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Internet Based Speed Control and Torque Analysis of a 3-Phase Induction Motor

Abstract. One of the most important stages of the engineering education is the laboratory experiments. This paper presents remote access to a real time experimental set of a three phase induction motor. In the developed experimental set the crystal report service is used so that users can report the results of the experiments as a document such as PDF, Word or Excel file format without losing time. Due to experimental set improved, the speed control, the torque analysis and the energy efficiency of 3-phase induction motor can be performed over the internet in real time.

Streszczenie. W artykule przedstawiono system zdalnego dostępu w czasie rzeczywistym do stanowiska eksperymentalnego, złożonego z trójfazowej maszyny indukcyjnej. Opracowane rozwiązanie daje możliwość tworzenia raportów i sprawozdań standardowych dokumentach (PDF, doc, Excel). (Zdalne sterowanie prędkością i momentem trójfazowej maszyny indukcyjnej poprzez połączenie internetowe).

Keywords: remote-access laboratory, induction motor, speed control, torque analysis.
Słowa kluczowe: laboratorium o zdalnym dostępie, silnik indukcyjny, sterowanie prędkością, analiza momentu.

Introduction

Three phase induction motor widely used in many industrial applications because of robustness, low manufacturing and maintenance cost, reliability and high efficiency have two basic components called the stator and the rotor [1]. Stator is fixed outer portion of the motor and the rotor is rotating portion. There are two types of rotor construction that they are squirrel cage and wound rotor. The vast majority of induction motors are produced as a squirrel cage rotor because squirrel cage type induction motors can be safely used in flammable or dangerous environments as well [2, 3]. On the other hand wound rotor induction motors have been employed intensively in wind turbines recently [4]. Many studies have been published to improve operation performance and determine fault detection of induction motors [5-14].

In engineering and vocational education, the laboratory experiments have an important role as theoretical knowledge because backing theoretical knowledge with practice increases the speed of learning and ensures a permanent learning. In addition to laboratory studies contribute development of students' practical skills and prepare students for the real industrial conditions. For this aim classically the real laboratories, also called proximal or "hands-on" laboratories, are used for years in educational institutions. Although the real laboratories give the students a chance of live interaction with the equipment and observing real experimental results, they are quite expensive to establish and operate, and have limited availability [15].

In recent years, with the development of technology and the computer in particular, web based laboratories systems can be considered as a serious alternative to the classical local laboratories [16]. All over the world many educational institutions use the web based laboratory systems instead of classical laboratory. There are two type web based laboratories systems. The first of these laboratories is virtual laboratory based on simulation studies of real experiments. Virtual laboratory ensures better understanding and quicker learning by simplifying complex systems. But due to lack of the live experiences, particularly engineering students do not derive benefit from virtual laboratory for their practical skill development [15]. Another important disadvantage of virtual laboratories is that results of simulation study do not always reflect the results of real experiments.

The other web based laboratory system is remote laboratory accessed to real laboratory equipment in real time. Thereby the students can carry out the real experiments with the real laboratory equipment and they can observe the influence of the real-time effects. In this way, several remote laboratories, based in new equipment's reducing the cost and size of classical equipment, have been developed for engineering courses [17-19]. Thanks to remote laboratories, disadvantage of virtual laboratory can be removed and students can be prepared for the actual industrial conditions [15]. Besides, while classical laboratories generally offer students to use old devices due to the cost of modernization of devices, using modern devices in remote laboratory attracts attention of students and provides that students can advance practice without time and place limitation [20].

Different designs of web based laboratory systems are reported in Refs. [20-23]. In reference [21], a remote laboratories system for teaching fault detection and diagnosis of induction motors was presented. Students can analyse several fault type of induction motor. Also the developed system allows testing the behaviour of the machine for different load types. The major advantage of this system relies on the fact that is implemented with only one healthy motor, with a very low cost. In the remote access laboratory performed by M. Stefanovic et al. after the architecture of web based laboratory was presented, an experiment "Coupled water tanks" that is developed using LabVIEW [22]. Also this paper exhibits results of survey performed at University of Kragujevac in order to determine advantages and effects of using web laboratory in control engineering education. In reference [20], remote laboratory application was presented four-quadrant speed control experiment of a direct current (DC) by using MATLAB web server. Due to the real experimental set placed in the laboratory, users can monitor the test by performing the experiment in the study. An integrated environment for real time speed control of vector controlled induction motor including simulation and experimental study was presented by B. Dandil [23]. Thus, users can comprehend the classical and intelligent motor controllers.

