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THE VIRTUAL MACHINES LABORATORY

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This document describes the Virtual Machines Laboratory – a project based at the Electrical Machines Laboratory in the Engineering School at the University of Auckland. The project follows on from one originally inspired and co-ordinated by Professor John Boys at the university in 1991. That original project involved the use of computers to aid and assist students completing laboratory experiments in the electrical machines field. The Virtual Machines Laboratory extends the concept by enabling students to participate in simulations of these experiments over the Internet.

KEYWORDS: electrical machines, engineering education, student-centred learning, flexible delivery, virtual laboratory.

INTRODUCTION

In the early 1990s the author was employed by the University of Auckland under the guidance of Professor John Boys to build hardware and software which would assist students in conducting laboratory experiments in the Electrical Machines Laboratory.

There were two main motivating factors. Firstly this group of experiments was seen as boring and irrelevant by large numbers of students, who subsequently did not pay much attention to them. Secondly these experiments had until that time involved much tedious and repetitive measurement taking and graph plotting, resulting in students being so overwhelmed by the detail that they missed the intent. It was felt that the use of computers to perform the recording and plotting of results would stimulate student motivation and enable students to concentrate on the concepts demonstrated by the experiments.

During the twelve months of employment, hardware was constructed and software written to cater for four experiments. Each experiment is based around one machine set: a transformer, a synchronous machine, an induction machine and a second synchronous machine used to illustrate symmetrical components.

Software for the PCs was written with Borland's Turbo Pascal for DOS using the standard procedural programming techniques of the time. The VGA screens becoming available then were taken advantage of by running the applications in a high resolution graphics mode.

Each experiment utilises a standalone microcontroller-based interface board to convert the analogue quantities of the machine involved into digital values. The microcontroller used is the Philips 80C552 which provides eight analogue to digital converter channels, as well as sufficient RAM to enable results to be recorded in real-time and downloaded to the PC at a later stage. The micro connects to the PC via a serial link.

Following the introduction of this equipment in the laboratory, several generations of students have benefited significantly. Firstly student attitude improved greatly. Secondly student understanding grew – aided by the fact that students now had time to discuss experimental results with the laboratory supervisor while the experiment was taking place. Thirdly the average mark and pass rates in these courses increased [1].

In more recent times, two significant upgrades have occurred. Firstly the software packages used by students in the laboratory were rewritten as Windows applications. Secondly a virtual interface to the experiments was created. This paper firstly makes a brief comparison of traditional and virtual laboratories, then goes on to describe the virtual interface which was created, and finishes with an account of the physical laboratories.

TRADITIONAL LABORATORIES vs VIRTUAL LABORATORIES

This section is not intended to provide a comprehensive coverage of the benefits and drawbacks of both traditional laboratories and virtual laboratories. Such a discussion would fill many pages and is outside the scope of this document. However, for completeness a selection of material is presented. It should be noted that virtual and remote laboratories are not the same thing. A virtual laboratory is a simulation of the real thing, while a remote laboratory typically involves conducting a physical experiment by remote control (usually from a website). A well-known paper by Poindexter and Heck [2] contains a section on both virtual and remote laboratories.

Traditional Laboratories

In a traditional laboratory students gain an experience as close as possible to real life given the limitations of the laboratory environment. The hands-on aspect often results in much wider student interest than a classroom lecture. This is the most significant advantage of a traditional laboratory.

The two major drawbacks of the traditional laboratory are cost and resource restrictions.

The cost of purchasing, storing and maintaining equipment can be high. As a result the institute may compromise by either purchasing fewer items than are necessary, or by choosing a cheaper, but less than ideal model.

Student access to laboratory rooms is typically restricted to the allotted laboratory hours, and is usually only permitted when a staff member is present. These rules are normally necessary both to safeguard the students, and to protect the equipment from vandalism or theft. As a result precious laboratory space and expensive equipment is unavailable for student use most of the time.

In fact pure logistics are often the main drawback of the traditional laboratory [3].

Virtual Laboratories

Virtual laboratories are computer-simulated laboratories that look like, operate as, and produce results similar to real ones [4]. In comparison to the traditional laboratory, the virtual laboratory is characterised by its versatility and flexibility because it is software based. Virtual laboratories are not new. In [5], an early version (1993) of a virtual laboratory running in a Windows 3.1 environment is discussed.

