for the internal storage of user-orientated instructions for implementing specific functions such as arithmetic, counting, logic, sequencing, and timing [23], [24]. A PLC can be programmed to sense, activate, and control industrial equipment and, therefore, incorporates a number of I/O points, which allow electrical signals to be interfaced. Input devices and output devices of the process are connected to the PLC and the control program is entered into the PLC memory (Fig. 1).

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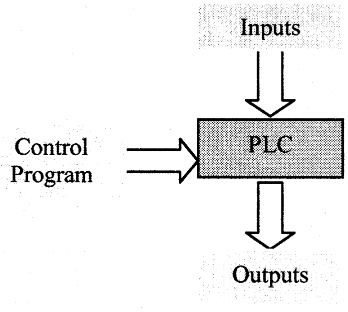

Fig. 1. Control action of a PLC.

In our application, it controls through analog and digital inputs and outputs the varying load-constant speed operation of an induction motor. Also, the PLC continuously monitors the inputs and activates the outputs according to the control program. This PLC system is of modular type composed of specific hardware building blocks (modules), which plug directly into a proprietary bus: a central processor unit (CPU), a power supply unit, input-output modules I/O, and a program terminal. Such a modular approach has the advantage that the initial configuration can be expanded for other future applications such as multimachine systems or computer linking.

III. CONTROL SYSTEM OF INDUCTION MOTOR

In Fig. 2, the block diagram of the experimental system is illustrated. The following configurations can be obtained from this setup.

a) A closed-loop control system for constant speed operation, configured with speed feedback and load current feedback. The induction motor drives a variable load, is fed by an inverter, and the PLC controls the inverter V/f output.

b) An open-loop control system for variable speed operation. The induction motor drives a variable load and is fed by an inverter in constant V/f control mode. The PLC is inactivated.

c) The standard variable speed operation. The induction motor drives a variable load and is fed by a constant voltage-constant frequency standard three-phase supply.

The open-loop configuration b) can be obtained from the closed-loop configuration a) by removing the speed and load feedback. On the other hand, operation c) results if the entire control system is bypassed.

IV. HARDWARE DESCRIPTION

The control system is implemented and tested for a wound rotor induction motor, having the technical specifications given in Table I. The induction motor drives a dc generator, which supplies a variable R load. The three-phase power supply is connected to a three-phase main switch and then to a three-phase thermal overload relay, which provides protection against current overloads. The relay output is connected to the rectifier, which rectifies the three-phase voltage and gives a dc input to the insulated gate bipolar transistor (IGBT) inverter. Its technical specifications [25] are summarized in Table II. The IGBT

