Virtual Laboratory Arrangement for Measuring Characteristic Power System Quantities

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***Abstract* - This paper outlines the potential of virtual laboratories with regard to complementing and extending the conventional laboratory experience and training of post-graduate students in the Electrical and Computer Engineering Department of Democritus University Thrace. It also describes a software program for laboratory training during undergraduate courses relative to power systems within the said Department. Students can obtain this software tool from the Department e-class educational platform. Basic concepts, a description of the software tool structure, indicative virtual laboratory exercises for measuring characteristic power system quantities and also experience of the application of this tool in the class are presented in this paper.**

Key Words- Education, laboratory training, power systems, virtual laboratory arrangement

INTRODUCTION

In the Electrical and Computer Engineering Departments, postgraduate studies incorporate both theoretical and laboratory training. The latter is traditionally realized with experiments using conventional laboratory equipment. However, rapid advances in technology have created a need for extensive cross-curricular postgraduate laboratory training for an increased number of students.

The above-mentioned factors in combination with the high cost of conventional equipment and the space in which to install it, have of necessity led to the adoption of virtual laboratory training methods in combination with relative software tools development.

Virtual laboratories are less time-consuming than real-world laboratories. So they can be repeated as necessary, making the concepts more comprehensible. They offer students the opportunity to visualize the engineering concepts they learn in the classroom. They also allow students to improvise in a risk-free environment and to perform the experiments on their personal computers any time they wish, provided they have the appropriate software.

The most serious disadvantage of virtual laboratories is the resulting lack of familiarity with the real-world equipment that students will be called on to use in the future as engineers. An ideal combination would be parallel training in real-world and virtual laboratories and the comparison of the relative results.

At the Electrical and Computer Engineering Department of Democritus University Thrace, undergraduate students attend three courses: “Power Systems I”, “Power Systems II” and “Power Systems III”, relative to power system operation in the steady state, power system fault analysis and electrical systems in buildings and manufacturing facilities. The above courses include lectures as well as class and laboratory exercises (experiments). Students, during the last (tenth) semester of their studies, are required to work out their diploma thesis. The power systems area is a popular selection for the students of the Electrical Power Engineering Module.

Laboratory exercises have been performed up to the present day using conventional power system equipment or models. In recent years the number of undergraduate students in this department has increased. Hence the decision to develop virtual laboratory exercises, not only with the same objectives as the exercises performed with conventional laboratory equipment but also with additional options. Students can obtain the relative software from the Department e-class educational platform before they come to the laboratory to practice with conventional equipment. Therefore, they can be properly prepared using their personal computer. Realistic measurements are then less time-consuming, more easily understood and students also have the opportunity to compare their results to those from the virtual laboratory exercises, which are more accurate.

This paper describes the Powerlab software tool, developed by an undergraduate student as a diploma thesis. This software is now used by the Power System Laboratory for the laboratory training of students of the Department in the “Power Systems I” course. Using this software the students can perform virtual laboratory exercises relative to:

- power, current and voltage measurements
- transmission line voltage drop and losses
- phasor diagrams of the transmission line parameters
- transmission line voltage compensation
- power factor correction for several loads e.t.c.

The most important feature of Powerlab is that students can read the measured quantities not only as values registered in edit boxes but also on instruments interconnected to a virtual measurement arrangement. That impresses on students an intuition as to how the quantities change and helps in the visualization of the electrical engineering concepts learned in the classroom.

The results of the virtual measurements and calculations can be registered in tables and/or be presented in the form of phasor or other diagrams. They can also be immediately compared to the results of measurements performed using conventional equipment, with simultaneous computation of the relevant error. The virtual arrangement can also be used to perform exercises where the power system parameters have values impossible for conventional equipment.

BASIC CONCEPTS

The basic concepts for the development of the Powerlab software are included in [1]-[3].

Figure 1 gives the single-phase equivalent of a three-phase power system containing source, line and load.

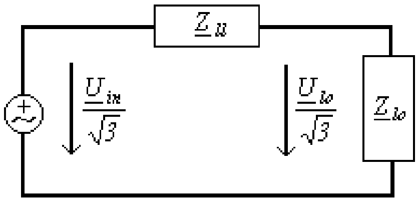

FIGURE 1
SINGLE-PHASE EQUIVALENT OF A THREE-PHASE POWER SYSTEM.

