

Teaching Power Conversion in a Virtual Laboratory

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Abstract: This paper describes 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 motors, transformers, controlled rectifiers and 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, single-phase and three-phase transformers, controlled rectifier, ac converter and a stepper motor. The virtual power laboratory text describes laboratory exercises utilizing these devices and a set of instruments in a completely realistic way; each one designed using a traditional laboratory experiment as a guide.

Keywords: Power Conversion Laboratory, Virtual Reality, Electric Machines, Power Electronics,

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, **VPLab**[®], 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 Compact Disk (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 as shown in Table 1.

Table 1. Advantages of a Virtual Laboratory

<ul style="list-style-type: none">• acquisition costs of equipment*• maintenance costs for equipment*• space requirements• equipment* damage and repair• hazardous environment	decreased or eliminated
<ul style="list-style-type: none">• range of device types• range of device ratings• range of device characteristics	increased
<ul style="list-style-type: none">• accessibility to disabled students• compatibility to distance learning programs	increased enabled

* 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.

II. DESCRIPTION

The **VPLab**[®], 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. 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 **VPLab**[®] software, which can be installed on any PC running Windows 95 or later, 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 values of the 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, **VPLab**[®] contains experiments examining the characteristics of the following power conversion devices.

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

III. TEACHING EXPERIENCE

A preliminary version of **VPLab**[®] was used in multiple sections of a power conversion laboratory course in Fall 1999, Winter 2000, Fall 2000 and Winter 2001 Quarters at Cal Poly. A typical section consists of 16 – 18 students. The response by both students taking the course and the faculty members teaching the course has been excellent. This experience has led to improvements in the text, the content of the experiments and the manner of course presentation. In the case of course presentation, we find that a blend of a short demonstration of the assigned laboratory, using actual equipment, with the virtual laboratory, is a very effective method of teaching.

IV. A MACHINE EXPERIMENT

The significant aspects of **VPLab**[®] 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 single-phase split-

phase induction motor. Of particular interest in this experiment are speed regulation, line current, power factor and efficiency under various load conditions.

The experiment (5.1) follows a text section on the theory of the single-phase split-phase induction motor and development of the equations that model its performance. This paper continues to Experiment 5.1 as follows:

Experiment 5.1

Speed/Torque Characteristic and Efficiency of a Single-Phase Split-Phase Induction Motor

In this experiment, we will make measurements on a six-pole, single-phase, squirrel-cage induction motor, rated one-third horsepower, 120 volts, 60 hertz. Its approximate dimensions are 15 cm in diameter by 17 cm long and is shown in Figure 5.1-1. Such a motor could be used to power a washer or dryer, refrigerator, fan, or water pump.

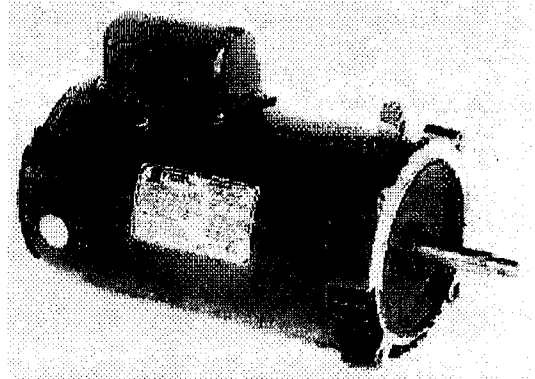


Figure 5.1-1 A Typical Single-Phase Squirrel Cage Induction Motor

In order to determine the speed/torque characteristic and efficiency of the motor we provide instrumentation as shown in Figure 5.1-2.

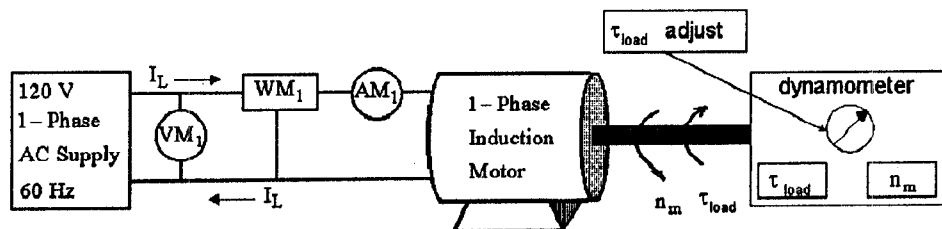


Figure 5.1-2 Instrumentation for Testing A Single-Phase Squirrel-Cage Induction Motor

The dynamometer is a means for loading the shaft of the motor with a known load torque, τ_{load} . Both τ_{load} and speed n_m are “read

out” by dynamometer instruments. The line voltage, V_s , is read by voltmeter VM_1 and line current, I_L , is read by ammeter AM_1 . An

instrumentation listing is shown in Table 5.1-1.

Table 5.1-1 Instrumentation for Experiment 5.1


Instrument	Measures	Units
Dynamometer Torque Meter	τ_{load}	newton-meter
Dynamometer Tachometer	n_m	rpm
Voltmeter	VM_1 V_s	volts, rms
Ammeter*	AM_1 I_L	amps, rms
Wattmeter*	WM_1 P_{in}	watts

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

The single-phase electrical power drawn by the motor is measured using wattmeter WM_1 . Total input power to the motor, is given by the expression:

$$P_{in} = V_s \times I_L \times \cos(\phi), \text{ in watts. } \cos(\phi) \text{ is the power factor of the motor.}$$

❖ **Procedure**

- 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.



- Left-click the Exp 5.1 Test button. This should launch Experiment 5.1, Speed/Torque Characteristic and Efficiency of a Single-Phase Split-Phase Induction Motor, in the Bench View mode.