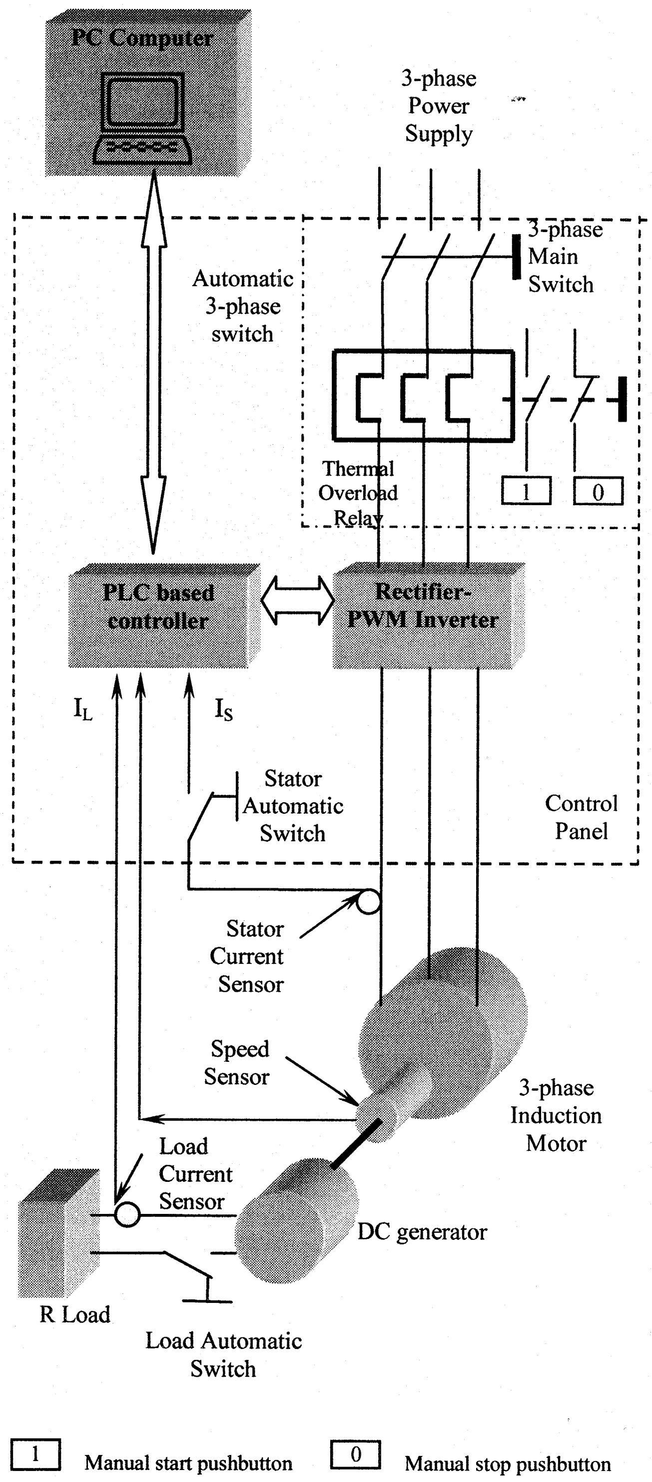

Fig. 2. Electrical diagram of experimental system.

TABLE I
INDUCTION MOTOR TECHNICAL SPECIFICATIONS

Connection type	Δ/Y
Input voltage	380/660 V ac
Input current	1,5/0,9 A
Rated power	0,6 kW
Input frequency	50 Hz
Pole number	4
Rated speed	1400 rpm

TABLE II
INVERTER TECHNICAL SPECIFICATIONS

Output voltage	380, 460 V ac
Output frequency	0, 480 Hz
Output current	2,5 A
Output overload	150% for 60s
Power supply voltage	380, 460−10% V ac
Input current	3 A
Dissipated power	46 W

inverter converts the dc voltage input to three-phase voltage output, which is supplied to the stator of the induction motor. On the other hand, the inverter is interfaced to the PLC-based controller.

This controller is implemented on a PLC modular system [5], [26]–[28]. The PLC architecture refers to its internal hardware and software. As a microprocessor-based system, the PLC system hardware is designed and built up with the following modules [29]–[37]:

- central processor unit (CPU);
- discrete output module (DOM);
- discrete input module (DIM);
- analog outputs module (AOM)
- analog inputs module (AIM)
- power supply.

Other details of the PLC configuration are shown in Tables III and IV.

A speed sensor is used for the speed feedback, a current sensor is used for the load current feedback, and a second current sensor is connected to the stator circuits [32]. Thus, the two feedback loops of the closed-loop system are setup by using the load current sensor, the speed sensor, and the AIM.

A tachogenerator (permanent magnet dc motor) is used for speed sensing. The induction machine drives its shaft mechanically and an output voltage is produced, the magnitude of which is proportional to the speed of rotation. Polarity depends on the direction of rotation. The voltage signal from the tachogenerator must match the specified voltage range of the AIM (0–5 V dc and 200-kΩ internal resistance). Other PLC external control circuits are designed using a low-voltage supply of 24 V dc.

For the manual control, the scheme is equipped with start, stop, and trip push buttons, as well as with a forward and backward direction selector switch. As shown in Fig. 2, all of the described components: a main switch, an automatic three-phase switch, an automatic single phase switch, a three-phase thermal overload relay, a load automatic switch, signal lamps (forward, backward, start, stop, trip), push buttons (start, stop, trip), a selector switch (for the forward/backward direction of rotation), a speed selector, a gain selector, as well as the PLC modules and the rectifier-inverter are installed in a control panel. The program is downloaded into the PLC from a personal computer PC and an RS232 serial interface.

V. SOFTWARE DESCRIPTION

PLC's programming is based on the logic demands of input devices and the programs implemented are predominantly logical rather than numerical computational algorithms. Most of the programmed operations work on a straightforward two-state "on or off" basis and these alternate possibilities correspond to "true or false" (logical form) and "1 or 0" (binary form), respectively. Thus, PLCs offer a flexible programmable alternative to electrical circuit relay-based control systems built using analog devices.

