A Real-time Analysis of Electric Machines through Electromagnetic Field Computation and Laboratory Implementation

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Abstract — This paper presents a system for visually analyzing the electromagnetic fields of electrical machines used in the energy conversion laboratory. The system utilizes the finite element method as well as various modules to achieve a real-time effect in the analysis of electrical machines while hand-on experimentation is in progress. The proposed system is aimed at developing a tool that would help improve the student's understanding of electromagnetic fields inside these machines and its use in calculating performance measures as well as operational concepts pertaining to the practical study of electrical machines.

Introduction:

Energy conversion courses in electrical engineering curricula feature in-depth theoretical aspects of energy conversion systems in addition to greater emphasis on practical laboratory experience. The laboratory compliments the theoretical concepts presented in the classroom and should be conducted in such a way as to facilitate the practical application of this theory. This involves enabling the student to use electromagnetic field solutions obtained numerically to calculate performance measures and operating characteristics. Laboratory experiments are utilized to help the students understand the electromagnetic concepts involved by combining a visual and interactive analysis system, which enable them to conceptualize the theory in real time. In the proposed system such analysis can be accomplished concurrently while hands-on experimentation is in progress and in real-time. This has recently been made possible due to the increase in computing and graphics capabilities of desktop computers.

The entire system developed for this purpose is comprised of three interconnected modules as shown in Figures 1 and 2. These modules are; the data acquisition, data control and data analysis module. A student can choose to perform an analysis involving any of the machines contained in the laboratory workstation. The signal conditioner shown provides an interface between these machines and all peripheral equipment involved including the computer, data acquisition card and the digital tachometer. The analog to digital (A/D) converter acquires analog signals from the machine chosen and converts these signals into digital code to be processed by the PC. Through the PC the student can also observe the field analysis results being done concurrently for the chosen machine at various load levels.

All the geometrical and material data of the various machines are contained in a database. Field analyses are created using the finite element method. The machines are linked to the data acquisition system via the PC. This link is an integral part of the system since it allows for a feedback loop between the machine and the PC. Not only does this feedback loop enable the students to vary the operating condition of the machine being tested, but also it enables them to adjust various working machine parameters and obtain corresponding field analysis results in real time.

An overall schematic block diagram of the system--Analysis Module Program (AMP)--is depicted in figure 2. This gives an outline of the various components involved and how they are interconnected. The overall scheme provides a means by which the student can perform various types of analysis on the machines directly while they are operating on an experiment.

