An Integrated Approach to the Design of Experiments

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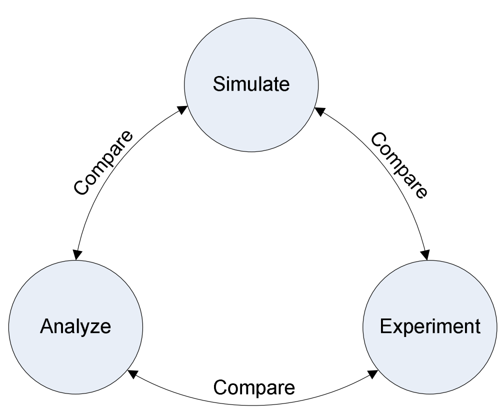
This paper defines a philosophy for the design of experiments which has been used to generate materials primarily intended for sophomore level engineering students in laboratory courses. It outlines integration of background course material, analytical work, computerized evaluation, and simulation which has been used successfully in our first electrical circuits laboratory.

Both the design and contents of our laboratory courses have been impacted by technical and societal changes. The complexity of both has increased dramatically and requires that we modify the design of our laboratory experiments. In order to provide a framework for this redesign we will outline the motivation and some of the objectives we hope to accomplish.

The beginning of a semester affords an opportunity to introduce students to software which is often new to them. This is the time when students are "treading water" while collecting components for their laboratory work. Part of the first laboratory hand out introduces both an analytical program and a simulation program. We often refer to this as "Lab Zero".

Rationale and Objectives

For many students this will be their first exposure to the lab. Through course work they have been taught circuit analysis but they have not had the opportunity to apply this new knowledge. Traditionally, laboratory courses have strengthened this knowledge by allowing hands-on application. This tradition is further strengthened by teaching simulation techniques to the students. This Analyze/Simulate/Experiment philosophy allows students better catch their mistakes as they are less likely to make the same mistake in all phases. The associations may be indicated as shown below.



The skills of the students are further strengthened by introducing the computer as a laboratory instrument. The use of software tools should be an integral part of the laboratory course, not an after the fact add-on. It should permeate the students' efforts and extend from the initial pre-laboratory work through the simulation, the data collection, analysis and the generation of the laboratory report.

In Lab Zero we introduce the use of MATHCAD to calculate nominal values, enter "measured" values, calculate percentage errors, and graph equations and "measured" values. The analytical and "experimental" works are corroborated by simulation. (The quotation marks indicate that the measured and experimental values are bogus and are intended for illustrative purposes only.) A copy of some of the introductory material is cited toward the end of this paper.

More complex laboratory equipment is introduced in both the simulation work and, when available, the laboratory itself. In some cases appropriate equipment is not available. For example although a Bode plotter is used in some of the later experiments, it is not available in the lab.

The experiments are designed such that the students must provide the underlying intelligence for the operation of the computer, rather than assuming that the computer provides intelligence. This encourages the students to use the software as a tool to analyze circuits rather than simply accepting the output of a computer as being "the answer".

Background information is included in the experiments which are assigned early in the semester to provide enough background to understand the experiment on a stand alone basis. Students who have already taken the lecture course associated with the laboratory may use this as a review or clarification of the concepts to which they have been exposed. Students who have not yet covered the topics involved may consider it to be an introduction to the concepts involved.

Each experiment begins with a pre-lab section in which the students are introduced to the appropriate instruments, analyze the circuit to find expected results and simulate the circuit to verify their work. Although this effort takes considerable time, the student is repaid by the fuller understanding of the material, the efficiency with which the experiment is performed, and the reduction of errors. Since theoretical, measured, and simulated values are developed and compared by the students coordination problems between the laboratory work and the associated course are reduced or eliminated.

Experiments are written using MATHCAD so that an instructor's key may be easily generated and modified automatically as they are written or updated. Both the student manual and instructor's manual are incorporated in the same file. In order to generate the component of the file intended for the student, this portion of the file may be selectively printed. Students may then utilize the same software to analyze circuits, log data, process it and write their reports.

The simulation work closely parallels the physical connections to be made during the experiment. Thus more thought is given to how the circuit will be constructed in the laboratory.

Since the laboratory reports are typically written in MATHCAD experiment data can be readily compared with analytical and simulation results. This allows students to be more efficient since the pre-lab analyses, the experimental data, the results and the documentation are all integrated in the students' files. This also allows the student to archive his or her work for future reference.

The skills developed using this approach may be transferred to other courses and other disciplines. Some students have used MATHCAD to do their homework for their mechanical engineering courses.