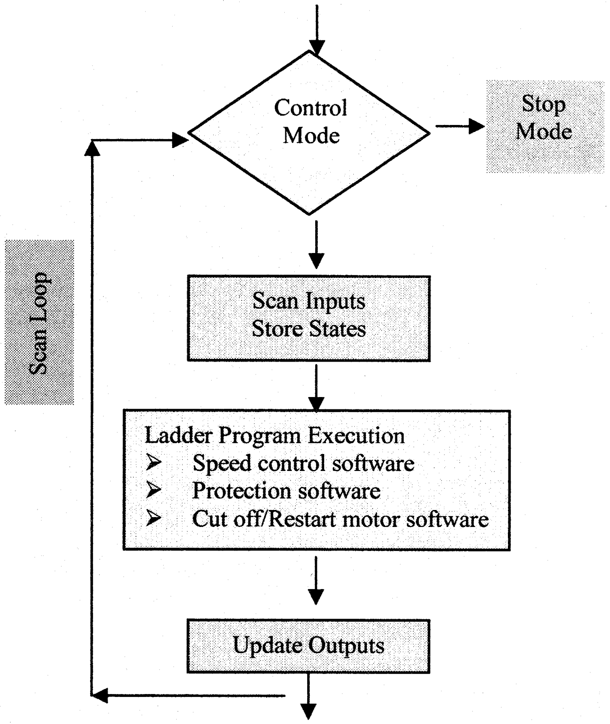

Fig. 3. Flowchart of the main program.

TABLE III
PLC CONFIGURATION

	Available	Used
Discrete Inputs (%I)	32	8
Discrete Outputs (%Q)	16	9
Analogue Inputs (%AI)	8	7
Analogue Outputs (%AQ)	8	6
Register Memory (%M)	540	

The programming method used is the ladder diagram method. The PLC system provides a design environment in the form of software tools running on a host computer terminal which allows ladder diagrams to be developed, verified, tested, and diagnosed. First, the high-level program is written in ladder diagrams, [33], [34]. Then, the ladder diagram is converted into binary instruction codes so that they can be stored in random-access memory (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 devices 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. The method for the direct representation of data associated with the inputs, outputs, and memory is based on the fact that the PLC memory is organized into three regions: input

TABLE IV
PLC MODULES AND I/O DESIGNATION

Motherboard				
Module 1	*Module 2*	*Module 3*	*Module 4*	*Module 5*
	Analog input module-AIM	*Discrete input module-DIM*	*Analog output module-AOM*	*Discrete output module-DOM*
1. CPU	1. Speed feedback signal (input)	1. Start pushbutton signal	1. Speed feedback signal (display)	1. Relay_1
2. Power supply	2. Load current feedback signal	2. Stop pushbutton signal	2. Speed set point signal (display)	2. Start Lamp (run)
	3. Stator current signal (input)	3. Trip pushbutton signal	3. Load torque signal (display)	3. Relay_2
	4. Speed set point signal	4. Forward switch signal	4. Inverter frequency reference	4. Stop Lamp
	5. Controller gain signal	5. Backward switch signal	5. Load relay	5. Relay_3
	6. Controller time constant	6. Trip pushbutton signal	6. Stator relay	6. Trip Lamp
	7. Inverter analog port	7. 24 V dc		7. Inverter digital port
		8. 0 V dc		8. 24 V dc
				9. 0 V dc

image memory (I), output image memory (Q), and internal memory (M). Any memory location is referenced directly using %I, %Q, and %M (Table III).

The PLC program uses a cyclic scan in the main program loop such that periodic checks are made to the input variables (Fig. 3). The program loop starts by scanning the inputs to the system and storing their states in fixed memory locations (input image memory I). The ladder program is then executed rung-by-rung. Scanning the program and solving the logic of the various ladder rungs determine the output states. The updated output states are stored in fixed memory locations (output image memory Q). The output values held in memory are then used to set and reset the physical outputs of the PLC simultaneously at the end of the program scan. For the given PLC, the time taken to complete one cycle or the scan time is 0, 18 ms/K (for 1000 steps) and with a maximum program capacity of 1000 steps.