ANALYSIS MODULE

This module provides the student with a comprehensive tool capable of analyzing the behavior of the electromagnetic fields in electric machines. A database of finite element solutions for each machine is created. These solutions are used to calculate a variety of performance measures, terminal parameters as well as operating characteristics of each machine under experiment. The module permits the user to select a particular machine to be analyzed. The finite element method is then used to obtain numerical solutions for each machine at discrete load levels. Manufacturer's specifications of each machine are used to obtain the particular machine geometry which is then modeled and exported to a finite element program for analysis.
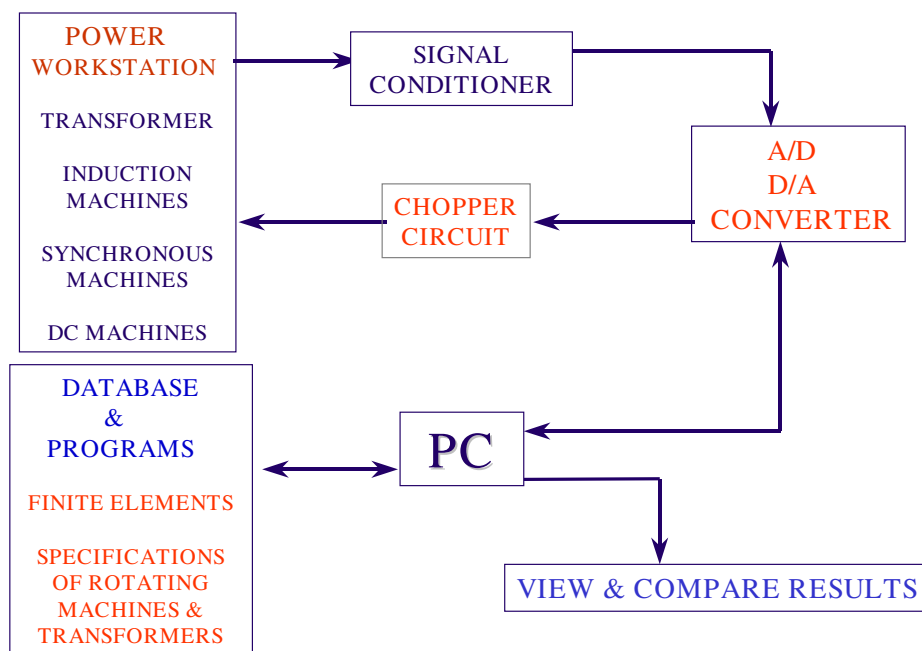
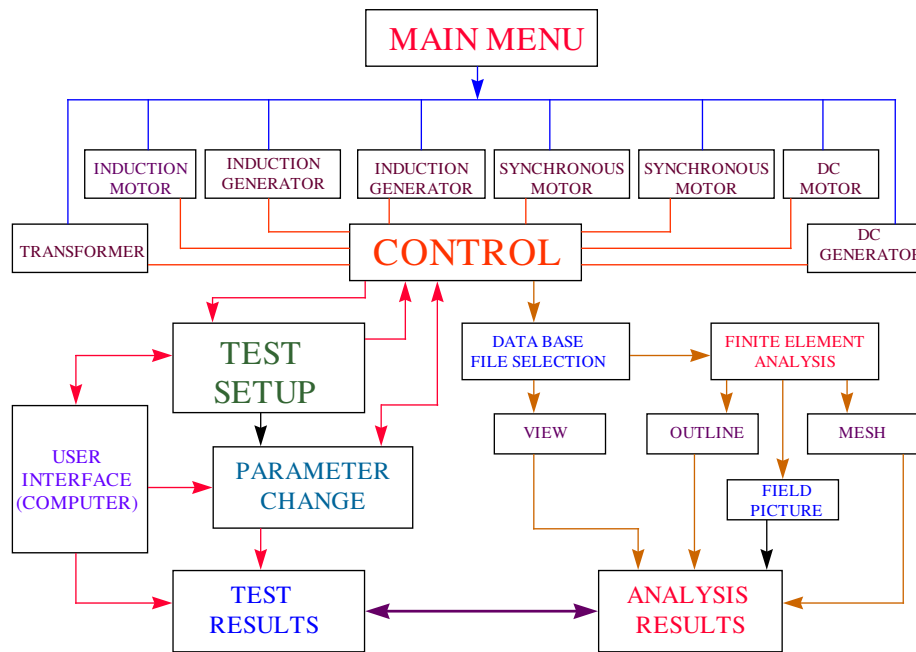Figure 1. Experimental /Analysis Scheme with Data Acquisition

Figure 2. Overview of Analysis Module

The analysis is performed at loads ranging from no-load to rated machine load as well as overload conditions. Solutions at each load are stored in a database where they can be easily retrieved by the data analysis module. The finite element (FE) solution obtained is based on the magnetic vector potential (MVP) formulation. As an example, a sample quadrant of the squirrel-cage induction motor (SCIM) that was modeled and is depicted in Figure 3. Elemental meshes were created for each machine modeled taking into account manufacturer's material geometrical data and other material and operating specifications. A mesh is then obtained as shown in Figure 4. The analysis was performed at various loads. A typical field picture of the squirrel-cage induction motor modeled under the no-load condition can be depicted in Figure 5. As will be explained later, the student is able to view the resulting field picture under the specific condition being experimented in real-time through an interpolation program, which takes its input from the experimental setup.