In this study, a remote laboratory system which can be done torque analysis and speed control of three-phase induction motor over the internet has been developed. Electrical variables of an induction motor such as the current, the voltage, the frequency and the speed information measured in real time are saved in a database and then transferred to the torque model designed using MATLAB Builder for NE toolbox. Torque-speed curves and power consumption of the 3-phase induction motor are

formed then the system developed exhibits the curves generated to users over an internet page as well as allowing the users to alter speed and direction of rotation of the 3-phase induction motor in real time. In the developed experimental set crystal report service is used so that users can report the results of speed control and torque analysis of the induction motor as a document such as PDF, Word or Excel file format without losing time. Due to experimental set improved, the speed control, the torque analysis and the energy efficiency of 3-phase induction motor can be performed over the internet in real time without any time and place limitation.

Problem statement and motivation

The selection of an induction motor in suitable power is very important on account of the energy efficiency. Induction motors can be efficiently operated in full load or close to full load values [24]. In generally, induction motors used in many building systems are preferred in big capacities to meet extra load conditions. However, most building systems such as ventilation systems, pumps, elevator, blowers and conveyor operate at their full load only for short periods of time. This often results in many systems operating inefficiently over long periods of time [25]. In reference [24] authors indicate the variations of motor efficiencies according to loading conditions as shown Fig. 1.
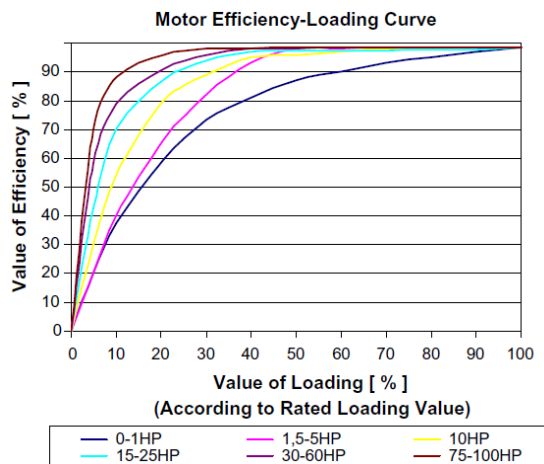

Fig.1. The variations of the motor efficiencies according to loading [24]

The efficiency of such motor systems that do not require full speed can be increased by varying their capacity to match actual load requirements. One of the methods used to improve the efficiency of induction motor is the adjustment of the mechanical power from the motor shaft depending on load. Although induction motors have lots of advantages in comparison with other electric motors, the speed control of them is more difficult. Induction motor speed control can be done by changing either frequency of input voltage or number of poles. As seen in Eq. 1, the speed per minute of a three phase induction motor is directly proportional to the frequency of input voltage and indirectly proportional to the number of poles.

$$(1) \qquad n_S = \frac{120.f_S}{p}$$

Where n_s is speed of stator rotating field, f_s is frequency of stator, p is number of poles. Normally number of poles changes of an induction motor is not preferable. Therefore speed control of the motor can only be achieved by changing frequency of stator. If the input frequency of the motor is changed by holding input voltage constant, then torque-speed curve of the motor can be given as in Fig. 2. While frequency of stator is increased, torque produced is decreased.
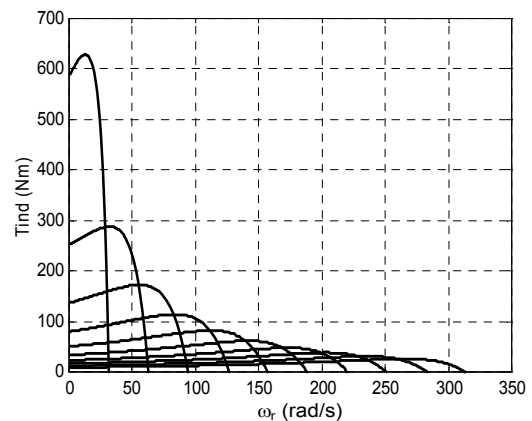

Fig. 2 The torque-speed curve of the 4 kW squirrel cage induction motor has been obtained by changing input frequency and by holding constant voltage [2].

