

# A Virtual Power Laboratory

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## Abstract

This paper describes **VPLab**, a virtual power laboratory designed to offer a virtual laboratory experience to students in the area of power conversion. Power conversion is a standard course in the electrical engineering curricula of many colleges of engineering. It deals with the conversion of electrical to mechanical power (motors); electrical power at one voltage level to electrical power at another voltage level (transformers); ac (alternating current) power to dc (direct current) power (rectifiers); and ac power to ac power (solid state ac controllers). A theoretical and practical background in this subject is essential to electrical as well as mechanical engineers.

Conceived as a computer based inter-active means for offering a laboratory course in power conversion, the virtual power laboratory, a computer simulation, can be utilized by students who have available a modest PC configuration. Within the virtual power laboratory are dc motors, ac motors, and single-phase and three-phase transformers, rectifier, converter and stepper motor. These devices are all modeled by the virtual power laboratory computer program to provide realistic operating characteristics. All of the device models have been designed to accurately produce the same results as actual equipment, which have been extensively tested in the laboratory. The virtual power laboratory contains a set of electrical instruments, (voltmeters, ammeters, wattmeters and oscilloscopes) and a set of mechanical instruments, (a dynamometer and tachometer). The virtual power laboratory text describes 15 experiments (laboratory exercises) utilizing the power conversion devices and instruments in a completely realistic way; each one designed using an actual laboratory experiment as a guide. Each experiment directs the student to exercise the device under study; collect and record data; and construct graphs and answer questions concerning the device, as illuminated by the experiment. A laboratory report may be submitted, as in a traditional laboratory, based on the experiment.

## I. Introduction

The power conversion laboratory is often at the heart of an electrical engineering program. In this laboratory, the college/university student is introduced to the characteristics of the electrical devices used in converting power from one form to another, for example, the conversion of electrical to mechanical power in an electric motor. In a one-quarter/semester laboratory course, the student may perform some seven to ten experiments to determine the characteristics of various machines, transformers and power electronic devices.

The Virtual Power Laboratory, **VP Lab**, was conceived as a means for offering a power conversion laboratory experience using an interactive computer program, that is, a virtual laboratory course. It consists of a laboratory text or manual and software stored on a CD. Presently, the Virtual Power Laboratory allows the user to "enter" a laboratory equipped to deliver 15 power conversion experiments. The nature of these experiments and the features of the laboratory are described in this paper.

The disadvantage of a virtual laboratory course is the obvious lack of student physical contact with the devices under study. The advantages are many:

<ul style="list-style-type: none"> <li>• acquisition costs of equipment*</li> <li>• maintenance costs for equipment*</li> <li>• space requirements</li> <li>• equipment* damage and repair</li> <li>• hazardous environment</li> </ul>	decreased or eliminated
<ul style="list-style-type: none"> <li>• range of device types</li> <li>• range of device ratings</li> <li>• range of device characteristics</li> </ul>	increased

\* Equipment refers to machines, devices, instrumentation and power supplies.

With these in mind, we have proposed the Virtual Power Laboratory as the basis for a first laboratory course in power conversion.

A preliminary version of **VP Lab** was used in a power conversion course in the Fall 1999 Quarter at Cal Poly. The response by both students taking the course and the faculty member teaching has been excellent.

## II. Description

The **VP Lab**, text and software, form a cohesive, complementary pair. The text defines the virtual laboratory in terms of the following parameters:

- devices to be tested
- instrumentation
- power supplies

For each of the 15 experiments, the text provides a general discussion and a theoretical description of the machine or device to be tested. The steady-state equations describing the machine or device are developed in this theory. Based on these, a schematic diagram for the experiment, with appropriate instrumentation, is shown. The student, armed with an understanding of the machine or device to be tested, and an instrumentation diagram, may now "enter the domain" of the virtual laboratory.