DATA ACQUISITION

The data acquisition system has a 25 MHz throughput as well as sixteen channels in unipolar mode or eight channels in bipolar mode. The high throughput and sampling rate allows the user to get a better idea of how quickly the machine data varies, under different loading conditions. As shown in Figure 1, all the signals generated from the machines in the laboratory are linked to the computer via the signal conditioner. A surge suppressor was also designed for use in this system. Included in this surge suppressor is a noise filter, which filters out any noise, generated by the AC/DC machines while operating under different loading conditions. Any surges, transients and noise generated by the AC/DC machines will first pass through this device where the signals are to be filtered for noise or any frequency beyond 200Hz before being coupled to the signal conditioner. When integrated with the other modules, this device adds an extra sense of

protection for any sensitive devices or other peripherals connected to the overall system. The user can simultaneously sample data from the machines and relay a command or message to the same machine or some other directly related machine. While an experiment is being performed, load data from a chosen machine is constantly being 'read-in' using the data acquisition system. A comparison between new load data and previously stored load data for the particular machine is made. If the current load value is equal to a stored load value this program will interpolate between stored data to produce the corresponding field picture or a desired performance parameter.

CONTROL MODULE

This module provides the student with a way of controlling the machine experiments directly from the PC. Since a DC motor was used as the prime mover for all the rotating machines analyzed, the control module provides speed control as well as speed monitoring of this motor. Speed monitoring is achieved through the use of a digital tachometer. The output of the tachometer is actually a voltage that is directly proportional to the rpm of the machine. The data acquisition system works both ways in that data can be acquired from the machine as well as it can be sent to the machine. The system is capable of sensing the speed of rotation and adjusting the speed if necessary by making comparisons to a specified reference value, as obtained through the digital tachometer.
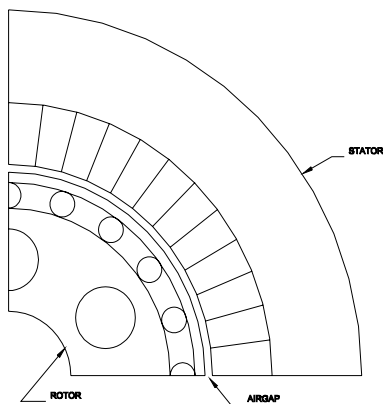

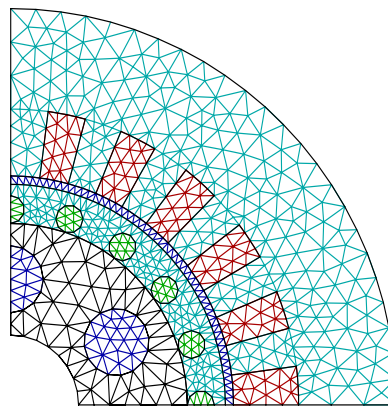
Figure 3. Outline for the SCIM
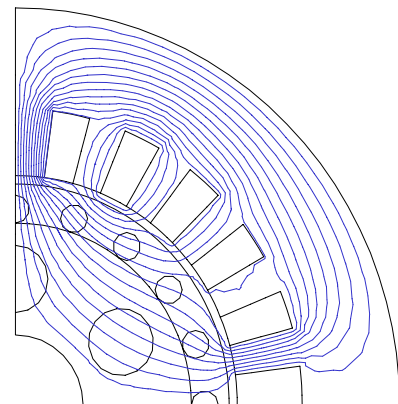
Figure 4. FE Grid created for the SCIM

Figure 5. No-Load Field picture of SCIM

Both the data acquisition system and control system work continually and are constantly accessing the main database of finite element solutions. Through these modules the user is able to acquire data and simultaneously control the peripheral devices associated with the experiments that are typically performed in the laboratory.

INTERPOLATION OF FIELD SOLUTIONS

Ranges of complete field solutions from no-load to overload conditions at discrete intervals were computed for each of the machines in the laboratory. These discrete load solutions are

stored in a database, which can be easily accessed by both the user and the data acquisition module. When an experiment is being performed, machine load data is continually being read in with the data acquisition system. A comparison between the existing stored discrete finite element solutions and the incoming machine operating point is made. If the current machine operating point approximates one of the stored solutions, to within a defined tolerance in the program, the corresponding field plot and performance parameters are displayed. If, however, the tolerance is not met, the nearest two points above and below the current operating point are located. An interpolating program is used. The interpolation program utilizes both linear and spline interpolation functions if we are interpolating amongst more than two complete discrete field solutions. Once the interpolation is performed, the corresponding field plot and performance parameters are once again displayed for the new load point. This process is repeated and the resulting new field solutions are continuously updated on the screen changing field picture and the calculated value of computed performance parameters. The newly calculated interpolated field solutions are appended to the database as another loading condition with a complete finite element solution. It is important to note that these field solutions can actually be used to calculate the performance parameters of the machines that are being used in the laboratory and the student receives an instant theoretical result for the concept being tested in the laboratory.