The flux (Φ) of the motor must be constant to hold constant the torque produced. As clearly seen in Eq. 2, Φ is proportional to V/f. Therefore, to hold torque constant when the frequency is changed, the voltage must also be changed at the same rate.

$$(2) \qquad V = 4{,}44\Phi N_S f_S$$

To overcome this disadvantage, induction motors are controlled by holding V/f ratio constant. Thus, induction motors can efficiently be operated lower than their nominal load condition in variable torque applications. The presented remote laboratory system allows the speed control, the torque analysis and the energy efficiency of 3-phase induction motor. The teachers or the students can use the system developed without any time and place limitation. Due to friendly interface prepared, it is very simple for students to analyse the torque-speed of induction motor.

Another feature of the developed system is the use of crystal report service. Thus, users can report results of the experiment as a document such as PDF, Word or Excel file format without losing time.

Hardware structure of the proposed system

In this study utilization of USB communication protocol has been preferred because of large number of data obtained from the system so communication speed and reliability of the designed system has been increased. The frequency inverter employed as a motor control unit has been managed by a microcontroller via USB communication. USB communication and control circuit are illustrated in Fig. 3.

Commands sent by host computer have been performed by interpreting by means of control circuit seen in Fig. 3. UA2803, which is a package transistor, has been used to change contacts of the role connected to terminal junctions of the frequency inverter. Therefore speed and direction of rotation of the induction motor managed with frequency inverter can be altered. Signals acquired from the optical sensor have been upgraded by using 74HC14 which is Schmitt trigger to appropriate level for the microcontroller and the revolutions per minute of the induction motor has been counted.
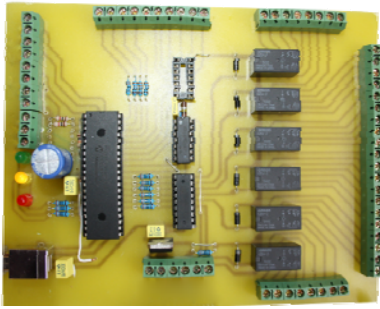
Fig. 3. USB communication and control circuit

Furthermore measurement cards have been designed to determine current and voltage values. Transformers whose conversion ratios are 220/9 V and rectifier circuit have been used to measure the voltage applied to stator windings in the voltage detection card. To evaluate the current value of the induction motor, in the current detection card HAS 50-S current transducer is used. Current and voltage detection cards are shown in Figs. 4a and 4b respectively.

a) The voltage detection card   b) the current detection card
Fig. 4. The measurement cards
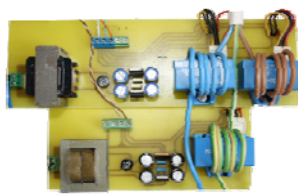
The revolutions per minute of the motor have been determined by using CNY70 which is optical sensor. For this aim, the shaft of the motor has been covered with black-white ribbon. The frequency of the voltage applied to motor has been obtained from the frequency inverter and transmitted to the microcontroller. Analogue data collected from the current-voltage measurement circuit and the optical sensor have been converted to digital data by the microcontroller and then these data have been sent to the host computer.

Micromaster 440 type frequency inverter which is manufactured by Siemens and can be operated induction motors up to 4.4 kW power has been utilized to control the induction motor. The direction of the induction motor has been implemented via its terminal ports. Also the frequency of voltage applied to the induction motor has been obtained from analogue output of the inverter. Then the frequency data has been registered by using the analogue channel of the microcontroller as an array. The induction motor used in the system is a 3-phase and 4 poles. The label values of the induction motor set to the frequency inverter are shown in Table 1.

Table 1. The label values of the induction motor

power	2.2 kW
number of phase	3
revolutions per minute	1420 d/d
voltage	380 V
current	5.2 A
cosφ	0.81
frequency	50 Hz

Software structure of the proposed system

In this study, the software used by host computer has been prepared by using C# language to be supported by .NET platform. On the other hand, the microcontroller software can be compiled with C programming language.