The **VP Lab** software, which can be installed on any pc running Windows 95 or 98, reveals for each experiment a laboratory bench holding the machine or device under test and the appropriate instrumentation for the experiment. The simulation is interactive and contains both visual and audio effects as would be experienced in a physical laboratory environment. Following along in

the text, the student performs the experimental procedure, changing inputs and recording outputs. When analyzed, these data reveal the fundamental, steady state, characteristics of the machine or device under test. The experimental process is strikingly similar to that of a physical laboratory--the student powers up the equipment, provides measured inputs and measures one or more outputs. Since the device models are robust, the experimental procedure may be modified to include a wide range of test variables. Thus, the experiment is no-way canned, and can be modified by either the instructor or the student. The text further contains a set of questions for each experiment which is designed to extend the laboratory learning experience.

At present, **VP Lab** contains experiments determining the characteristics of the following power conversion devices.

- dc motor
- single-phase ac motor
- three-phase squirrel-cage ac motor
- three-phase wound-rotor ac motor
- three-phase synchronous ac motor
- single-phase transformer
- three-phase transformer
- stepper motor
- phase controlled inverter
- phase controlled rectifier

### III. A Machine Experiment

The significant aspects of **VP Lab** will be illustrated by selecting a specific experiment from the list of 15 and moving (swiftly) through it. For this purpose, we have selected an experiment focused on the operating characteristics of a three-phase squirrel-cage ac motor. Of particular interest in this experiment are speed regulation, line current, power factor and efficiency under various load conditions.

The experiment (4.1) follows a text section on the theory of the three-phase ac induction motor and development of the equations that model its performance. The text continues to Experiment 4.1 as follows:

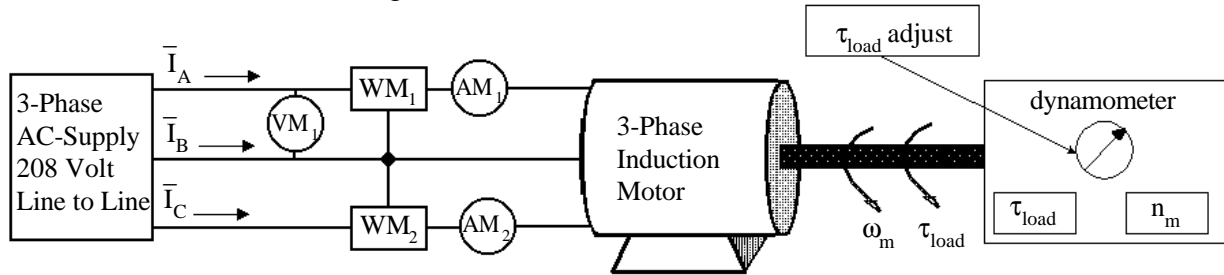
#### **Experiment 4.1**    **Speed/Torque Characteristic and Efficiency of a Three-Phase Squirrel-Cage Induction Motor**



In this experiment, we will make measurements on a four-pole, three-phase squirrel cage induction motor, rated one horsepower, 208 volts line to line, 60 hertz. Its approximate dimensions are 6 inches in diameter by 9 inches long and is shown in Figure 4.1-1. Such a motor could be used to power a compressor, blower, or small conveyer line.

**Figure 4.1-1 A Typical Small Three-Phase Squirrel Cage Induction Motor**

In order to determine the speed/torque characteristic and efficiency of the motor we provide instrumentation as shown in Figure 4.1-2.



**Figure 4.1-2 Instrumentation for Testing A Three-Phase Squirrel-Cage Induction Motor**

The dynamometer is a means for loading the shaft of the motor with a known load torque,  $\tau_{load}$ . Both  $\tau_{load}$  and speed  $n_m$  are “read out” by dynamometer instruments. The line to line voltage is read by voltmeter  $VM_1$ . Since this is a balanced three-phase system, the magnitude of  $I_A = I_B = I_C = I_L$ , and this value is read by  $AM_1$  and/or  $AM_2$ . An instrumentation listing is shown in Table 4.1-1.

**Table 4.1-1 Instrumentation for Experiment 4.1**

Instrument		Measures	Units
Dynamometer Torque Meter		$\tau_{load}$	newton-meter
Dynamometer Tachometer		$n_m$	rpm
Voltmeter	$VM_1$	$V_L$	volts
Ammeter*	$AM_1$	$I_A$	amperes
Wattmeter*	$WM_1$	$P_1$	watts
Ammeter*	$AM_2$	$I_C$	amperes
Wattmeter*	$WM_2$	$P_2$	watts

\* The ammeter and wattmeter are combined in a single instrument.