It will be much easier to have a system in which the operating point, having been acquired through a data acquisition system, is then input to a finite element program for analysis to obtain a field solution. Obtaining a new field solution takes a considerably long and if this method were implemented, the essence of the *'real-time'* analysis and instant feedback would be lost. However, when the solution is obtained via an interpolation method such as the one described, not only would the overall process be speeded up greatly but the *'real-time'* analysis would also be achieved. The accuracy of this quicker process shall be proportional to the accuracy of the interpolation polynomial chosen. If we were to experiment with non-linear analyses for example, then interpolation amongst five and six points may be necessary to achieve similar accuracy as those obtained in linear analyses.

EXAMPLE AND COMPARISON OF RESULTS

In order to show the effectiveness of the proposed system as an educational tool an experiment involving transformers was performed. The objective of this experiment is to study the electromagnetic field in a single-phase transformer under no-load and load conditions. The efficiency of the transformer was calculated using both the proposed interpolation method, as well as the conventional laboratory experimental results. A comparison between the results of each was done. The following are some solution steps carried out to arrive at the comparison yielded. Using the manufacturer's specifications, a model of the transformer was created. The mesh of this model is shown in figure 6. This mesh is quite adequate to obtain the required comparisons. The mesh data, along with corresponding loading acquired directly from the experiment as well material parameters are the input to the solution/analysis program. After analyzing the above model at different loads, field picture data along with each model's performance parameter was stored in a database. A typical field picture for comparison purposes is shown in figure 7, at no-load conditions. Figure 8 shows the transformer when it is 30% loaded. The student could also choose to look at the field direction by selecting the appropriate

view as shown in figure 9. The experiment was performed using the hands-on approach as well as with the analysis system and a comparison of the results are given in Table 1.

The entire system is implemented on a Visual Basic platform. The finite element program is written in C++. An 'Active–X' control is designed to yield a 'control' that is included in the visual basic toolbox and implemented onto a Visual Basic form. Through the introduction screen, the user will be able to select different machines and find other information such as theoretical data, design data, analysis results at other load conditions, manufacturer data and other pertinent information. This introduction screen will eventually lead into the actual "analysis" screen, the control program and complete instruction on how to achieve real time analysis.

HARDWARE IMPLEMENTATION

In this section, we explain the hardware implementation of the real-time electromagnetic field analysis system for the energy conversion laboratory.

The initial work was originally developed using the Visual Basic environment (VB5), but with a hardware manufactured by the American Data Acquisition Corp. (ADAC), based on a Data Acquisition board 5500MF. With the continuous development of computer tools, that package became obsolete and considerably limited in I/O channels and control capabilities, compared with the options offered by the newly acquired National Instruments package [6], based on a Data Acquisition Card PCI-6025E and the Component Works™ software. It was necessary to continue with the conversion of the existing program code to match the National Instruments package (FE software, ActiveX controls, and data acquisition hardware) keeping the same display format as Figure 10).

TABLE I
Tabulation of Results Comparison

Resistance [Ω]	Experimental Efficiency %	FE Efficiency %	% Error
333.3	90	90.35	0.389
400	88.24	89	0.861
500	85.71	87	1.505
666.7	82.61	83.8	1.441
1000	76.92	77.9	1.274
2000	62.5	64.2	2.72

The second direction was towards the manufacture and supplies of all the necessary hardware required to carry on satisfactorily the experiments and communicate with the computer in a safe manner, as well as being practical and easy to operate by the students.