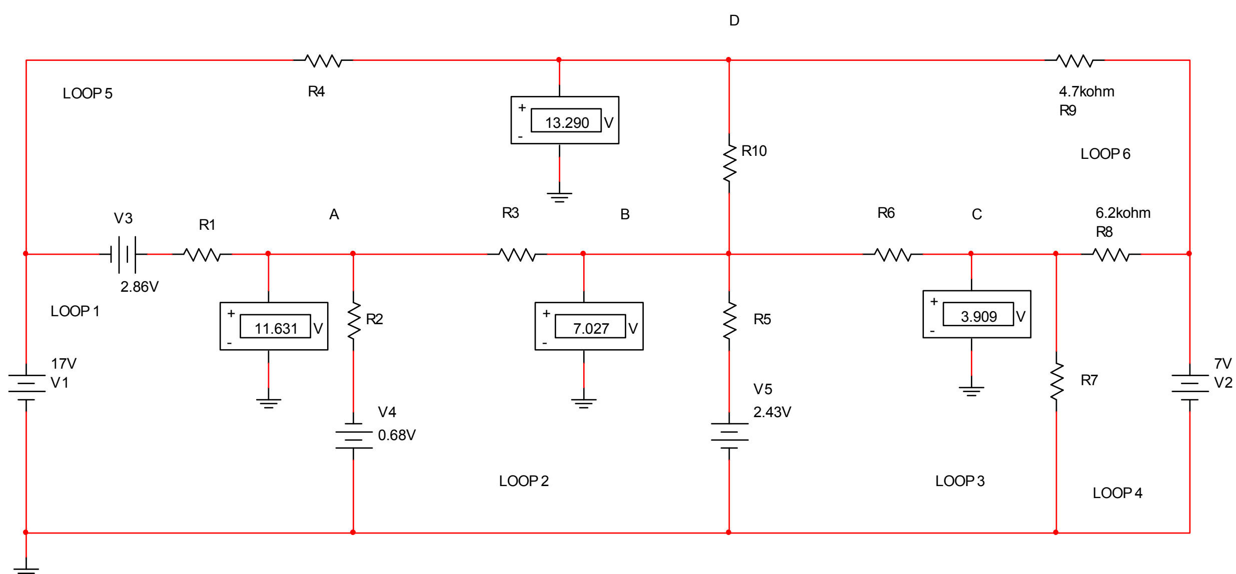
The lab manual is written in an informal style so that students find it easy to read and understand. It is intended to embody both conciseness and accuracy.

Structure of Laboratory Manual

The complete laboratory manual consists of a MATHCAD file that contains both the manual for the students and the instructor's manual and related MULTISIM files. The portion of the MATHCAD files intended for the student is written on the left page while comments intended solely for the instructor or grader are on the right. Since the program offers the option of printing only the left page (single page width) or the whole file, the student's manual may be selectively printed by printing only the left page. Should it be desired to distribute the manual in electronic form to students who have a suitable copy of the program, the left page may be "cloned" and copied to a separate file for their use. Changes made to the manual are carried through both the students' portion and the instructor's portion.

The MULTISIM files may also be provided for students who have a copy of this program, but these files are not dynamically linked to the MATHCAD files, so changes must be made manually.

Circuit diagrams. The circuits used in the experiments are written in MULTISIM as shown below:



When the circuit is to be a part of the instructor's manual the simulation is run and the meter readings are shown as in the above example. In the students' manual the simulation is not executed so that the meter readings indicate zero. Students must generate the circuit, analyze it, simulate it and compare their results. Elements are cited by their literal names so that their values may be changed in later versions of the manual.

Component values Component values for circuits may be generated automatically for the lab manual by a pseudo random selection process from sets of allowable values. As an example, resistors are selected from a table of standard resistor values. We used values for 5% tolerance resistors, 10, 12, 13, 16, 18, 20…91 Ohms. A facsimile of the MATCHCAD program which generates a set of resistor values is shown below. First we establish the seed value for the pseudo-random number generator. (This statement appears in the instructor's manual.)

SET SEED HERE
SEED IS IN TOOLS/WORKSHEET/OPTIONS; USED 03102.

GENERATE A SET OF NINE RESISTORS:

```
NRV:= 22                                      ; NUMBER OF R VALUES
RINDEX:= 1..NRV                               ; RANGE OF R INDEX
NRS:= 9                                       ; GENERATE 9 RESISTORS
RNO:= 1..NRS                                  ; NUMBER RESISTORS 1 TO NRS
RVALS:= floor(runif(NRS,1,22.999))            ; GENERATE RANDOM POINTER
PWR10_RNO:= -1                                ; POWER OF 10 SCALING FACTOR
R_RNO:= SRT_(RVALS_RNO) * PWR10_RNO           ; DEFINE RESISTOR VALUES
```

R_{RNO} =

1.3
5.6
3.9
1.6
2.2
3
7.5
1.2
4.7
1.2

Since the "Standard Resistor Table" was defined for the decade from 10 to 91 Ohms, the resistors in the experiment have each been scaled by 0.1 and are interpreted as kilo Ohms. (The scaling array allows each value to be scaled by its own power of ten so that wide ranges of resistances can be used if so desired.) The values that are thus obtained are more "reasonable" for electronics laboratory work.