This different software has been integrated in a single structure. The block diagram of the implemented system is indicated in Fig. 5.
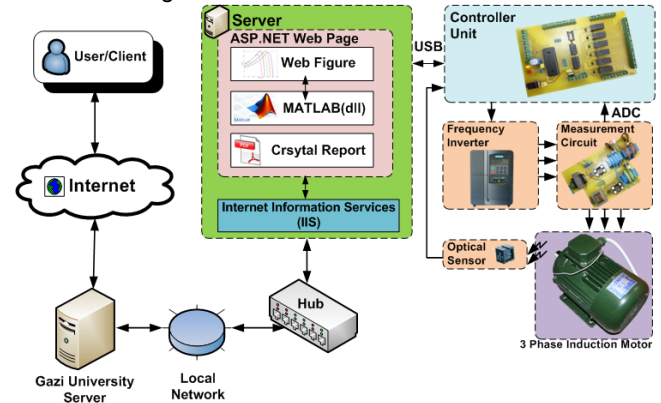

Fig. 5. The block diagram of the implemented system

Internet information services (IIS)

The additional software is required in order that the designed internet pages and computer applications can be remotely attained by users. This software provides the access to external communication paths of these applications [26]. For this aim, Internet Information Services (IIS) developed by Microsoft is used in this study. The designed internet pages are installed a directories of internet page prepared using IIS, and so it can be accessed by external networks.

MATLAB Builder for NE

Matlab, which is developed by Mathworks and a high-performance software package for technical computing in all engineering fields, easily integrates visualization, data analysis, numerical calculations and programming. Therefore Matlab are widely used in all engineering fields worldwide. What is increasing requirement establishes a connection between applications implemented with Matlab models nowadays. To satisfy this requirement, additional toolboxes are supplemented by Mathworks. One of the toolboxes is Matlab Builder for NE. Matlab models prepared by using this toolbox can be integrated other applications supported by .NET software platform [27].

In the study, firstly the Matlab model is developed in order to carry out torque analysis of the induction motor. The background application communicated between the Matlab model with the experimental set is designed. This application saves the information acquired from the microcontroller in a database and then this information is transferred from the database to the torque model developed in Matlab. Torque versus speed graphs that are obtained from the torque model are again transferred to the background application by means of NET software platform.

ASP.NET internet page

Remote access applications are rapidly increased due to spread usage of internet in daily life. For this aim, different interfaces, which are user friendly, are designed to control and observe in various fields such as industry and education. The designs of this interface can be in various shapes like computer application, internet page or mobile phone application. ASP.NET is one of the languages commonly used to create interactive and scalable web pages [28]. In this study, internet pages are developed by using ASP.NET software architecture. Designed internet pages are opened access over IIS. WebFigures service contained by Matlab Builder for NE is used in order to enhance visual appeal of the internet pages. Therefore users can observe experimental results as a Matlab graphs on this interface.

Microcontroller software

In this study, the microcontroller software is constituted and compiled by using C programming language. USB access library are added to the software because USB communication protocol is used in the application. Sub-functions are created to read in real time the data obtained from analogue channels of the microcontroller, and control the system. To count the revolutions per minute of the induction motor speed, RB0 pin of the microcontroller, which is one of the external interrupts, is used. Due to black-white ribbon covering the shaft of the motor, the optical sensor generates a pulse once per revolution and sends RB0 pin. The pulses obtained from optical sensor are counted by using an internal counter and so the revolutions per minute of the motor are detected. The data read from the analogue channels of the microcontroller like the current, the voltage and the speed of induction motor are registered to the memory of the microcontroller as arrays. If these data are desired by the host computer, the data communication is realized by using the sub-functions.

Crystal reports service

Results of the studies and the experiments implemented in computer based usually stay in digital environment. If users want to print the outputs of the information in digital environment, it is required that they should convert to appropriate format and arrange again these results. To overcome this problem, crystal report service is added to the system [29]. With usage of this service, the data are directly transmitted to a document as well as creation date of the document and the figures composed from the experimental study are added to the document. Therefore users can easily obtain and collect the document as PDF, Word or Excel and can directly print from printer without losing time.