The development system comprises a host computer (PC) connected via an RS232 port to the target PLC. The host computer provides the software environment to perform file editing, storage, printing, and program operation monitoring. The process of developing the program to run on the PLC consists of: using an editor to draw the source ladder program, converting the source program to binary object code which will run on the PLC's microprocessor and downloading the object code from the PC to the PLC system via the serial communication port. The PLC system is online when it is in active control of the machine and monitors any data to check for correct operation.

A. PLC Speed Control Software

In Fig. 4, the flowchart of the speed control software is illustrated. The software regulates the speed and monitors the constant speed control regardless of torque variation. The inverter being the power supply for the motor executes this while, at the same time, it is controlled by PLC's software. The inverter alone cannot keep the speed constant without the control loop with feedback and PLC.

From the control panel, the operator selects the speed setpoint n_{sp} and the forward/backward direction of rotation. Then, by pushing the manual start pushbutton, the motor begins the rotation. If the stop button is pushed, then the rotation stops. The corresponding input signals are interfaced to the DIM and the output signals to the DOM as shown in Table IV.

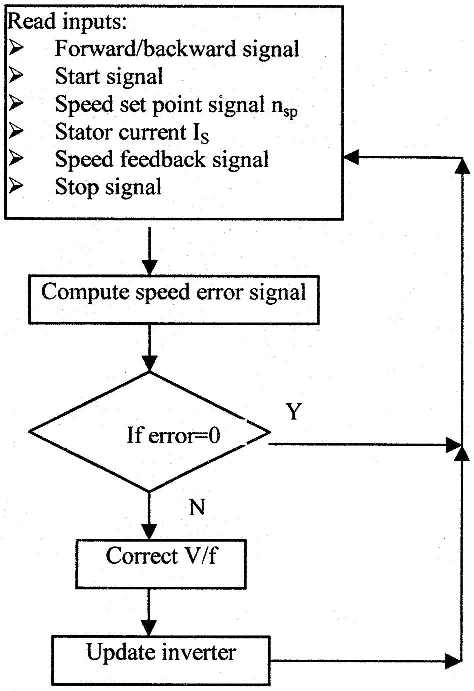

Fig. 4. Flowchart of speed control software.

The AIM receives the trip signal I_S from the stator current sensor, the speed feedback signal from the tachogenerator, and the n_{sp} signal from the control panel. In this way, the PLC reads the requested speed and the actual speed of the motor. The difference between the requested speed by the operator and the actual speed of the motor gives the error signal. If the error signal is not zero, but positive or negative, then the PLC according to the computations carried out by the CPU decreases or increases the V/f of the inverter and, as a result, the speed of the motor is corrected.