The line current according to Fig.1 is:

$$\underline{I} = \frac{\underline{U}_{in}/\sqrt{3}}{\underline{Z}_{ll} + \underline{Z}_{lo}} = \frac{\underline{U}_{in}/\sqrt{3}}{\underline{Z}_{tot}} \quad (1)$$

where:
$\underline{U}_{in}$ the line-to-line input voltage
$\underline{Z}_{ll}$ the line impedance

$$\underline{Z}_{ll} = R_{ll} + jX_{ll} \quad (2)$$

$\underline{Z}_{lo}$ the load impedance
$\underline{Z}_{tot}$ the total impedance.

The load can be represented according to its character (inductive or capacitive) by a parallel connection of a resistance R and an inductance X_L or a capacitance X_C respectively. When a series load connection is selected, the conversion of the series components R_s and X_s to equivalent parallel components R_p and X_p is possible using the following equations:

$$R_p = \frac{\left(X_s^2 + R_s^2\right)}{R_s} \quad (3\text{ a})$$

$$X_p = \frac{\left(X_s^2 + R_s^2\right)}{X_s} \quad (3\text{ b})$$

The voltage on the load is:

$$\underline{U}_{lo}/\sqrt{3} = \underline{U}_{in}/\sqrt{3} - \underline{I}\cdot\underline{Z}_{ll} \quad (4)$$

The percent voltage drop on the line is:

$$\varepsilon\% = \frac{U_{in} - U_{lo}}{U_{in}} 100 \quad (5)$$

The active, reactive and apparent input powers are:

$$P_1 = \sqrt{3}\cdot U_{in}\cdot I\cdot cos\rho \quad (6\text{ a})$$

$$Q_1 = \sqrt{3}\cdot U_{in}\cdot I\cdot sin\,\rho \quad (6\text{ b})$$

$$S_1 = \sqrt{3}\cdot U_{in}\cdot I \quad (6\text{ c})$$

where ρ is the phase angle of impedance $\underline{Z}_{tot}$.

The relative powers on the load are:

$$P_2 = \sqrt{3}\cdot U_{lo}\cdot I\cdot cos\varphi \quad (7\text{ a})$$

$$Q_2 = \sqrt{3}\cdot U_{lo}\cdot I\cdot sin\,\varphi \quad (7\text{ b})$$

$$S_2 = \sqrt{3}\cdot U_{lo}\cdot I \quad (7\text{ c})$$

where φ is the phase angle of impedance $\underline{Z}_{lo}$, which determines the load power factor $cos\varphi$.

The line losses are:

$$P_{ll} = 3\cdot I^2\cdot R_{ll} \quad (8)$$

When the load consists of a resistance R and an inductance X_L or a capacitance X_C connected in parallel, the power factor for inductive load is:

$$cos\varphi = cos\left[atan\frac{R}{X_L}\right] \quad (9)$$

and for capacitive load is:

$$cos\varphi = cos\left[atan\left(-\frac{R}{X_C}\right)\right] \quad (10)$$

When a power factor correction from $cos\varphi$ to $cos\varphi'$ is desirable, a suitable capacitor or a coil must be connected parallel to the load correspondingly. The relative capacitance or inductance are given by the relations:

$$X_{CC} = \frac{X_{new}\cdot X_L}{X_{tot} - X_L} \quad (11\text{ a})$$

$$X_{LL} = \frac{X_{new}\cdot X_C}{X_{tot} - X_C} \quad (11\text{ b})$$

where:

$$X_{new} = R/tan\,\phi' \quad (12)$$

By connecting a suitable capacitance X_{CI} parallel to the load it is possible to have $U_{lo}=U_{in}$ (transmission line voltage compensation). The condition determining the value of X_{CI} is:

$$\frac{U_{lo}}{U_{in}} = 1 = \frac{\left|\frac{-jX_{CI}(R_s + jX_s)}{R_s + j(X_s - X_{CI})}\right|}{\left|R_{ll} + jX_{ll} - \frac{-jX_{CI}(R_s + jX_s)}{R_s + j(X_s - X_{CI})}\right|} \quad (13)$$