Mathematical model of the system

Speed of induction motor depends on both the frequency of voltage applied to stator and number of poles of motor. On the other hand, torque produced by induction motor can be found by using Eq. 3 in case of knowing of rotor input power (P_{AG}) and angular speed (ω_s).

(3) $$T_{ind} = \frac{P_{AG}}{\omega_s}$$

Rotor input power can be calculated as seen in Eq. 4.

(4) $$P_{AG} = 3\left(I_r'\right)^2 \frac{R_r'}{s}$$

Where, I'_r represents rotor current transferred to stator, s represents slip, and R'_r represents rotor resistance altered with slip. If I'_r is computed, torque produced by induction motor can easily be found. For this aim, a single phase simplified equivalent circuit of induction motor is depicted in Fig. 6.
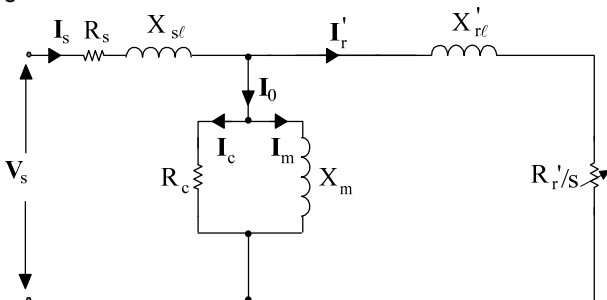
Fig. 6. Single phase equivalent circuit of induction motor whose rotor circuit is transferred to stator circuit [2]

R_c resistor, which represents core loss of induction motor in single phase equivalent circuit, is very bigger than

X_m, which represents leakage reactance of excitation circuit. So, R_c resistor may be neglected with small error, and X_m only stays in excitation circuit as seen in Fig. 7.
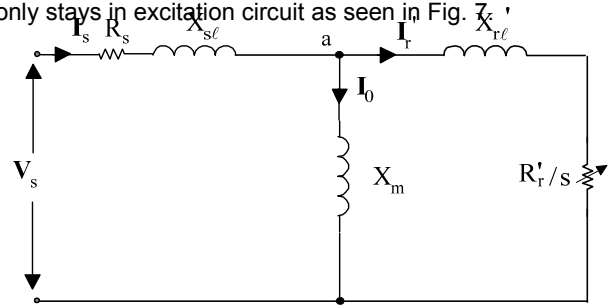
Fig. 7. Single phase equivalent circuit of induction motor neglected R_c resistor [2].

Then Thevenin's equivalent circuit of this circuit can be found with respect to a-b points, and Thevenin's equivalent voltage (V_{th}), and Thevenin's equivalent resistance (R_{th}) are calculated as seen in Eqs. 5 and 6 respectively.

(5) $$V_{th} = \frac{V_s X_m}{\sqrt{R_s^2 + \left(X_{sl} + X_m\right)^2}}$$

(6) $$R_{th} = R_s \left(\frac{X_m}{X_m + X_{sl}}\right)^2$$

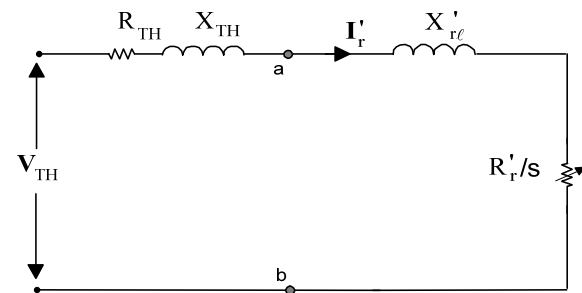The single phase equivalent circuit composed by using Thevenin's theorem is shown in Fig. 8.

Fig. 8. Single phase equivalent circuit acquired by using Thevenin's theorem [2]

Finally I'_r and torque produced by induction motor can be calculated by using real time data of induction motor from Eqs. 7 and 8 respectively.