Like traditional laboratories, virtual laboratories have a number of advantages and disadvantages. Overall, in many situations the advantages of a virtual laboratory can outweigh the disadvantages, thus making it a feasible option.

Among their advantages can be:

Cost. As the computer replaces some or all of the laboratory equipment, purchase, maintenance and storage costs are all likely to be reduced. This is offset however by the cost involved in developing the software required [6].

Safety. Safety concerns often limit the scope and scale of traditional experiments [6]. A virtual laboratory can either filter out what would be potentially destructive parameter settings in real life, or simulate the damage that would be caused.

Availability. If a laboratory is fully simulated and available via a web browser, then it can be performed at any time, from anywhere [3]. In this case a special laboratory room is not even required.

Presentation of Material. The multimedia capabilities of computers make it possible to present material in a variety of ways, potentially increasing student learning.

Result Recording. If a computer forms part of a laboratory with real equipment (rather than in the fully simulated laboratory situation), then it can be used to automatically record, process and present measurements. This reduces student procedural overhead and can provide more time for other more useful activities during the scheduled laboratory hours.

Administration. The computer can easily keep records of which students have completed laboratories, reducing the administrative burden on staff. In many cases the computer can provide online automatically marked assessments and record keeping as well.

Of course virtual laboratories have disadvantages too. Some of these disadvantages are:

Unrealistic. Where the computer completely simulates a piece of equipment, students can find the laboratory too far removed from reality to be useful. Real life apparatus always contains an element of unpredictability, which in some cases can provide valuable lessons in a laboratory situation. Many educators remain suspicious of virtual laboratories [7].

Poor Design. Virtual laboratories need to be carefully designed. If not designed properly, computer based laboratories can amplify previous problems and even create new ones [8].

Lack of Student Control. In most cases students must complete virtual laboratories in the order dictated by the computer, although of course the better designed packages allow students to repeat sections as required. The lack of face to face contact with the supervisor means there is little opportunity to discuss ideas or concepts which fall outside the range covered by the simulation.

In many cases it seems as if the ideal solution is, where possible, to combine a virtual laboratory with a traditional laboratory. As the project outlined in this paper demonstrates, with suitable resources the virtual laboratory can aid students in their preparation for carrying out the traditional laboratory. In the traditional laboratory software can further aid students by performing tasks such as result-keeping, and can reduce staff overhead by carrying out tasks such as instruction delivery and assessment.

THE VIRTUAL INTERFACE

One of the original benefits following the development of the experiments in 1991 was the time made available for discussing results with the supervisor, as the three hour experiment no longer involved over two hours of result recording and graph plotting.

However since the experiments were first used, student numbers at the university have increased tremendously. Unfortunately this has led to huge pressures being placed on the equipment. In order to accommodate the large numbers of students, lab group sizes have been increased, the time each group spends in the lab has been decreased, and now only selected portions of each experiment are performed. The original benefit of increased discussion time between tutor and students has been eroded over the years, and hence the desire to take this project further.

The virtual interface involves creating simulations of the machines experiments on a website. Students log in, configure parameters such as voltages and then “perform” the experiment. Simulations return results consistent with the machines in the laboratory. It is envisaged that in this way, all students will be able to perform all parts of all experiments in their own time. Students will still attend “hands-on” laboratory sessions to conduct selected parts of the experiments as physical resources permit.

Software Overview

Early on in the design it was decided that the simulation packages would be developed as a distributed application written in Java. Java was chosen for the following reasons [9]:

- It allows projects to be developed as applications (suitable for running stand-alone on the developer’s computer), and then later to be converted to applets (suitable for distribution via the Internet).
- Support for servlets make it well-suited for distributed computing and computing based on the client/server architecture.
- It is completely object-oriented.
- It is portable – Java applets and applications can be run on any platform that has a Java Virtual Machine.

The application would be available over a network (including the Internet), and accessible via a web browser. The individual experiments are contained in Java applets. Many virtual laboratories require users to install some software on their PCs. This is especially true of those which incorporate tools such as LabVIEW and MatLab [10], [11]. An advantage of incorporating all the functionality into applets is that no user installation is required – the entire session executes within the web browser environment.