In cases of lines with negligible R_{ll} compared to X_{ll} , the value of X_{CI} resulting from (13) is:

$$X_{CI} = \frac{R_s^2 + X_s^2 + X_s X_{ll} + \sqrt{\left(R_s^2 + X_s^2 + R_s X_{ll}\right)\left(R_s^2 + X_s^2 - R_s X_{ll}\right)}}{2X_s + X_{ll}} \tag{14}$$

SOFTWARE STRUCTURE

Powerlab software, has been written in Delphi 7 under the Windows XP operating system. The Delphi programming language enables the programmer to create a very user-friendly interface.

Figure 2 shows the main program window, where there is a three-phase power system with voltage source, transmission line and a Y-connected load. Voltmeters, ammeters, wattmeters, varmeters and phase angle meters are connected to this system to measure the relative quantities. The accurate values of these quantities are also shown in the edit boxes at the bottom of the window. These quantities are either introduced as inputs during the virtual laboratory exercises (input voltage, transmission line parameters, load data), or they are resulting from measurements (current, voltage phase angle, load voltage, active and reactive power) and computations (voltage drop, power factor, apparent power, transmission line losses).

The input data that are necessary to perform any virtual laboratory exercise are input voltage and line and load impedances.

The selection of input voltage U_{in} is initially obtained via a wheel button, which is positioned beneath the three-phase source in Fig. 2. Wide voltage variations occur on rotation of this button. Therefore, if someone wants smaller variations, he must use the double action switch, which is to the right of the wheel button.

The user selects the transmission line impedance by pressing any one of the three buttons with the indication "Z_{ll}". Each selection of the line parameters appears on the window of Fig. 3 as a graphical representation. The selected line parameters are also registered in the relative edit boxes on the window of Fig. 2.

The examined loads are balanced. Therefore, the load impedance is selected, in proportion to the line impedance, by pressing one of the buttons with the indication "Z_{lo}" in the arrangement of Fig. 2. The load selected in this way (Fig. 4), is connected to the network and the relative edit boxes of Fig. 2 are posted up.

The virtual laboratory algorithm works for parallel combinations of the previously selected load components. If someone wants to study a load with series connected components in the laboratory, he has to transform this connection to the equivalent parallel one, before performing a virtual laboratory exercise. This transformation is obtained by selecting "Series to parallel conversion" from the main menu of the window shown in Fig. 4.

For each load selection, its impedance Z_{lo} and power factor $cos\varphi$ are calculated and appear in the relative edit boxes of Fig. 2.

After the selection of the source voltage and the line and load parameters, the measuring instruments in Fig. 2 show the values of the relative quantities. The accurate values of these quantities are automatically recorded in the