(7) $$I_r' = \frac{V_{th}}{\sqrt{\left(R_{th} + \frac{R_r'}{s}\right)^2 + \left(X_{th} + X_{rl}'\right)^2}}$$

(8) $$T_{ind} = \frac{3}{\omega_s} \frac{V_{th}}{\left(R_{th} + \frac{R_r'}{s}\right)^2 + \left(X_{th} + X_{rl}'\right)^2} \frac{R_r'}{s}$$

Experimental Study

In this study, users can separately carry out what they want to apply the experiments which are the torque analysis and the speed control of an induction motor over the internet in real time. For this aim, the designed experiment set is given in Fig. 9.
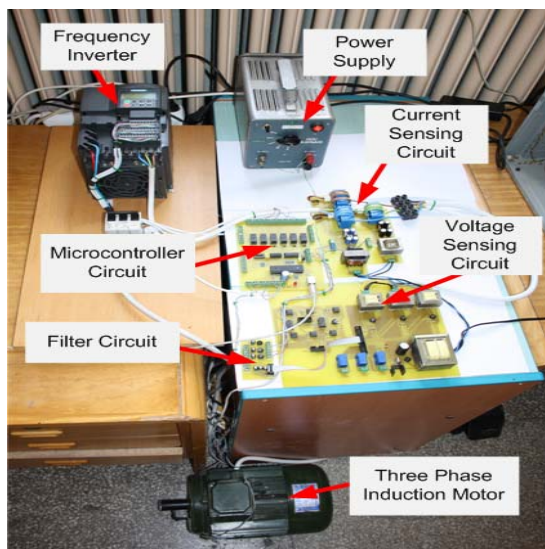
Fig. 9. The test rig

Real Time Torque Analysis

Real time torque analysis of the induction motor is implemented for five different frequency values of the voltage applied to the motor in first part of this study so that users can examine and observe how to affect the produced torque. The frequency value is automatically altered and the torque curves of the induction motor are drawn for each frequency values. To operate the prepared torque model of the induction motor by opening the web page designed as seen in Fig. 10 "Torque Analysis" option is selected.
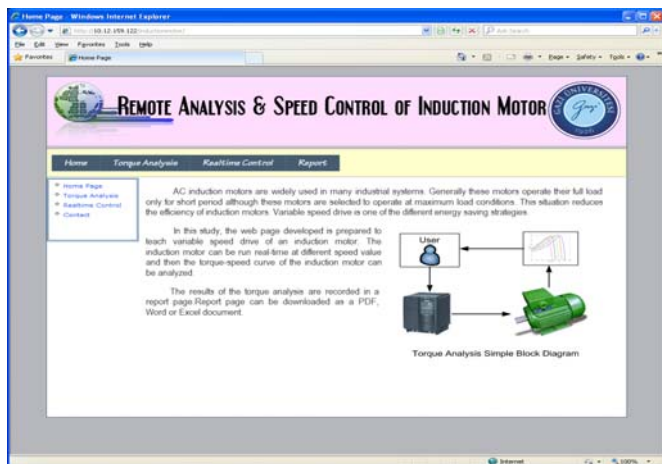

Fig. 10. The designed web page

In this option, real time torque analysis can be employed by clicking "Start Analysis" button. With initiation of the torque analysis, the background application prepared previously starts up and sends command to the microcontroller to run the induction motor. The microcontroller evaluating the command transmitted by computer turns on inverter terminal ports, which are required to start the induction motor via a relay. While the motor is running in 50 Hz which is starting frequency value adjusted by frequency inverter, the microcontroller copy the voltage, the current, the frequency and the speed values of the induction motor by means of its analogue channels. After the motor run about 3 second, the microcontroller send a new command to the frequency inverter so as to break the motor operation and reduce the frequency of voltage applied to the induction motor from 50 Hz to 45Hz.