When a student selects an experiment from the website, the appropriate applet is downloaded to their PC and executes locally. Although there is some delay while the applet is initially downloaded, once that download is complete the applet executes with no further delays. The advantage of this approach is that the student is encouraged to repeat parts of the experiment, varying different parameters as required, as there is little downtime between requests.

An alternative approach is where the student (the client) configures the parameters they require and submits them to the server, the server processes the request and returns the result which is then displayed on the client's screen (as a graph for example). Under this approach the student may be discouraged from experimenting by the time taken for each request to be processed and returned. This time would also increase with increased load on the server and internet.

The client-server interface is written using Java Servlet technology. Briefly, Java Servlets are an alternative to the traditional CGI (Common Gateway Interface) approach. In both techniques the client's browser sends requests to the server. The server processes the request by executing the specified application program which resides on the server. CGI scripts are typically written in Perl, while Java Servlets are written in Java. Java Servlets have several advantages over CGI:

- They execute as a thread rather than a process. This reduces the overhead on the server when multiple clients issue requests simultaneously.
- They are vendor (and server) neutral.
- They have access to all the Java APIs.

The software design can be broken down into three major groups. Those groups are:

- Server-side software

The following figure shows an outline of the design.

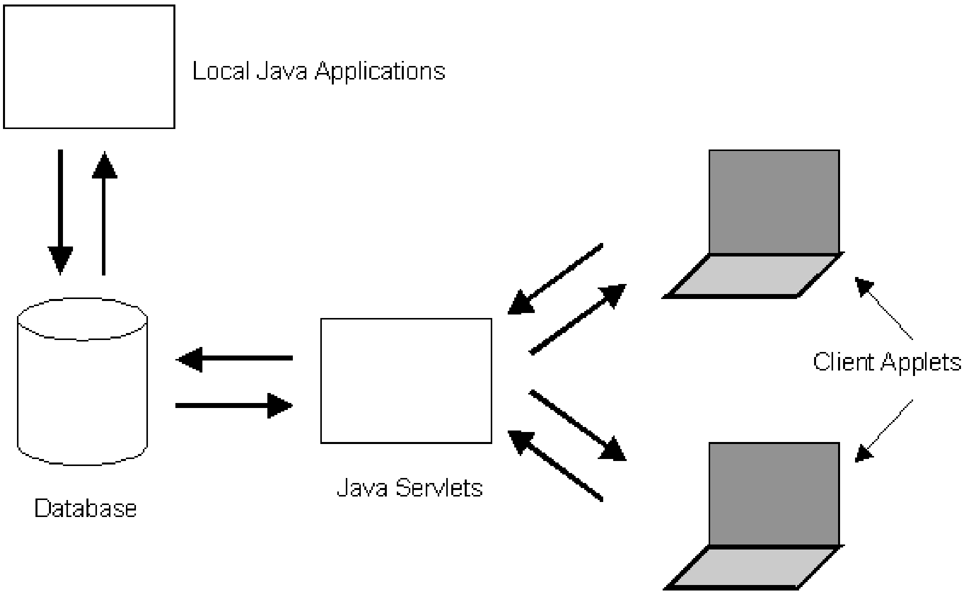

Figure 1 Outline of Software Design

Each group is now briefly described.

Server-side software. The server-side software consists of two components: the local database and several local administrative applications.

The database in this case was implemented using Microsoft Access 2000, although any SQL database could have been used. It maintains information about students who are authorised to use the system, and banks of test questions which are used to generate the assessments.

The administrative applications are Java applications created to enable teachers or administrators to easily maintain the information in the database without requiring any database skills. The applications allow authorised users to update student records, group students into class sets, and maintain the banks of test questions.

Client-Server interface. The client-server interface consists of two Java Servlets deployed on Apache Tomcat. Tomcat is a part of the Jakarta project run by the Apache Software Foundation. Although servlets can be served by newer versions of Microsoft's web server (Internet Information Services), Tomcat is the most popular servlet server. The servlets connect to the database using JDBC-ODBC (Java Database Connectivity – Open Database Connectivity).

The first servlet is used to allow clients to download applets from the server. Once a user selects the laboratory they wish to perform, an HTTP (Hyper-Text Transfer Protocol) POST request is created by the client browser and sent to this servlet.