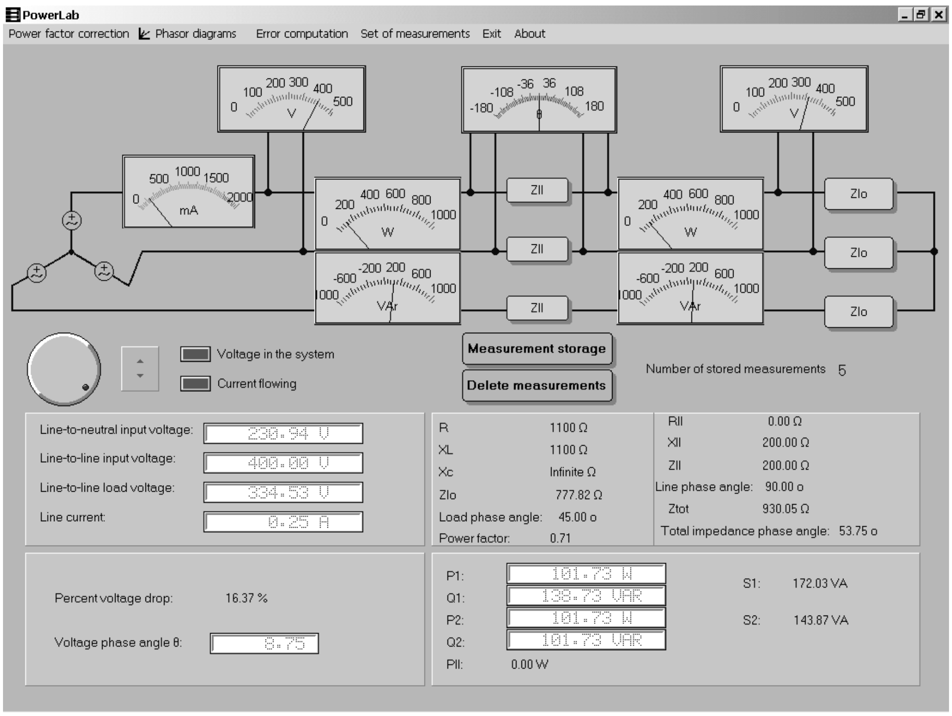

FIGURE 2
MAIN PROGRAM WINDOW.

relative edit boxes of Fig. 2. Additional quantities such as voltage drop ε on the line, as a percentage of the source voltage, line losses P_{ll} and input and output apparent power, S_1 and S_2 correspondingly, are also automatically calculated and registered in relative edit boxes.

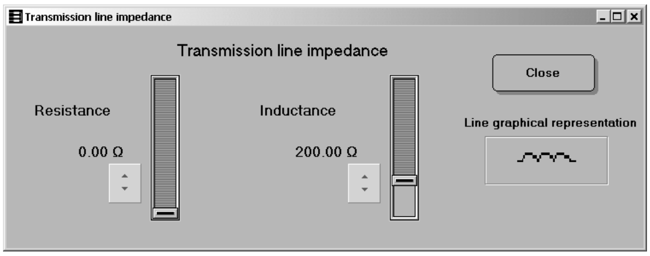

FIGURE 3
WINDOW FOR THE LINE PARAMETERS SELECTION.

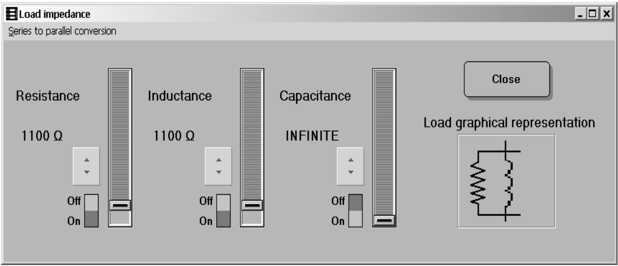

FIGURE 4
WINDOW FOR THE LOAD COMPONENTS SELECTION.

Three scales are provided for the ammeters. The same applies to the wattmeters. Therefore, the measurements of the above instruments are accurate and clear.

The user has the possibility of seeing and printing the phasor diagrams of line-to-neutral voltages (source, line and load voltages) and the line current, by pressing the "Phasor diagrams" button in the main menu of the window of Fig. 2 (an example is given in Fig. 5).

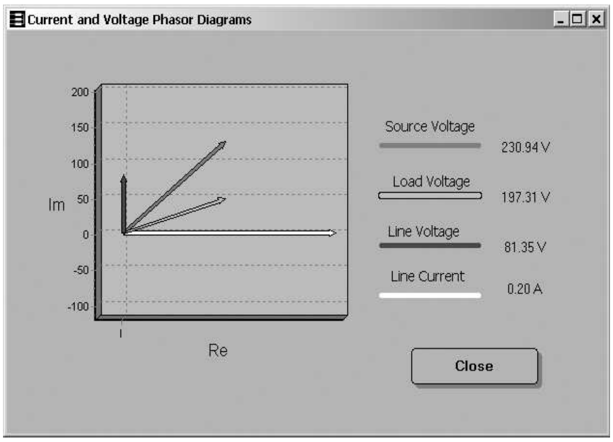

FIGURE 5
CURRENT AND VOLTAGE PHASOR DIAGRAMS.

Another option is to press the "Power factor correction" button in the same menu. Then the user can select "Full compensation" or "Selected correction". For the former, the window of Fig. 6 appears, where the value and character of the existing power factor, the reactance of the element which must be connected parallel to the load for full power compensation, the line current before and after this compensation and the fact that the load reactive power is equal to zero in the case $\cos\varphi = 1$ are recorded.