The experiments are grouped in a manner that with no changes in physical connections, different characteristics of the machines can be observed and evaluated, under different operating and load conditions. This is the reason why the selection of the additional experiments to be included in the application was based on their similarity. Through the introduction screen (Figure

11), any of the experiments of the same group can be picked from a list, with no changes in the connections. When working locally, this feature allows the students to dedicate more time to the understanding of the experiment, more than the setup.
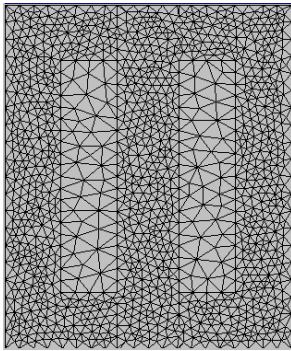
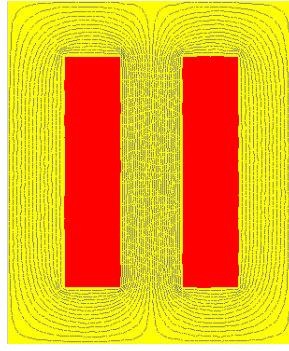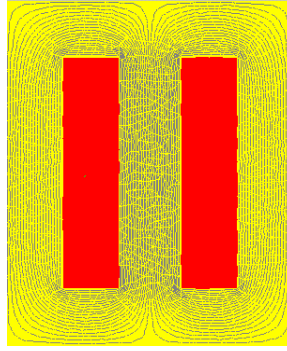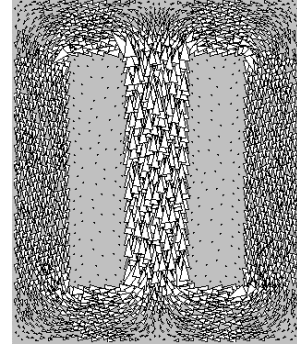| Figure 6 Triangular Mesh used for FE Analysis | Figure 7 Field Plot of Magnetic Vector Potential Plots at no-load | Fig. 8 Field Plot of Magnetic Vector Potential Plots at 30% load | Figure 9 Direction Magnetic Flux Density at 30% Load |

As it was mentioned earlier, to transfer the necessary signals of voltage and current to the computer, a signal conditioner is used. This equipment is designed to carry and convert power signals (the signals of the machines in operating condition) more than control signals. The workstation, as a whole, is designed and implemented to read but not to conduct data in low ranges. In order to transfer values of current in the order of mA, the channels available are in the ranges of 0~10 amps AC/DC for input and 0~5 VDC for output.

It becomes very difficult to obtain an acceptable read-out of the values from the machines, due to the conversion ratios. At these rates, let's say when the current of a particular machine (as an INPUT to the signal conditioner) is expected to rise from 100 mA to 450mA., the accuracy of the OUTPUT value becomes literally nonexistent. Most of the values required for current are definitely too low to be properly converted by the signal conditioner and analyzed by the VB5 application. This dictated the need to create an alternate method to transfer the readings properly, keeping the accuracy within a spectrum that spreads along the corresponding range with ease. That method is the use of an auxiliary resistor box (Figure 13, item 2) developed and adapted to match with the standard setup of the workstation, creating a voltage drop, which now will utilize the voltage channels (either AC or DC) to condition the signals sent to the computer. Once captured by the VB5 application, they are reconverted to mA. These adaptations create the necessity of an addendum to the manual of experiments so that the students could utilize these modifications in the laboratory sitting. Among the reasons we have:

- The connections must include the resistors, and in the case of a locally conducted experiment, for comparison purposes, the meters must be relocated.
- The new added values of the resistors must be considered and distributed properly when test loads are used, to keep the load balanced.

In addition to the signal conditioning, there is a safety issue directly related to the National Instruments hardware as well as the computer itself, which is extremely important within this