A similar random selection process is used to generate inductor and capacitor values although the "standard values" are now defined to be those readily available in our laboratory. The range of allowable values may be restricted for experimental convenience. For example we may restrict an LC product so that the resonant frequency is within a desired range.

The component values generated automatically can be over-written by the instructor or grader if so desired. This may occur if the resulting values of elements are undesirable. As an example, a Thevinin equivalent voltage source turns out to be, say, 0.357 Volts. It is also possible to regard such an event as educational for the student in that nature seldom cares about our numerical preferences.

The component values may be overwritten by the instructor should the resulting values be unacceptable. They may also be overwritten to match the actual components a student or lab group actually used. This makes grading more efficient and less time consuming since the grader need only overwrite the component values using those the students used. This change is then carried through the subsequent calculations automatically.

Examples Elements from the lab manual are included in this section to illustrate the nature and concepts involved in this manual. They have been transferred from MATHCAD and MULTISIM documents which has led to some awkward formats.

Excerpt from Lab Zero - Introduction

INTRODUCTION

This manual is an attempt to integrate analysis, computer simulation and experimentation. In order that you get the benefits from this approach it will be necessary for you to do the pre-lab work (analysis and simulation) before the experimental phase is performed. Although this will "cost" you time before the lab, it will save you time after the experiment is performed because you will know what to do and what to expect (thus minimizing confusion and time consuming rework).

Enough background material is included in the early experiments so that they are (hopefully) independent of the course material and sequence. The background information also includes an association with concepts from Mechanical Engineering and Physics so that mechanical engineering majors can develop an understanding of electrical circuits by analogy and electrical engineering majors can develop a better understanding of mechanical systems.

LABORATORY ZERO

COMPUTER USE IS MANDATORY IN THIS LAB. THE SOONER YOU LEARN TO USE IT, THE MORE QUICKLY YOU WILL BE ABLE TO DO HOMEWORK AND LAB REPORTS --- IT SAVES YOU TIME, MINIMIZES ARITHMETIC ERRORS, AND MAKES YOUR REPORTS MORE LEGIBLE. DO THE MATHCAD TUTORIAL AND/OR TALK TO YOUR FRIENDS WHO HAVE HAD EXPERIENCE WITH MATHCAD. **USE EWB, CIRCUITMAKER, PSPICE OR SOME EQUIVALENT SPICE PROGRAM TO SIMULATE THE CIRCUITS AND VERIFY THE PERFORMANCE YOU EXPECT.**

USE NOMINAL VALUES FOR YOUR PRELIMINARY CALCULATIONS; USE ACTUAL MEASURED VALUES TO IMPROVE AGREEMENT BETWEEN THEORETICAL AND MEASURED PERFORMANCE.

EXAMPLE. Suppose you want to calculate the the current through R1 and the voltage across R2 in FIGURE SMI1

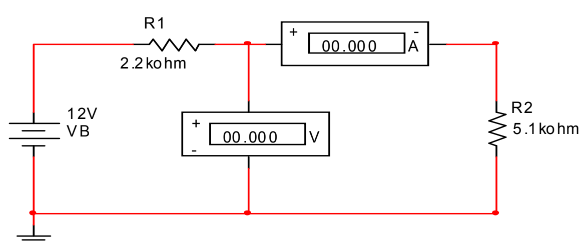


FIGURE SMI1 A SIMPLE CIRCUIT (NOMINAL VALUES)

Analysis shows that the current through R1 and the voltage across R2 will be

$IR1(R1,R2) := \frac{VB}{R1 + R2}$ $\qquad$ $VR2(R1,R2) := \frac{R2}{R1 + R2} \cdot VB$

VB was not included as an argument of these functions that we have defined because we have assumed that it will be set to 12 Volts as indicated in the diagram. (If we wanted to make the calculations for different values of VB we would have included it in the argument list.)

Next we define the nominal values for R1 and R2:

$R1N := 2.2\ k\Omega$ $\qquad$ $R2N := 5.1\ k\Omega$ **NOTICE THAT WE HAVE ADDED AN "N" TO INDICATE NOMINAL VALUES**

NOTICE THAT WE HAVE ADDED EXPLANATIONS OF NOTATION!