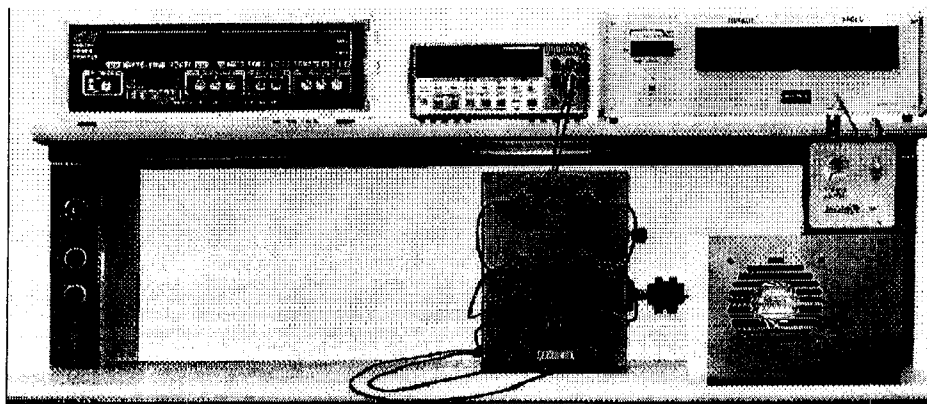
Other choices available to you, at any time during the experiment, are the Schematic and Constants views. To obtain any view, simply Left-click the appropriate button.

Bench View and Constants View are shown below.

Constants for Experiments 5.1

Item	Symbol	Name	Value	Units
1	V	rated line voltage	120	volts
2	I_L	rated line current	5.2	amperes
3	f	frequency	60	hertz
4	n_s	synchronous speed	1,200	rpm
5	τ_c	rated load torque	2.08	newton-meters
6	P_{rated}	rated power	1/3	horsepower

- The 120-volt, single-phase ac power supply is the source of power for this experiment. This supply is connected to your laboratory bench by clicking the **start-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 (1,200 rpm). The centrifugal switch has opened, de-energizing the split-phase winding.
- The motor is mechanically loaded by a dynamometer, which is coupled to its shaft. Load torque, τ_{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 τ_{load} of zero newton-meters (n-m).
- Vary τ_{load} from zero to three newton-meters (n-m) in 6 steps of approximately 0.5 newton-meters each. For each value of τ_{load} , record a set of data (τ_{load} , I_L , P_{in} and n_m as measured by the appropriate instruments).
- Complete the following table (Table 5.1-2). Show sample calculations for Data Set 4.



Bench View

Table 5.1-2 Data from Experiment 5.1

Data Set	Experimental Data				Calculated Data		
	τ_{load} n-m	I_L amps, rms	P_{in} watts	n_m rpm	P_{out} watts	slip percent	η percent
1	0						
2							
.....							
7							

❖ Analysis - Experiment 5.1

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

- (1) Speed (n_m) vs Load Torque (τ_{load})
- (2) Efficiency (η) 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 power to the load.

(B) Determine the speed regulation of the motor from no-load to rated load torque.

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

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

- C) The efficiency approaches a constant value as the power output increases. What is that value of efficiency.
- D) 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.

❖ Questions - Experiment 5.1

Associated with each experimental exercise are a number of questions designed to deepen understanding of the experiment and of the machine under study. Further, the questions are aimed at integrating the information gained in the experiment and generalizing on it.

The questions, which normally are given in this section of the experiment, are excluded for brevity.

V. 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] **VPLab**® 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 of the assigned experiment is presented.
- Students then perform an experiment similar to that demonstrated, 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 **VPLab**® 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. The **VPLab**® experiment on synchronous motors could be used to fill in this gap.

VI. SIMULATION

A critical feature of **VPLab**® 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 were to:

- faithfully model the steady-state 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 **VPLab**® these are attained in a WINDOWS environment using a PC with the following minimum features:

- operating system is Windows 95, Windows 98, Windows NT or Windows 2000.
- at least 32 mbytes of ram
- resolution of 1024 x 768, high color or better, large font

VII. CONCLUSION

VPLab[®] 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. **VPLab**[®] in its present form simulates a number of important machine types and device types.

Within the **VPLab**[®] shell the number of types can be increased readily. For example, the content of **VPLab**[®] could be increased to encompass both a laboratory course in electric machines and a laboratory course in power electronics.

VIII. REFERENCES

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IX. BIOGRAPHIES

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Saul Goldberg is a Professor of Electrical Engineering at California Polytechnic State University, San Luis Obispo, California. He received the Bachelor of Science Degree (Electrical Engineering) from Fairleigh Dickinson University and the Master of Engineering and Doctor of Philosophy (Engineering) from the University of Florida at Gainesville. His industrial experience includes assignments at Bendix-Eclipse Pioneer Division, Mount Sinai Hospital (Department of Radiology, Miami Beach, Florida), Southern California Edison Company and Pacific Gas and Electric Company. His university teaching spans 30 years, with three years as department chairman; he has taught courses in control systems, power systems, biomedical engineering and computer software and hardware.

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 laboratories in many engineering disciplines.

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William F. Horton is a Professor of Electrical Engineering at California Polytechnic State University, San Luis Obispo, California. He received the Bachelor of Science and Master of Science Degrees (Electrical Engineering) from the California Institute of Technology and the Doctor of Philosophy Degree (Engineering) from the University of California at Los Angeles. His industrial experience includes assignments at Westinghouse Electric Company, Lear-Siegler, Hughes Aircraft, Pacific Gas and Electric Company and San Diego Gas and Electric Company. He has been a professor of Electrical Engineering for 25 years and Associate Dean of the College of Engineering at California Polytechnic State University, San Luis Obispo for 5 years. His teaching specialties have included control systems, power systems, electromagnetics and random processes.

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