system. This is the sudden generation of transient voltages or spikes within the machinery in use, or their conveying through unprotected sources. To filter any surge coming from any of these sources we used commercial surge protectors for the 120 VAC powered devices (as the computer or the power input to the signal conditioner for its operation). However, assuming that a surge can be generated and reach the computer through the electric machines in use, to filter this potential risk, it was required to build a surge protection box specially designed to work as a bridge across the leads that go to the signal conditioner (Figure 13, item 1). The theory behind the surge protector is the same found in any commercial device, based on MOV and inductors. The difference is the type of connections used (compatible with the leads) and that were made able to handle eight channels, which covers all the options of signals required for the experiments. The surge protector was fabricated with eight channels plus ground, which are:
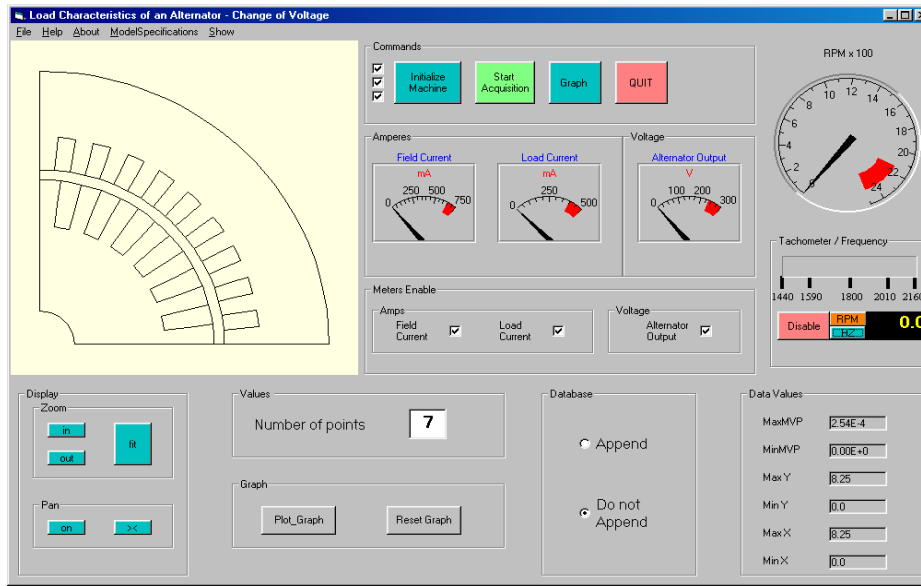

Figure10. Screen display for one of the experiments

A digital tachometer AIRPAX Tach•Pak 3™ (Figure 13, item 3) is also utilized to read the speed of the electric machines and transmit it to the computer as a voltage signal. As a result of these added devices, the general setup for the workstation now varies compared with the original (Figure 14).

TABLE II Channel Assignments

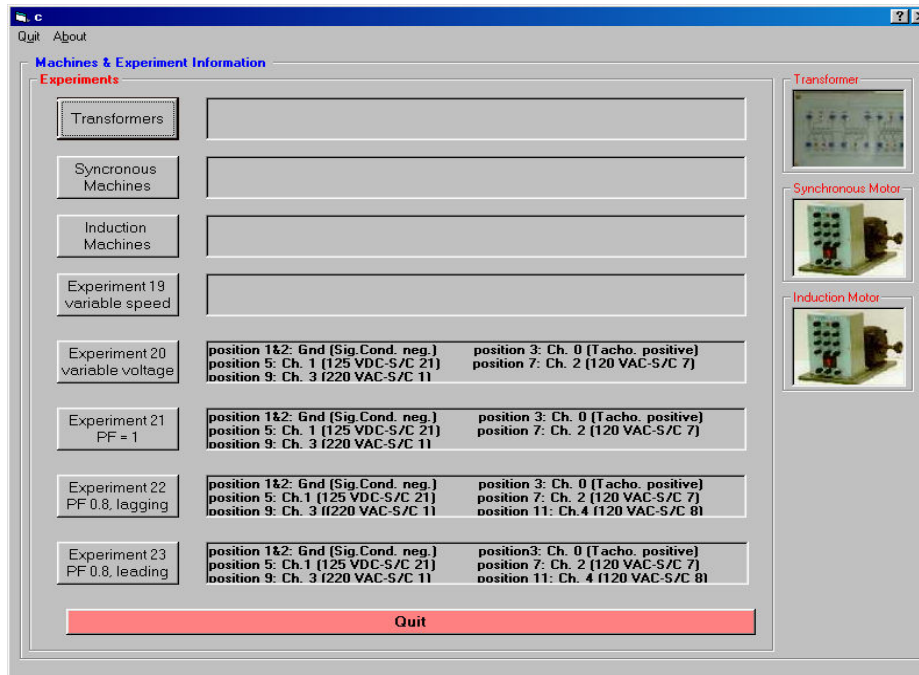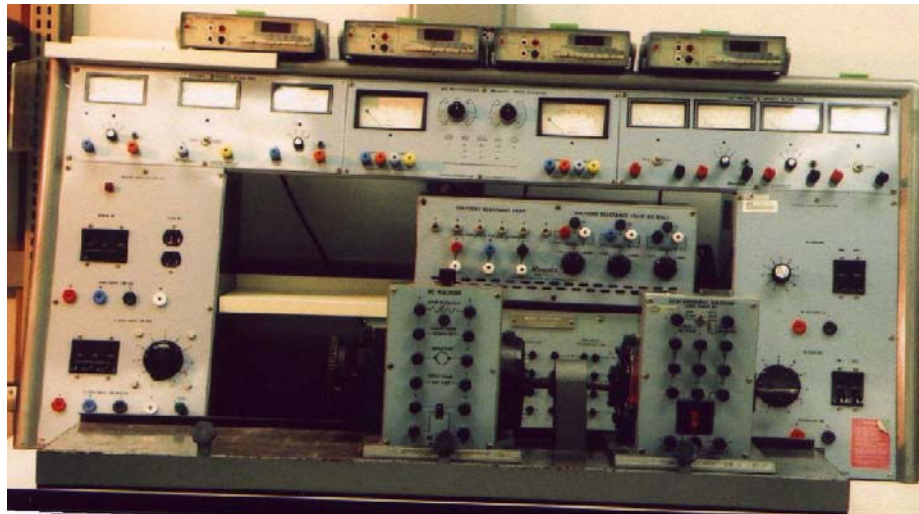| CHANNEL	QTY
220 VAC	02
125 VDC	01
120 VAC	03
10 AMP	02
GROUND	01