Thereby the relay used to change the frequency of the inverter terminal ports to stop the motor at 50 Hz operation. The data obtained from 50 Hz operation are transmitted from the microcontroller to the host computer. These data which are digital value of current, voltage, frequency and speed of the induction motor are saved in a database in the host computer. Frequency value of the inverter is set to 45 Hz for the purpose of preparation for the next experiment before the motor is stopped in 50 Hz operation. Then, the microcontroller again starts the induction motor for 45 Hz. While the motor is running at 45 Hz, the microcontroller saves the voltage, the current, the frequency and the speed values of the induction motor during the interval of speed-up and constant speed by means of its analogue channels. After the motor run about 3 second, the microcontroller sends new command to the frequency inverter so as to break the motor operation and reduce the frequency of voltage applied to the induction motor from 45 Hz to 40 Hz. The data obtained from 45 Hz operation are transferred from the microcontroller to the host computer and saved in a database. Experimental steps described above for 50 Hz and 45 Hz are repeated for 40 Hz, 35 Hz and 30 Hz respectively. The flowchart of torque analysis software is illustrated in Fig. 11.
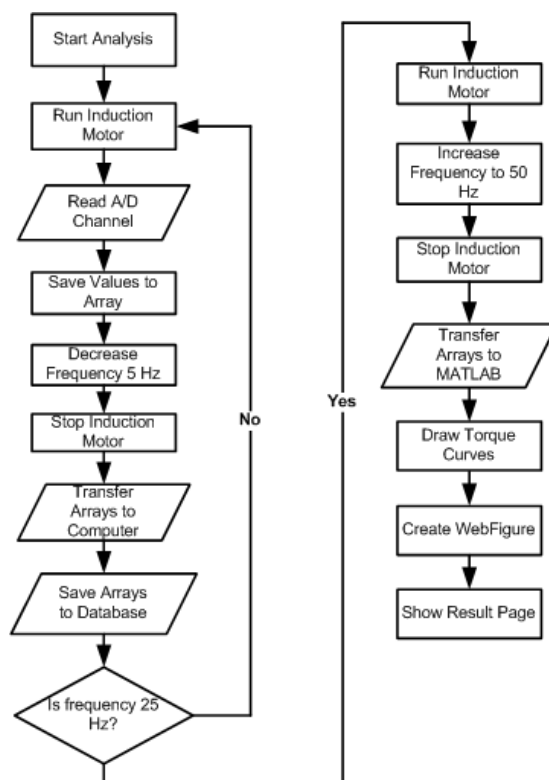

Fig. 11. The flowchart of torque analysis software

As a result of 5 experiments, the current, voltage, frequency and revolution per minute of the induction motor are gathered on a host computer for each experiment. These data are transferred from the database to the torque model prepared by using MATLAB Builder for NE toolbox. In the torque model of induction motor, the data pertain to each frequency value separately process and torque-speed curves are drawn for whole frequency values. These curves can be shown on the web page designed by using WebFigures component.

Furthermore power consumption of the induction motor for each frequency value is shown to users thanks to power model developed by using MATLAB Builder for NE toolbox. Users can compare the change of power consumption of

the motor with the torque produced. Thereby a virtual environment is prepared to change the power consumption of the induction motor by holding constant ratio of V/f of the induction motor over the internet.

Users can zoom in/out and rotate the figures which are torque and power consumption curves of the induction motor as 3D. Thus the graphical interface prepared is more interactive. Besides these, users can print the results acquired from the graphical interface or save them on their own computer as a PDF, Word or Excel file format due to crystal report service added. The result page of real time torque analysis and power consumption of the induction motor is given in Fig. 12.
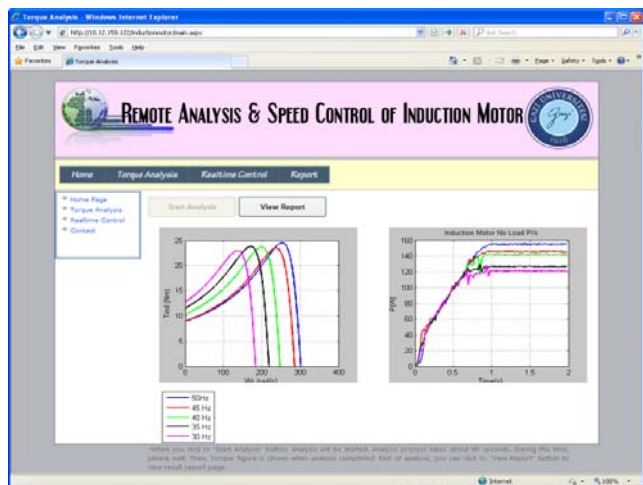

Fig. 12. The result page of torque analysis and power consumption of the induction motor by holding constant ratio of *V/f*