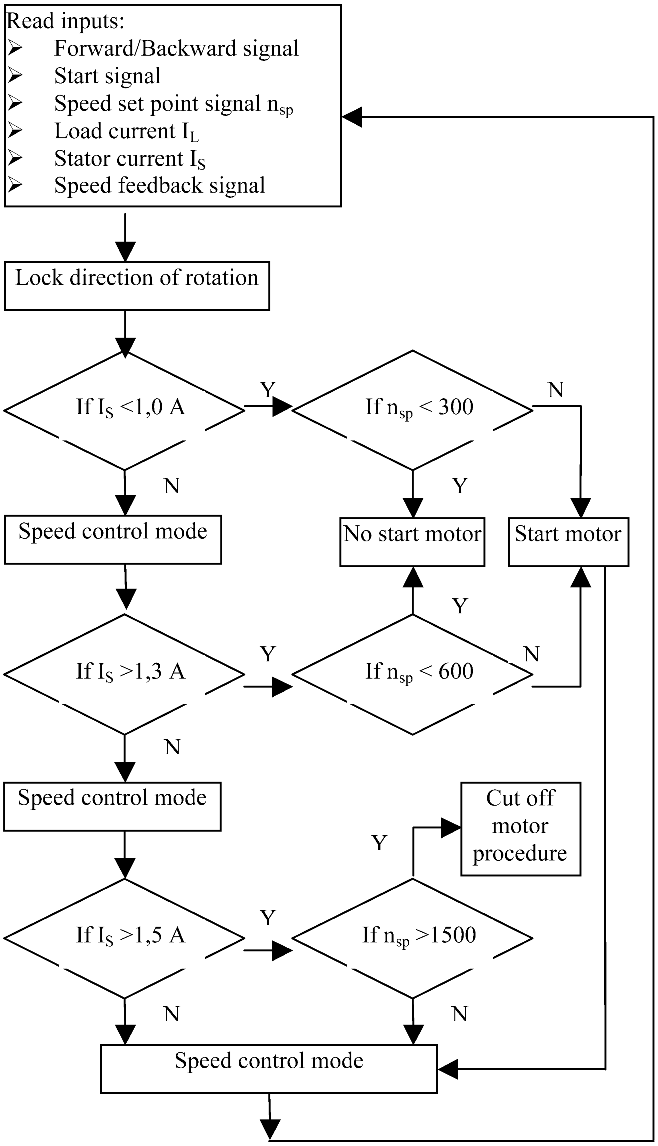

Fig. 5. Flowchart of monitor and protection software.

The implemented control is of proportional and integral (PI) type (i.e., the error signal is multiplied by gain K_p, integrated, and added to the requested speed). As a result, the control signal is sent to the DOM and connected to the digital input of the inverter to control V/f variations. At the beginning, the operator selects the gain K_p by using a rotary resistor mounted on the control panel (gain adjust) and the AIM receives its voltage drop as controller gain signal (0–10 V).

The requested speed n_{sp} is selected using a rotary resistor and the AIM reads this signal. Its value is sent to the AOM and displayed at the control panel (speed set point display). Another display of the control panel shows the actual speed computed from the speed feedback signal. A third display shows the load torque computed from the load current signal in Newton-meters (N · m). Their corresponding signals are output to the AOM (Table IV).

B. Monitor and Protection Software

In Fig. 5, the flowchart of this software is shown.

During motor operation, it is not possible to reverse its direction of rotation by changing the switch position. Before direction reversal, the stop button must be pushed.

For motor protection against overloading currents during starting and loading, the following commands were programmed into the software.

i) Forward/backward signal is input to DIM.
ii) Speed setpoint signal n_{sp}, the load current I_L, the stator current I_S, and the speed feedback signal are input to AIM.
iii) At no load $I_S \leq 1,0A$, if the speed set point is lower than 20% or $n_{\mathrm{sp}} < 300$ r/min, the motor will not start.
iv) At an increased load over 0, 4 N · m (40% of rated torque), $I_S \geq 1,3A$, and a speed setpoint lower than 40% or $n_{\mathrm{sp}} < 600$ r/min, the motor will not start.
v) If the load is increased more than 1, 0 N · m (rated torque) $I_S \geq 1,5A$ and if the speed set point exceeds 100% or $n_{\mathrm{sp}} \geq 1500$ r/min, the motor enters the cutoff procedure.
vi) In all other situations, the motor enters in the speed control mode and the speed control software is executed as described in Subsection A.

C. Cutoff and Restart Motor Software

In Fig. 6, the flowchart of this software is shown.

- In overloading situations, the motor is cut off and the trip lamp (yellow) is lit. The operator must release the thermal relays and then must turn off the trip lamp by pushing trip or stop button. The thermal relays are set to the motor rated current 1, 5 A. Following this, the motor can be started again.
- The motor can be cut off by the operator pushing the stop button: the display of the actual speed is set to zero, the start lamp (green) turns off, and the stop lamp (red) turns on and remains lit for 3 s.
- The load must be disconnected immediately after the motor cuts off and before the drive system is restarted. The motor will not start before 3 s after cutoff even if the start button is pushed.

VI. RESULTS

The system was tested during operation with varying loads including tests on induction motor speed control performance and tests for trip situations. The PLC monitors the motor operation and correlates the parameters according to the software.

At the beginning, for reference purposes, the performance of induction motor supplied from a standard 380 V, 50-Hz network was measured. Then, the experimental control system was operated between no load and full load (1, 0 N · m) in the two different modes described in Section III:

a) induction motor fed by the inverter and with PLC control;
b) induction motor fed by the inverter.

The range of load torque and of speed corresponds to the design of the PLC hardware and software as described in the previous sections.