Figure11. Experiment selection screen

Figure12. Workstation in its original configuration

CONCLUSION

The system proposed here provides a complete analytical and practical approach to the understanding of electrical machines and energy conversion concepts. The student will be able to visualize what is happening *inside* the machines he uses in performing the experiments and their theory of operation as well as the associated electromagnetic field concepts. As a result he will have a better understanding of how the machine works under different operating conditions. This system is geared toward creating a means by which the student can improve his/her understanding of electromagnetic fields and their use in calculating performance characteristics

as well as operational concepts pertaining to electric machines. The data acquisition, data control process is a continuous one and as a result a real-time analysis of the rotating machine model can be obtained. The integration of the modules and systems described above provides the means for an efficient student oriented laboratory 'tool.' Not only will this 'tool' help boost the student's creativity and confidence but it will also lead to an increased participation and understanding of concepts and theories presented during the course. The presented tool will help meet the ever-changing need in educational tools and electrical engineering curricula and especially electromagnetic field education.
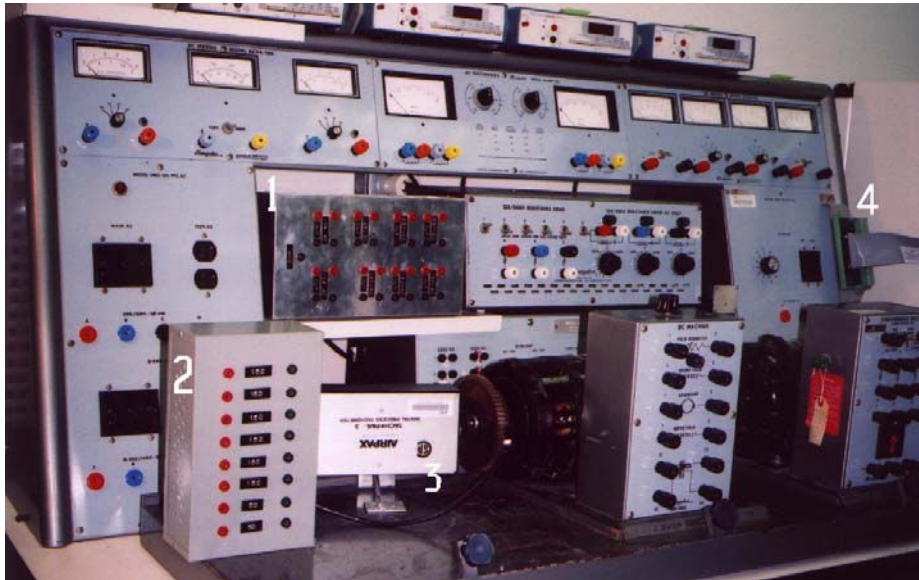