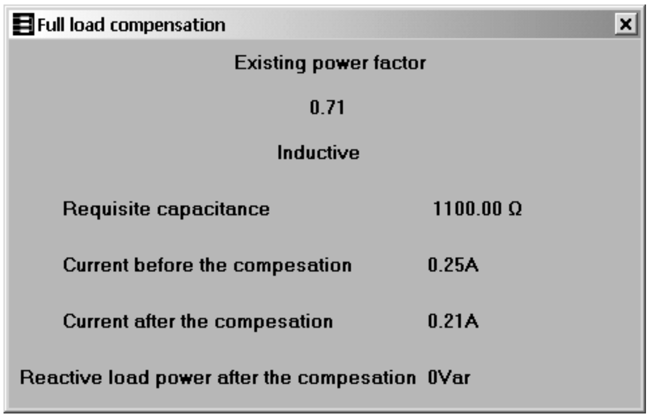

FIGURE 6
FULL REACTIVE LOAD POWER COMPENSATION WINDOW.

The window of Fig 7. appears by pressing "Selected correction". Here the existing power factor value and character are recorded. Then the desirable power factor value and character are selected and the reactance and character of the element, which must be connected parallel to the load to achieve this result, are recorded.

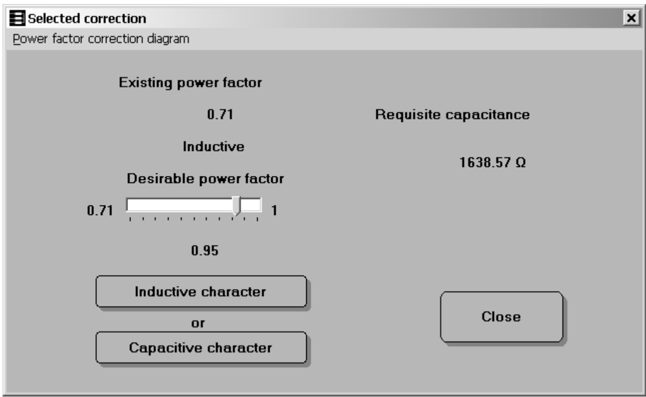

FIGURE 7
WINDOW FOR SELECTED POWER FACTOR CORRECTION.

With the additional selection of "Power factor correction diagram" from the main menu of the window of Fig. 7 the window of Fig. 8 becomes available. Here a table appears with the quantities: line current I, line losses P_{ll} and requisite reactance X for a power factor increasing from the existing value to a unit with a step equal to 0.02. The user can see and print diagrams, presenting each one of the quantities of this table as a function of the power factor $\cos\varphi$, by making a relative selection on the left lower end of the window of Fig. 8. Figure 8 shows a relative diagram for the line current.

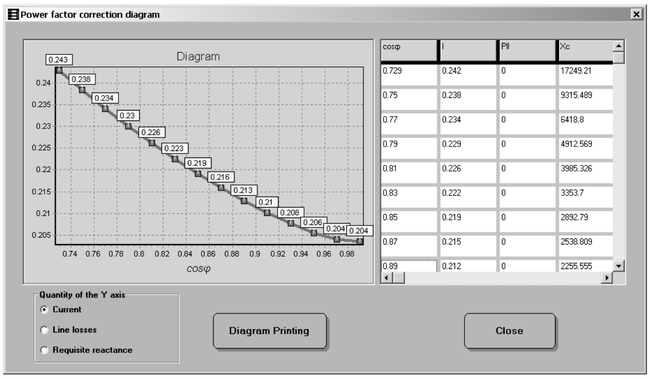

FIGURE 8
POWER SYSTEM QUANTITIES FOR GRADUAL POWER FACTOR CORRECTION.

A series of measurement results can be stored in a table by pressing the "Measurement storage" button (Fig. 2). The number of these measurements appears on the right of the above button. The stored measurement results may be used for the drawing of error diagrams. Specifically, the window of Fig. 9 appears by selecting "Error computation" from the main menu of the window of Fig. 2. From the left lower end of this window the user can select an output quantity of the virtual laboratory and then the stored values of this quantity are registered in the first column of the table of Fig. 9. The user introduces the relative values of the above quantity resulting from measurements in conventional equipment using the second column. By selecting "Error computation" the difference between the relevant values appears in the third column and the percentage error in the fourth column. The user can see the error diagram, by pressing "Diagram drawing".