The speed versus torque characteristics were studied in the range 500–1500 r/min and is illustrated in Fig. 7. The results

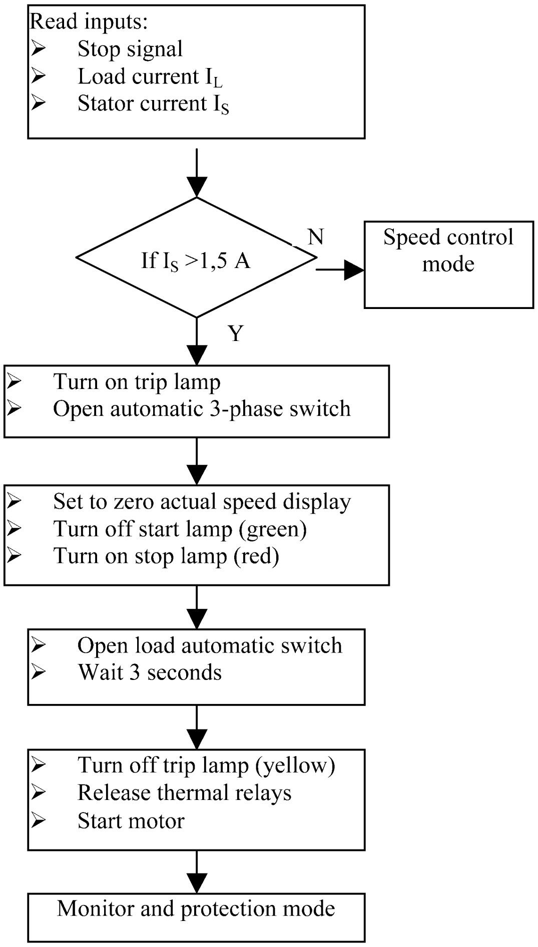

Fig. 6. Flowchart of cutoff/restart motor software.

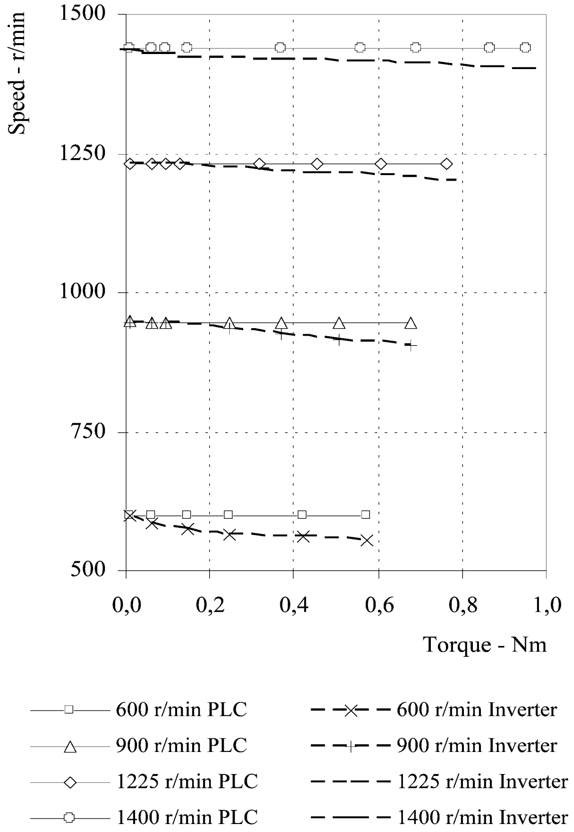

Fig. 7. Experimental speed–torque characteristics with PLC and inverter.

show that configuration b) operates with varying speed-varying load torque characteristics for different speed setpoints n_{sp}. Configuration a) operates with constant-speed-varying load torque characteristics in the speed range 0–1400 r/min and 0–100% loads. However, in the range of speeds higher than 1400 r/min and loads higher than 70%, the system operates with varying-speed-varying-load and the constant speed was not possible to be kept. Thus, for $n_{\mathrm{sp}} \geq 1400$ r/min both configurations a) and b) have a similar torque-speed response. This fact shows that PI control for constant speed as implemented by the software with PLC is effective at speeds lower than 93% of the synchronous.