The second servlet establishes communication with the applet once it has been downloaded and begins to execute on the client's browser. It serves three main functions:

- It is used to authenticate the user against the list of valid users in the database.
- It serves test questions to the user when they are ready to undertake the assessment.
- It receives the user's response to the questions, stores them in the database and marks those questions which can be marked automatically.

Client-side software. The graphical user interface (GUI) has been implemented using applets. One applet has been developed for each laboratory simulation. The simulations are described in more detail in the next sub-section. An additional applet handles the on-line assessment.

Simulation Implementations

The Java applets contain code which simulates the experimental results. The simulations were originally developed in MATLAB by Nigel Shepstone, a lecturer at Manukau Institute of Technology. They were converted into Java code as part of a final year undergraduate research project by Roopak Sinha [12]. As already noted, this has the advantage of not requiring any software to be installed on users' machines as applets execute within the web browser environment.

The Java applets have been designed to have a similar "look and feel" to the application software in use in the actual laboratories, thus familiarising the student with the environment. At points where students are required to perform some physical activity in the actual laboratory, the simulation describes what will be involved and gives additional background information to aid with understanding. So often in a laboratory, students perform steps mechanically, simply following instructions with little comprehension of what is actually happening. In these laboratories the student should gain sufficient prior learning from the simulation to ensure that this is not the case.

Much of the work in the actual laboratories involves varying different quantities to enable a graph of some kind to be plotted. The simulations provide a graphical output which the student constructs step by step. Between each step some kind of adjustment is made to a control (simulating the altering of the actual quantity in the experiment) before the next point on the graph is plotted. The data points on the graph are generated by combining the measured parameters of the actual machines in the laboratory with the appropriate mathematical model. It would of course be possible to introduce a small amount of random variation in the calculations at this point, resulting in a slightly different simulation experience for each student. This was not done in this case.

The following figure shows a sample output of the simulation.

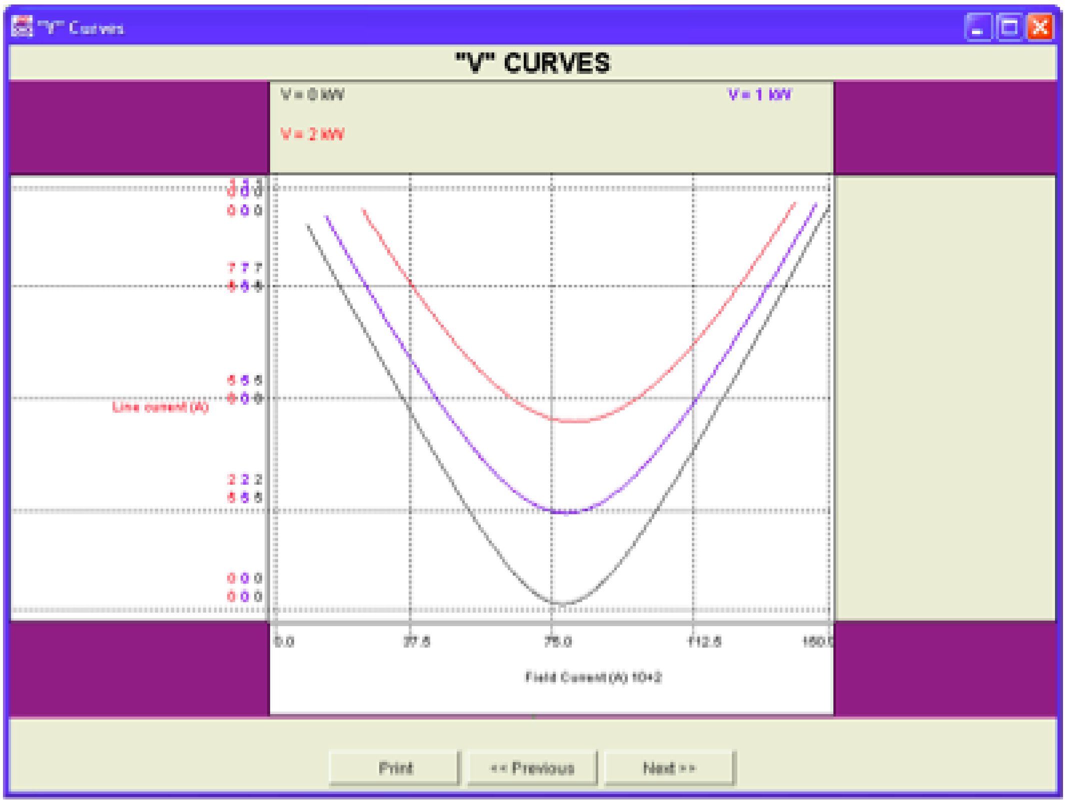

Figure 2 Sample "V" Curve Simulation (Synchronous Machines Experiment)

Student Assessment

In addition to simulating the operation of the software used in the actual laboratories, the Internet opens up new avenues for student learning and assessment. Following the experimental simulation the student is presented with a series of questions designed to test their understanding of the principles involved.