For this experiment,  $V_L$  is set at 208 V ac (rated voltage of the motor). The three-phase electrical power drawn by the motor is measured using the two-wattmeter method.  $P_{in}$ , the total input power to the motor, is given by the expression:

$P_{in} = \sqrt{3} \times V_L \times I_L \times \cos(\phi)$ , in watts.  $\cos(\phi)$  is the power factor of the motor. In the two-wattmeter method,  $P_{in} = P_1 + P_2$ .

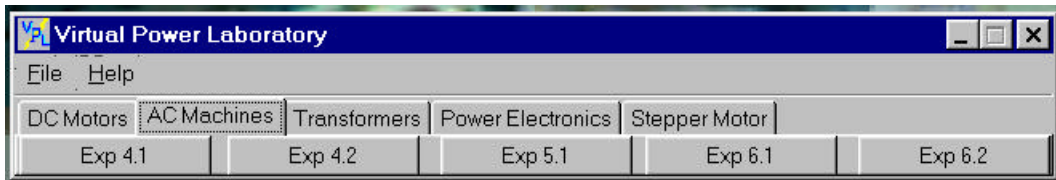
It can be shown that:

$$P_1 = V_L \times I_L \times \cos(\phi + 30^\circ), \text{ watts, and } P_2 = V_L \times I_L \times \cos(\phi - 30^\circ), \text{ watts}$$

This assumes ABC phase rotation and defines  $\phi$  to be positive for an inductive load (lagging power factor load).

## ❖ Procedure

1. Double left-click the **VPLab**® icon  which is located on your desktop. Left-click the ac machines button which launches **VPLab**® with the start-up screen shown below.



2. Left-click Exp 4.1 Test button. This launches Experiment 4.1, Speed/Torque Characteristics and Efficiency of a Three-Phase Squirrel-Cage Induction Motor, in the Bench View mode. Other choices available to you, at any time during the experiment, are the Schematic and Constants views. To obtain any view, simply Left-click the appropriate button.



3. The 208-volt, three-phase ac power supply is the source of power for this experiment. This supply is connected to your laboratory bench by clicking the **power-on** switch, located on the left side of the bench. Notice that the red pilot light comes on and the motor starts to run when the switch is activated. The motor should be running at close to synchronous speed (1,800 rpm).
4. The motor is mechanically loaded by a dynamometer, which is coupled to its shaft. Load torque,  $\tau_{load}$ , is set by placing the cursor on the dynamometer **torque-adjust** control knob and left-clicking the up/down arrow. The first data point will be recorded for a value of  $\tau_{load}$  of zero newton-meters (n-m).
5. Vary  $\tau_{load}$  from zero to six newton-meters (n-m) in 6 steps of approximately 1.0 newton-meters each. For each value of  $\tau_{load}$ , record a set of data ( $\tau_{load}$ ,  $I_L$ ,  $P_1$ ,  $P_2$  and  $n_m$  as measured by the appropriate instruments).

6. Complete the following table (Table 4.1-2).

**Table 4.1-2 Data from Experiment 4.1**

Data Set	Experimental Data					Calculated Data		
	$\tau_{load}$ n-m	$I_L$ amperes	$P_1$ watts	$P_2$ watts	$n_m$ rpm	$P_{out}$ watts	slip percent	$\eta$ percent
1	0							
2								
.....								
7								

❖ **Analysis - Experiment 4.1**

A) In order to display the test results in a concise, easily understood form, plot the following:

- (1) Speed ( $n_m$ ) vs Load Torque ( $\tau_{load}$ )
- (2) Efficiency ( $\eta$ ) vs Output Power ( $P_{out}$ )
- (3) Slip (s) vs Output Power ( $P_{out}$ )
- (4) Line Current ( $I_L$ ) vs Output Power ( $P_{out}$ )

Mark on each plot the data point corresponding to operation at half-rated and full-rated load.