The efficiency for different values of n_{sp} was also studied. In Fig. 8, the efficiency is shown normalized, using as base value or 1 p.u. the efficiency of the induction motor supplied from the standard network. As depicted in Fig. 8, the results show that configuration a) in all cases has a higher efficiency than configuration b). Also, at operation with loads higher than 70%, the normalized efficiency is $\eta(pu) > 1$, meaning that the obtained efficiency with PLC control is higher than the efficiency of induction motor operated from the standard 380-V, 50-Hz network without the control of PLC and without the inverter. According to this figure, the efficiency of PLC-controlled system is increased up to 10–12% compared to the standard motor operation. From a theoretical point of view, if we neglect magnetizing current, an approximate value for the efficiency is

$$\eta = \frac{1 - s}{1 - s \cdot R_S / R_R}$$

where s is the slip and R_S, R_R are the stator and rotor winding resistances, respectively. As can be seen from Fig. 7, the PLC-controlled system a) works with very low slip values, almost zero. In all speed and load torque conditions, the configuration a) has a smaller slip than configuration b), thus the higher values of efficiency can be justified and especially at high speeds and frequencies. At lower frequencies, the magnetic flux increases and, thus, there is an increase in magnetizing current resulting in increased losses.

Fig. 9 shows the stator voltage versus stator frequency characteristics of the inverter with PLC control for the same range of speeds and torques as in Fig. 7. For each one of the speed–torque characteristics from Fig. 7, the relationship between stator voltage and stator frequency is constant. However, this relationship, which corresponds to the motor flux, increases with the decrease of frequency from 8, 3 at 50 Hz up to 11, 25 at 12 Hz, as shown in Fig. 10. Thus, as can be seen from Fig. 7, where the available torque decreases from 100% at 50 Hz up to 60% at 20 Hz, when both voltage and frequency decrease, there is an increase in magnetic flux with a decrease of maximum available torque.

The regulator gain K_p is plotted in Fig. 11 for all speed and torque ranges. The results show that it presents an almost linear

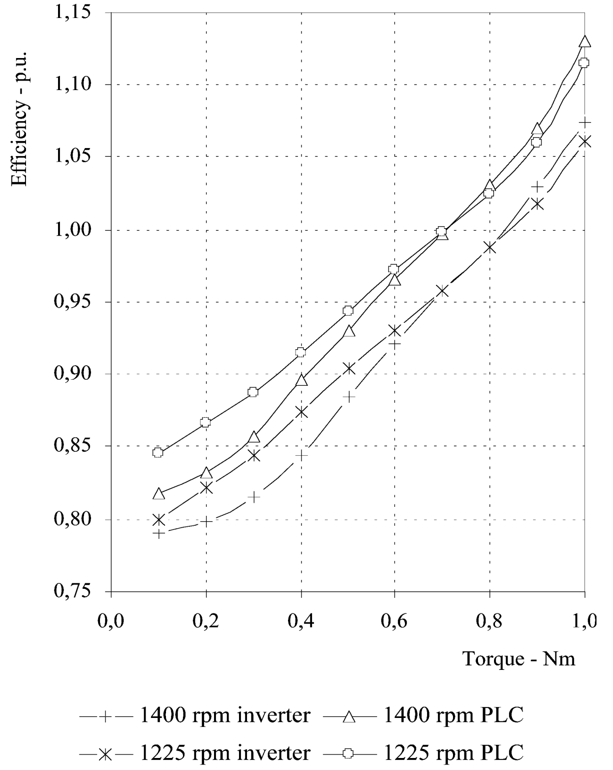

Fig. 8. Efficiency of controlled system with and without PLC per unit of efficiency of standard supplied motor.

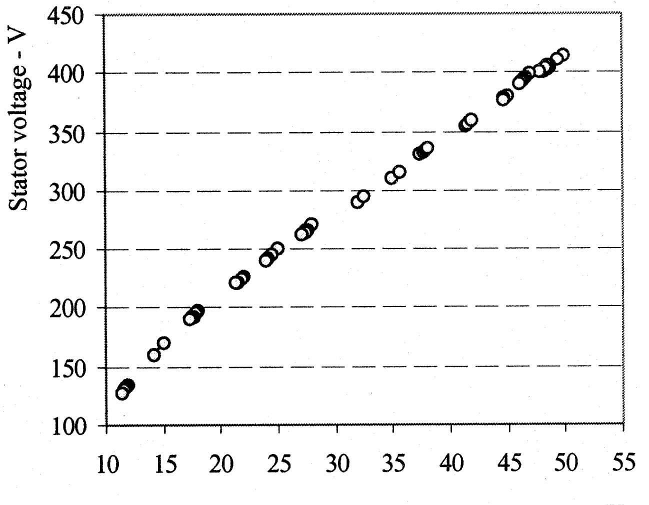

Fig. 9. Stator voltage versus frequency characteristics of an inverter with PLC control.

variation with n_{sp} for varying loads, with small displacements between characteristics.