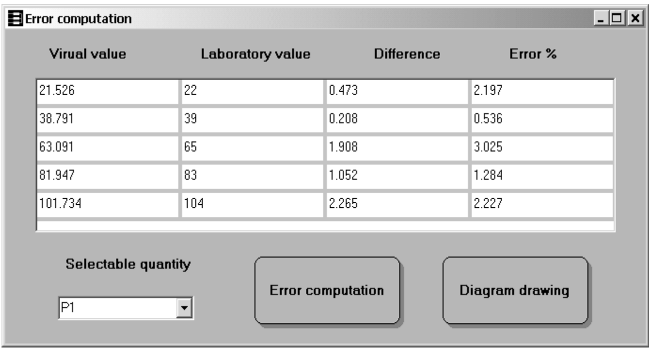

FIGURE 9
WINDOW FOR ERROR CALCULATION.

Pressing the button «Delete measurements» in the window of Fig. 2 results in the deletion of the stored measurements.

The button "Set of measurements" in Fig. 2 gives an additional possibility. By pressing this button the window of Fig. 10 appears. Using this window the execution of a series of measurements is possible, albeit without having visual access to the instruments. The user declares the desirable number of measurements and the table of Fig. 10 acquires a relative number of rows. Each row has 13 columns where the input data are inserted and the results of the virtual laboratory measurements are recorded. Specifically, the user selects only those of the load components R, X_L, X_C and the line components R_{ll}, X_{ll} to be inserted in the columns of the table, with five switches on the left upper end of the window of Fig. 10. Then the values for these components and the source voltage value are recorded in the relative cells. The values of the quantities P_1, Q_1, U_{lo}, P_2, Q_2, θ and I can be calculated and registered in the table, by pressing the button "Result computation".

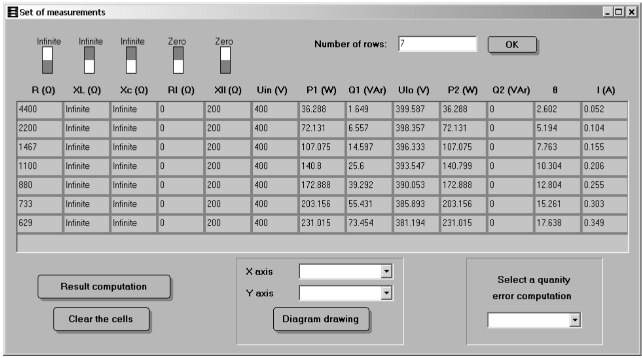

FIGURE 10
WINDOW FOR A SET OF MEASUREMENTS

From the window of Fig. 10 the selection of a quantity of the table, the comparison of its values to the corresponding measured values in conventional equipment, and the computation of the relative error (error values and diagram) are possible in the same way as in Fig. 2.

A diagram with any two of the quantities of the table in Fig. 10 as coordinates can be drawn by selecting "Diagram drawing" in Fig. 10.

INDICATIVE VIRTUAL LABORATORY EXERCISES

The students can perform different laboratory exercises on the virtual arrangement of Fig. 2. Indicative exercises are:

- Power measurement of a directly fed consumer.

The student selects a value for the input voltage U_{in} and different combinations for the values of the load parameters R, X_L and X_C. Taking the line impedance as zero, he is measuring the active, reactive and apparent power as well as the voltage on the load (P_2, Q_2, S_2, U_{lo} respectively). He is also recording the reactive power flow direction between the source and the load.

- Power measurement of a consumer fed via a transmission line.

For the data of the previous exercise and the impedance of transmission line $\underline{Z}_{ll}$ as additional data the students measure the active, reactive and apparent power at the line input and output (P_1, Q_1, S_1, P_2, Q_2 and S_2). The measurement results are compared to relevant results of the previous exercise and comments are expressed. The voltage drop on the line is also calculated and how the load character affects this voltage drop is examined.

- Measurement of the phase angle θ between the source and the load voltages and of the voltage drop on a transmission line.