(B) Determine, experimentally, the speed regulation of the motor from no-load to a load torque of three newton-meters.

$$SR = \frac{n_m|_{no-load} - n_m|_{specified-load}}{n_m|_{no-load}}$$

Speed-regulation is a measure of the speed droop of the motor as load increases from no-load to a specified load.

- C) Determine, experimentally, the efficiencies at an output power of approximately 100 watts.
- D) Determine the power output at which maximum efficiency occurs.
- E) The no-load losses of an induction motor consist of the following components: friction and windage loss, hysteresis and eddy current loss, and stray load loss. What is the value of the no-load losses of the motor as a percent of rated output power.
- F) Plot power factor versus power output. Determine the power output at which the maximum power factor occurs.

❖ **Questions - Experiment 4.1** - The questions, which normally are given in this section of the experiment, are excluded for brevity.

IV. Course Delivery

In our experience, a university level first course in power conversion consists of a one-semester/quarter combination of lecture and laboratory. This is offered in the upper division with

3 units allotted to the lecture and one unit to the laboratory. There are a number of excellent texts for the lecture portion of the course. [1-7] **VP Lab** would provide both the laboratory manual and the laboratory for this type of course. In situations in which a more *hands on* experience is desired, the following course format could be implemented.

- One set of equipment is set-up for demonstration and viewing.
- A short demonstration lecture is delivered before each of the **VP Lab** experiments is assigned.
- Students then perform the same experiment as the demonstration, or an expanded experiment, on their own pc.

This format requires a minimal investment in equipment but allows student observation and interaction with conventional laboratory equipment.

Another approach allows **VP Lab** to extend the capability of an existing laboratory. It does that by providing virtual laboratory equipment that does not exist in the physical laboratory. For example, a laboratory may have several types of motors but not a synchronous motor. **VP Lab** on synchronous motors could be used to fill in this gap.

## V. Simulation

A critical feature of **VP Lab** is its *look and feel*. The simulation, both of the machine or device being tested and the surrounding bench and equipment, is designed to look as life-like as possible. Our objectives are to:

- faithfully model the characteristics of real devices,
- provide a computer scene which appears to be a real laboratory,
- provide a means for interacting within the virtual laboratory,
- provide realistic and active instruments within the scene,
- provide realistic visual and audible feedback,
- provide *help* if needed.

In **VP Lab** these are attained in a WINDOWS environment using a pc with the following minimum features:

- operating system is Windows 95, Windows 98 or Windows NT
- 32 mbytes of ram
- resolution of 1024 x 768, high color or better, large font

## VI. Conclusion

**VP Lab** is an alternate approach to the conventional power conversion laboratory. It makes use of the pc which is readily available to the university student in place of or in addition to physical laboratory equipment. **VP Lab** in its present form simulates a number of important machine types and device types. Within the **VP Lab** shell the number of types can be increased readily. For example, the content of **VP Lab** could be increased to encompass both a laboratory course in electric machines and a laboratory course in power electronics.

Clearly, **VPLab** is a step toward *learning at a distance*. With the **VPLab** text and accompanying software, a student is able to complete a power conversion laboratory course at a considerable distance from a physical laboratory.

**VPLab** has been reviewed by a number of engineering educators. They have consistently commented on the uniqueness of the approach. We believe that it is applicable to a wide range of engineering laboratories.

## VII. References

- [1] Chapman, S. J., 1998, *Electric Machinery Fundamentals*, 3<sup>rd</sup> Edition, McGraw-Hill.
- [2] El-Hawary, M. E., 1986, *Principles of Electric Machines with Power Electronics Applications*, Prentice Hall.
- [3] Fitzgerald, Kingsley and Umans, *Electric Machinery*, McGraw-Hill.
- [4] Gonan, Turin, 1998, *Electrical Machines*, Power International Press.
- [5] Sarma, M. S., 1994, *Electric Machines: Steady-State Theory and Dynamic Performance*, 2<sup>nd</sup> Edition, PWS Publishing Company.
- [6] Sen, P. C., 1996, *Principles of Electric Machines and Power Electronics*, 2<sup>nd</sup> Edition, John Wiley and Sons.
- [7] Vithayathil, J, 1996, *Power Electronics Principles and Applications*, McGraw-Hill.

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