Real Time Speed Control and Rotating

In the other experiment, users can freely operate the induction motor in real time and control speed in revolutions per minute and rotate the direction of the motor. For this aim, another web interface is prepared as shown in Fig. 13. The web page designed to control the induction motor is opened by selecting "Realtime Control" button. The speed in revolutions per minute, the frequency, the voltage and current value can be observed on the web interface designed.
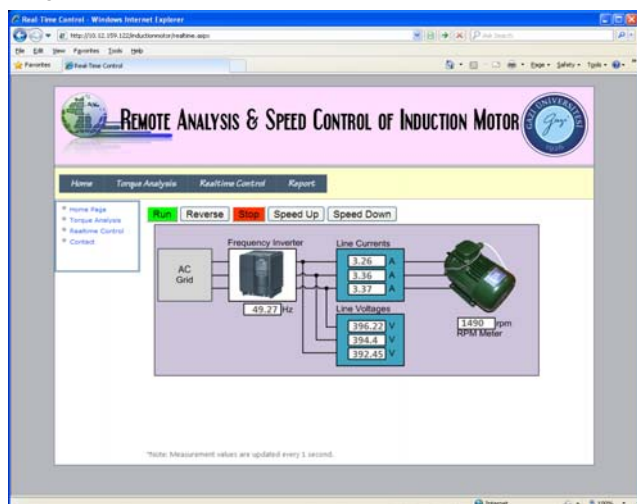

Fig. 13. The web interface for real time control

There are buttons for real-time control of the induction motor on the web page designed. When the "Run" button is selected by user, the host computer sends command the microcontroller in order to start the induction motor. The microcontroller drives the relay, which is connected to the frequency converter terminal point, via the transistor connected its output. Thus, the induction motor is run under the reference frequency and voltage value. If "Speed Up" button is selected on the web page, the speed of induction motor can be accelerated by increasing the frequency value of the voltage applied the induction motor. The upper limit of this frequency value of the voltage is 50 Hz. Another button on the web page is "Speed Down". If "Speed Down" button is selected, the speed of induction motor can be decelerated by decreasing the frequency value of the voltage applied the induction motor. In this way user can control the speed of the induction motor as requested. Furthermore, the user can alter direction of rotation of the induction motor by clicking "Reverse" button under the reference values while the induction motor is stop or run. Finally the user can put an end to motor control process via "Stop" button. The reference frequency and voltage value applied to the motor by frequency inverter is enrolled in memory of the frequency inverter when the motor is stopped. If the motor is run again, this reference values are used. To start, stop and change direction of rotation of the induction motor, Ramp time is regulated as 3 second. While user carries out whole this the motor control processes over the control panel designed, the data, which are the voltage applied to the motor, the frequency of this voltage, the winding current of the motor and the speed of the motor, are shown real-time by transferring from the experimental set to host computer through the display panel prepared. So, the user can follow which parameter is affected from the changes performed by the user.

Conclusions

In this study, a remote laboratory platform is designed and implemented for electrical engineering students. The experimental system allows the students for torque analysis, speed control and energy efficiency of a 3-phase induction motor by keeping V/f ratio constant over the internet in real-time. Particularly, the power consumption curves of the induction motor drawn in order to emphasize energy efficiency are very important on account of increasing students' awareness. The system is created by using up to date software and hardware units. All interfaces designed by using Asp.NET platform are user friendly. Thus user can easily analyse and operate the system by changing parameters desired. The Matlab model is developed in order to carry out torque analyse of the induction motor because Matlab software provides powerful graphical representation and solutions to differential equations. Matlab Builder for NE is used in order to connect between applications implemented with the Matlab model developed. Torque-speed curves and power consumption of the induction motor can be monitored for various frequency and input voltage values applied to the motor. Also users can zoom in/out and rotate the figures as 3D thanks to Matlab Web Figure with interactive features. Furthermore crystal report service has firstly been used in like such remote laboratory platform in the literature. With usage of this service, the data are directly transmitted to a document as well as creation date of the document and the figures composed from the experimental study are added to the document. Therefore users can directly print from printer or easily save their own computer to obtain and collect the document as PDF, Word or Excel file format without losing time. The accuracy of results obtained from remote laboratory platform presented has been verified by comparing the results obtained by hands-on measurements from the system.

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