Figure13. Added devices. 1) Surge protector, 2) Resistor box, 3) Digital tachometer, 4) Connector.
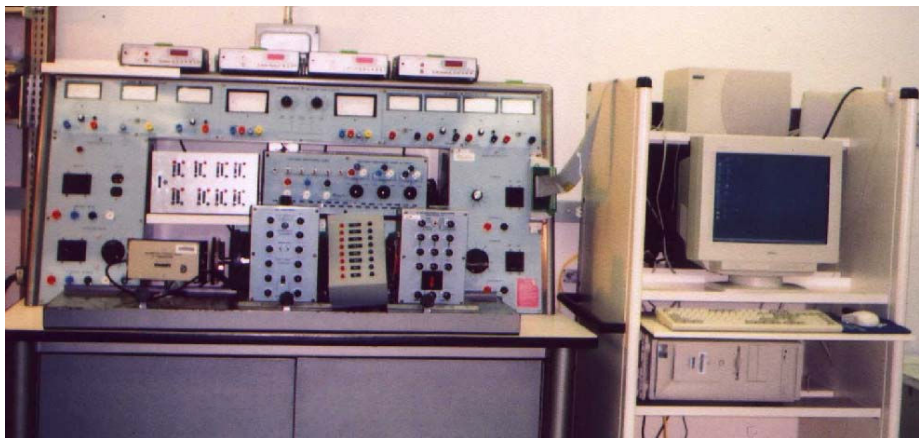

Figure14. Complete real-time experimental analysis system

We have been able to 'observe' the electromagnetic field generated inside the machines, in real-time and under different load conditions. Although the control of the machinery still has to be executed manually, the use of the National Instruments package can provide digital and analog outputs on demand, plus the signal conditioner and some coming electromechanical work,

will leads us to control the machines from the computer. The physical connections will not be modified on demand, unless a person takes care of it. This requires a more rigid standardization of the setup. Actually, the most efficient way to set the standards is by using the same physical configuration for a variety of experiments, where the machines and loads are already interconnected.

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Acknowledgement

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Dr. Osama A. Mohammed received his M.S. and Ph.D. degrees in Electrical Engineering from Virginia Polytechnic Institute and State University. He has many years of teaching, curriculum development, research and industrial consulting experience. He authored and co-authored more than 230 technical papers in the archival literature as well as in National and International Conference records in addition to additional numerous technical and project reports and monographs. He specializes in Electrical Power Systems, design optimization of electromagnetic devices, Artificial Intelligence Applications to Energy Systems as well as Electromagnetic Field Computations in Nonlinear Systems. He has current interest in Shipboard power systems and Integrated motor drive systems. Dr. Mohammed has been successful in obtaining a number of research contracts and grants from industries and Federal government agencies. He is also interested in Developing Asynchronous Learning Environments and educational techniques for Internet based delivery and virtual laboratories.

He received many awards for excellence in research, teaching and service to the profession. Professor Mohammed has chaired sessions and programs in numerous International Conferences and has delivered numerous invited lectures at scientific organizations in North America, Europe and Asia. He was the General Chairman of the 1993 COMPUMAG International Conference and was also the General Chairman of the 1996 International Conference on Intelligent Systems Applications to Power Systems (ISAP'96) as well as the General Chairman of the 1994 IEEE Southeast conference. He was the technical program chair for the IEEE CEFC conference in Milwakee, WI, June, 2000 and is the Publication Chair for the IEEE conference on Nanoscale Devices and System Integration, IEEE-NDSI 2004, Miami, FL February 15-19, 2004. Dr Mohammed is the General Chair for the upcoming IEEE CEFC conference to be held in Miami, May 2006. He also was the 1992 Technical Program Chairman for the SOUTHCON Conference and Convention. Dr. Mohammed also organized and taught many short courses on power systems, Electromagnetics and intelligent systems in the U.S.A and abroad.

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Dr. Yen has served the profession in various capacities. He is a past Chairman of the IEEE Miami Section and currently is professional activities committee chairman.