This system presents a similar dynamic response as the closed-loop system with V/f speed control. Its transient performance is limited due to oscillations on torque [32] and this behavior restricts the application of this system to processes that only require slow speed variation.

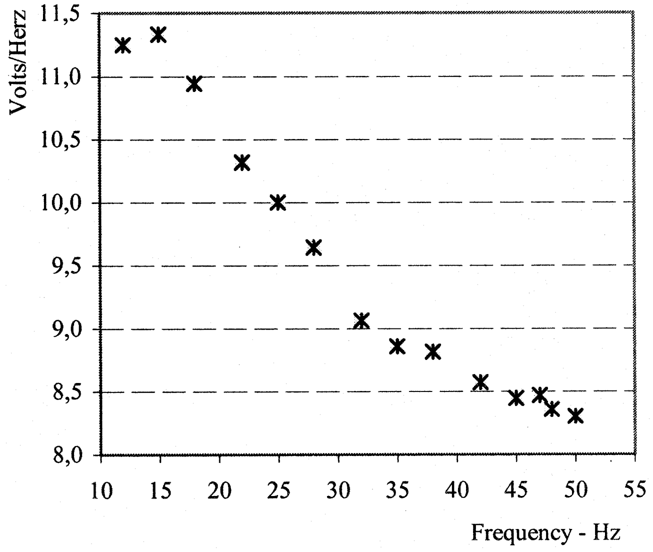

Fig. 10. Rate for stator voltage/stator frequency.

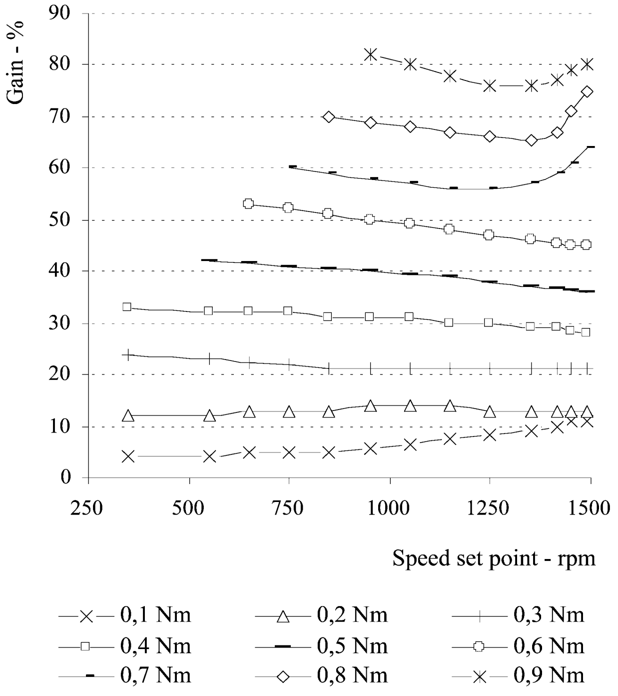

Fig. 11. Control characteristics of PLC.

VII. CONCLUSION

Successful experimental results were obtained from the previously described scheme indicating that the PLC can be used in automated systems with an induction motor. The monitoring control system of the induction motor driven by inverter and controlled by PLC proves its high accuracy in speed regulation at constant-speed-variable-load operation.

The effectiveness of the PLC-based control software is satisfactory up to 96% of the synchronous speed. The obtained efficiency by using PLC control is increased as compared to the open-loop configuration of the induction motor fed by an inverter. Specifically, at high speeds and loads, the efficiency of PLC-controlled system is increased up to 10–12% as compared to the configuration of the induction motor supplied from a standard network.

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;
- very good accuracy in closed-loop speed control scheme;
- higher efficiency;
- overload protection.

Thus, the PLC proved to be a versatile and efficient control tool in industrial electric drives applications.

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