During the assessment phase, the applet functions as a client in a client/server relationship. The server draws questions from test banks. The detail of them (for example the value of different components in the experimental setup) can be varied automatically as they are delivered, and hence each student receives a personalised set of questions.

As the student answers questions their responses are sent to the server. The questions are either multi-choice or short answer questions, enabling them to be automatically marked by the server. The student can thus immediately see their result. In addition the server collates the results and makes them available to the tutor so that they can form part of the assessment for the course if required.

THE “PHYSICAL” LABORATORIES

Computer assisted experiments were originally developed in 1991 for four machine sets. Each of them has been upgraded as part of this project. It was decided to use Borland’s Delphi environment to perform this upgrade as the original code was written in Pascal (Delphi is Pascal-based).

The four experiments are now briefly described. The first three are used by year 2 BE students, the fourth one by year 4 BE students.

The Transformer

The transformer in use in the laboratory is an ESEC 3kVA 400V model. It can be used as either a single phase or a three phase transformer. A resistive load bank, an inductor and a capacitor are used to provide the transformer with loads of different power factors.

There are three main parts in the experiment.

In part 1, the no load characteristics (i.e. the properties of the transformer when no load is connected) are investigated.

Students plot a graph of primary line voltage (V_1), secondary phase voltage (V_{2p}), and primary line current (I_1) vs time for a period of 40 ms (i.e. two complete periods at 50 Hz). This graph is repeated for 5 different values of V_1. For each different value, a B-H curve (or hysteresis loop) is produced.

Once the 5 graphs have been generated the software displays a graph of no load power vs primary voltage. This enables X_m (the magnetising branch reactance), R_m (the magnetising branch resistance) and P_{fe} (the core loss) to be calculated [13].

In part 2, the short circuit characteristics (i.e. the properties of the transformer when its output is short circuited) are investigated.

A short circuit is applied across the secondary side of the transformer. Students plot a graph of R_e (the leakage resistance), X_e (the leakage reactance) and W_{sc} (the short circuit power) for 5 different values of I_1 [ii].

In part 3, the on load characteristics (i.e. the properties of the transformer when a variety of loads are connected to it) are investigated.

Students plot a graph of V_{2p} against dV (the change in V_1) as the resistive load on the transformer is increased.

Phase regulation is then investigated. Resistive, inductive and capacitive loads are in turn connected and in each case a phasor diagram showing V_1, V_{2p} and I_2 is produced.

Finally in part 3, a curve of efficiency vs I_2 is plotted.

The Synchronous Machine

This experiment models a synchronous machine being used as a generator (as might be found in a hydro-electric power station for example). For practical reasons the motive power for the machine in the laboratory is provided by a Schrage electric motor rather than water driven turbines however.

The objectives for this experiment are to provide a "hands-on" experience in the practicalities of connecting a generator to the national grid and maintaining it once synchronised. To this end the hardware of the experiment (the connection switches, the power adjustment controls and the so-called "three lamps") provide the tangible interface to the system while the computer and its software serve as guide and note-taker.

The machine is rated at 400V, 6kVA. The power developed by the Schrage may be varied by altering the brush position. This is achieved in the laboratory by means of a chain drive which brings the control up to the bench top.

There are three main parts in the experiment.

Part 1 is performed with the machine's output not connected onto the 400V mains. Students perform an open circuit test (plotting output voltage vs DC field current) and a short circuit test (plotting output current vs DC field current). From these two graphs the synchronous reactance can be calculated [14].

To complete part 1, the machine is synchronised onto the 400V mains. This is achieved by driving it up to its synchronous speed (1000 rpm), adjusting the DC field current until the output voltage reaches 400V, and using the "three lamps" method to determine when to close the switch connecting the output to the mains.