For definite input voltage and transmission line impedance students select a clearly resistive load R of different values. Then they measure the input and output line voltages U_{in} and U_{lo}, the phase angle θ between them and the input and output line powers. The voltage drop on the line is also calculated. Diagrams of U_{lo} and θ as a function of the load active power P_2 are drawn. Comments regarding the influence of the load resistance on the load voltage are expressed.

- Transmission line voltage compensation.

The measurements of the previous exercise are repeated by connecting a suitable capacitance X_{CI} parallel to the resistive load in order to compensate the transmission line voltage. Quantities relative to that of the previous exercise are measured or calculated, relevant diagrams are drawn and comments on the results of respective measurements are expressed.

- Load compensation.

a) Full load compensation.

The line current I, the reactive power Q_2 and the load power factor are measured, for definite input voltage and transmission line impedance and for different values of an inductive load. A selected capacitance, which is connected parallel to the load, achieves full load compensation ($cos\varphi=1$). The values of the requisite capacitance for the different load values and the new values of the line current are recorded.

b) Selected load compensation.

For definite input voltage, transmission line and load impedances, the values of line current I, power factor $cos\varphi$ and line losses P_{ll} are measured or calculated. The power factor increases from its existing value to a unit with a concrete step. For every new value of the power factor, the line current is measured and the line losses, as well as the requisite capacitance for the concrete power factor correction, are calculated. Diagrams of the above quantities, as a function of the power factor, are drawn.

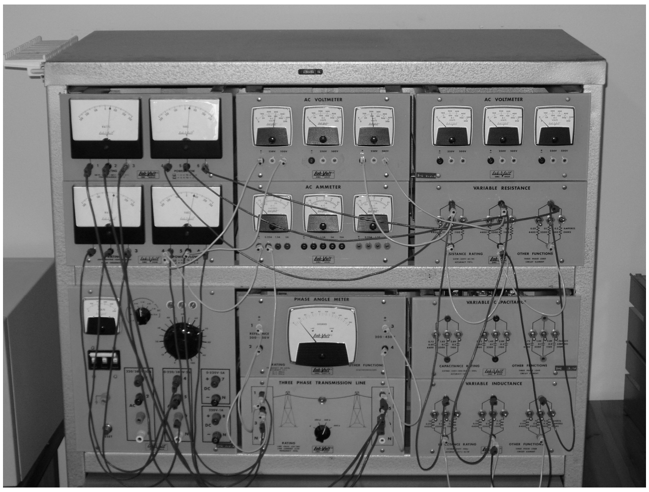

FIGURE 11
EXPERIMENTAL SETUP FOR MEASUREMENTS IN CONVENTIONAL LABORATORY EQUIPMENT.

Figure 11 shows an experimental setup for the measurement of characteristic quantities of a three-phase power system in conventional laboratory equipment. The virtual laboratory exercises are also performed with this equipment and error diagrams are drawn.

CONCLUSIONS

Described above is a software tool, developed by an undergraduate student as a diploma thesis for the upgrading of the laboratory training of undergraduate students of the Electrical and Computer Engineering Department of Democritus University Thrace in power systems. Students can obtain this software tool from the Department e-class educational platform and by using it, they can perform different virtual laboratory exercises on their personal computers in order to measure or calculate characteristic quantities of a three-phase power system. The results of the virtual measurements can be immediately compared to the results of measurements performed using conventional equipment, with the simultaneous computation of the relevant error.

The Powerlab tool has already been successfully tested in four classes of our Electrical and Computer Engineering Department during the years 2004, 2005, 2006 and 2007, in the context of the course “Power Systems I”. It is clear from these applications that its main advantages are:

- easy access
- user-friendly interface
- the visualization of the concepts learned in the classroom
- easy and immediate comparison between real-world and virtual experiment results.

One of our immediate plans is the enrichment of the arrangement of Fig. 2 with additional elements such as voltage sources (interconnected systems), inductive motors as loads, transmission lines parallel to the existing one, regulating transformers for voltage phase angle and magnitude control, step up and step down transformers. Undergraduate students in the context of their diploma thesis will develop all the aforementioned and this is another educational advantage of Powerlab tool. Then, future undergraduates will be able to perform additional virtual laboratory exercises relative to power flow, power distribution in parallel lines, power systems interconnections etc.

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