Part 2 investigates the behaviour of the machine under steady state conditions. The machine is firstly synchronised onto the mains, and then two tests are performed, resulting in a family of "V" curves and another family of "P-□" curves.

The so-called "V" curves are a plot of line current vs DC field current. At the point of synchronisation, the line current flowing is minimum (in fact in a perfect system it would be zero as there is no power transfer between the machine and the mains bus). If the field current is increased from this point, the line current increases and the power factor becomes leading (ie the system becomes capacitive). This forms the right hand arm of the "V". If the current is decreased from the synchronisation point, the line current also increases – however in this case the power factor becomes lagging (i.e. the system becomes inductive). This forms the left hand arm of the "V".

The so-called "P-∂" curves are a plot of power transfer vs load angle (∂). The load angle is the difference in phase between the mains and the generator. Again at the point of synchronisation, the power and load angle should both be zero. The power transfer is then increased by increasing the power supplied by the Schrage. At this stage the machine is generating (i.e. supplying power to the national grid). As this occurs, ∂ becomes positive. Once ∂ reaches 90° the machine will "pole-slip" as it loses synchronisation and jumps one cycle ahead of the mains. If the power supplied to the Schrage is decreased from the point of synchronisation, the machine begins motoring (i.e. drawing power from the national grid). ∂ becomes negative and once it reaches -90° the machine will again "pole-slip", this time as it falls one cycle behind the mains.

In part 3, students plot the so-called "Swing" curve. The machine is firstly synchronised. The power supplied to the Schrage is then increased so that the machine begins generating and ∂ becomes positive. The Schrage is then switched off altogether, suddenly forcing the machine into motoring mode and causing ∂ to swing negative. The Schrage is then switched on again causing ∂ to swing positive back to its initial value. When the sudden changes occur, ∂ of course does not immediately settle on a new value but overshoots the mark, and then oscillates around the new value, the oscillations gradually dying out over time. The "Swing" curve is generated by plotting ∂ vs time as the Schrage is switched off and then on again.

The Induction Machine

The equipment for this experiment is a Mawdsley set comprised of an induction machine driving a dc machine. The dc machine is present to provide a load for the induction machine. The armature current of the dc machine is dissipated in a resistor load bank. The amount of load the dc machine creates may be varied by adjusting the field current supplied to it.

There are three main parts in the experiment.

In part 1, three tests are performed in order to determine the machine's parameters. Six parameters are found: R_1 and R_2 (the stator and rotor resistances), X_1 and X_2 (the stator and rotor reactances) and R_m and X_m (the magnetising resistance and reactance).

Firstly the rotor of the machine is physically prevented from turning while rated current is supplied to it. This enables $R_1 + R_2$ and $X_1 + X_2$ to be found. Secondly the machine is run at rated voltage with no load. Input power and current are plotted against voltage as the supply voltage is decreased. This enables R_m and X_m to be calculated. Thirdly a low DC voltage is supplied across one of the stator windings and the resulting current measured, allowing R_1 to be calculated. R_2 can now be found as the sum $(R_1 + R_2)$ is already known. X_1 and X_2 are found by assuming that $X_1 = X_2$ [15].

Once part 1 is complete, the machine's equivalent circuit is drawn.

In part 2, the behaviour of the machine during a Direct On Line (DOL) start is investigated. From an educational point of view, this particular part of this experiment is the highlight of the entire project. The primary objective of having the computer perform the record keeping and result presentation is not only neatly demonstrated here, it is in fact surpassed as it would be impossible to carry out this valuable part of the experiment without this equipment.

The software is triggered automatically when the machine is switched on, and captures 4.5 seconds of data in real time. The data is firstly plotted against time, and then re-plotted against speed. The speed graphs contain plots of current, voltage, input power, torque and efficiency presented in real time. The torque is calculated using the relationship

$$T = J\frac{dw}{dt}$$

where J is the moment of inertia of the machine and dw/dt is the derivative of the speed curve.

Efficiency is calculated using the relationship

$$Eff = \frac{Tw}{P_{in}}$$

where T is the torque, w is the speed in radians/second and P_{in} is the input power.

DOL starts are performed at several different voltages, and also with the machine pre-loaded. In all cases the graphs produced by the experiment are compared with theoretical graphs produced using the equivalent circuit derived in part 1.

To complete part 2, the three phases of the rotor and stator currents are plotted during a DOL start. During the start period the currents that flow are usually unbalanced and are known as inrush currents.

In part 3, the machine is run under steady state conditions while various loads are applied to it. Torque, current and input power are plotted by the student as the load on the machine is increased. After each graph is complete the software calculates Q (reactive power), efficiency and power factor using the following formulae:

$$Q = \sqrt{(3VI)^2 - P^2}$$

$$Eff = \frac{Tw}{P}$$

$$PF = \frac{P_{in}}{3VI}$$

In this part also the graphs are compared with theoretical graphs produced using the equivalent circuit derived in part 1.

Symmetrical Components

Here a dc machine drives a synchronous machine acting as a generator. The synchronous machine generates a 400V three phase supply completely isolated from the mains. Thus the effects of unbalanced loads and fault conditions applied to the supply are more easily seen.

There are two main parts in the experiment.

In part 1, the star point of the load is disconnected from the system ground (i.e. it is left to float). Various three phase unbalanced loads are then applied. These loads can be made up of any combination of resistors, inductors and capacitors selected by the student. After applying a load, the software displays the phasor triangle, thus demonstrating how the star point is displaced from the centre of the triangle by the load. For purely resistive loads, the power factor remains at zero and the star point is displaced in phase with one of the three phasors (i.e. it will move only along the red, yellow or blue phasors). If inductive and/or capacitive loads are applied, the star point can be driven in any direction and even forced outside the original balanced triangle.

Fault conditions are investigated in part 2. The star point of the load is fixed to the system ground and then various short circuits are applied to the output. The faults simulated are line to ground (e.g. red phase to ground) and line to line (e.g. yellow phase to blue phase). The software resolves the output into voltage sequence components and current sequence components and sums them graphically on the screen.

PROGRESS TO DATE

All four “hard” experiments have been rewritten in Delphi and now have a modern “look and feel”. All except the synchronous machines experiment have been in regular use since the beginning of the 2001 academic year.

As stage 1 of this project did not contribute anything new from the students' point of view (other than an updated environment), there is little point in attempting to measure any kind of outcome.

At the time of writing the transformer, synchronous machine and induction machine experiments have been implemented as virtual laboratories and are ready for field testing. The symmetrical components simulation is currently on hold. The automated assessment tools are also functioning and complete. As this stage of the project is not yet in general student use it is too early to form any conclusions about the impact it may have.

CONCLUSION

This paper has compared and contrasted virtual laboratories with traditional laboratories. As part of the discussion of virtual laboratories it has described the difference between a remote laboratory (where a physical experiment is conducted by remote control – often via a website) and a virtual laboratory (which is a computerised simulation of a physical experiment).

As a result of this comparison the following conclusions were reached:

- Virtual laboratories can be a feasible alternative to traditional laboratories.
- Virtual laboratories are most effective when used in conjunction with a traditional laboratory.
- Virtual laboratories must be designed well, and use multimedia appropriately.

The paper also describes how a virtual laboratory was combined with a computer-assisted laboratory. Students complete the virtual laboratory on the Internet prior to attending the scheduled laboratory session. They are therefore familiar with the concepts and aware of the kind of results that should be obtained before they attempt the practical session. In the practical session, software with a similar “look-and-feel” to the simulation software guides the student through the experiment and records the results.

This combination of approaches yields some of the advantages of purely virtual laboratories (such as increase in availability and automation of administrative tasks) while overcoming what is often the main criticism of a virtual laboratory – that it is unrealistic. In addition it enables better use of physical resources to be made as the amount of tutor-directed hands-on lab time allocated to each student can be reduced.

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Vic Church is the technician in charge of the Electrical Machines Laboratory, and in fact has held that role since prior to 1990. He has played a key part in keeping the experiments running over the years.

Roopak Sinha, a final year undergraduate student at Manukau Institute of Technology in 2002, has contributed to the synchronous machine and induction machine simulations, as well as to the automated assessment tools.

Nigel Shepstone, a fellow lecturer at Manukau Institute of Technology, developed the MATLAB simulations of the electrical machines.

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15 T. J. Roberts, "The Induction Machine Experiment", Department of Electrical and Electronic Engineering, University of Auckland, 1990.

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