$IR1N := IR1(R1N, R2N)$ **NOTICE THAT THIS DOESN'T WORK. WHY? (BECAUSE WE DIDN'T DEFINE VB.)**

$VB := 12\ V$ **NOTE THAT WE INCLUDED UNITS**

$IR1(R1,R2) := \frac{VB}{R1 + R2}$ $\qquad$ $VR2(R1,R2) := \frac{R2}{R1 + R2} \cdot VB$

START CLONE (CITED LATER)

$IR1N := IR1(R1N, R2N)$ $\qquad$ $VR2N := VR2(R1N, R2N)$

$IR1N = 1.644\ mA$ $\qquad$ $VR2N = 8.384\ V$ **END CLONE**

The use of laboratory equipment Experiment 6 is used to illustrate how laboratory equipment functions and how it is used both in simulations and in the laboratory.

Experiment 6 Meet Your Lab Instruments

You have met only the DVM at this time, but there are many other instruments that are extremely useful in the laboratory. In this experiment you will become more familiar with both the virtual instruments in EWB and the physical instruments in the lab.

THE FUNCTION GENERATOR

The purpose of the function generator is to produce square waves, triangular waves or sine waves at a chosen frequency with a given amplitude and desired DC offset. Some of the differences between the EWB virtual function generator and the physical function generator are that

IN EWB

- Quantities are set "exactly" (to the limits of quantization error.) and don't drift.
- Outputs are available in "non-inverted" or "inverted" phasing. (Actually they are mutually out of phase, so which one is inverted?)
- The duty cycle - the fraction of the period that a pulse is high - is adjustable. (This capability is included in some of the more expensive function generators.)
- The rise and fall times may be set by the user within wide limits.
- The amplitude and DC offset are virtually infinite.
- The output impedance is zero. (That is the Thevinin equivalent source resistance you've grown to know and love.)

IN THE PHYSICAL FUNCTION GENERATOR

- Frequencies and amplitudes are approximate. (In particular someone may have gotten ambitious and twisted the frequency adjust knob too far so that the set screw slips and the calibration setting becomes more decorative than informative.)
- There is typically only one signal output (although there may be s sync output to feed an oscilloscope to start its sweep)
- The range of the output is limited. (This may clip the peaks of signals either at a positive level or at a negative level.)
- The DC offset range is much more limited, although this is seldom a problem.
- The output impedance is typically either 600 Ohms as is often used for audio work or 50 Ohms as is more typical for RF work. (The HP function generators have a 600 Ohm output and the Tektronix generators have a 50 Ohm output impedance.)

This is a discussion of the oscilloscope and its features. It is generic, not directed at any particular make or model, because there are many different types available in our labs.

BASIC FUNCTION The oscilloscope generates graphs of voltage as a function of time or, in less common usage a parametric representation of Y(X(t)) where Y is fed as a voltage to one input and X is fed as a voltage to another input. In this case the graph produced is Y as a function of X.

In its typical role the scope (Go ahead. Sound like a pro. Call it a "scope" rather than an "oscilloscope". It's shorter anyway.) It displays Y as a function of time. It is necessary to set the sweep speed (time interval per horizontal division), the vertical sensitivity (voltage per division) and the triggering mode and conditions. The Y scale and the time (X) scale are fairly obvious, but it may be less apparent what "triggering" is about.

SYNCHRONIZATION Although transient or "one shot" signals may be of interest at some times, we are usually interested in periodic signals...ones that repeat every T seconds where T is the period. If the beam were to sweep across the screen, return to the left side and repeat without regard to the input signal, the input signal would not be at any predictable starting point. The signal would be smeared across the screen and you would see, in general, just a band of green or sporadic traces that wouldn't hold still. In order to hold the trace stable it is necessary for the sweep starting point to be initiated at the same point in the cycle.

The process of establishing a particular point on the input waveform at which the sweep is initiated is called synchronizing the scope. This may be done for particular conditions such as
- when the input signal reaches a particular level with a particular slope on a channel
- when a signal on another input occurs (external sync) (Many generators have a "sync output" to make the sweep start at a particular time.)

Use of external sync When there are other signals or noise present, the conditions (voltage level and slope) to initiate a sweep may occur at different times on the desired signal. The starting time of the sweep will wander and the signal will jitter. External sync allows us to feed a "clean" strong signal to start the trace at the right time.

ADDING WAVEFORMS Scopes often afford the opportunity to add or subtract waveforms, A + B. Alternately channel B may be subtracted from A by INVerting channel B before adding it.

CHOPPED MODE Another way to present two traces on the screen "simultaneously" is for the beam to trace a small portion of the trace for channel A, then switch and to a small portion of channel B, then back to A and so forth. Although you might expect the traces to look like dashed lines this is not, in general, what you will observe. Because the chopping frequency is set by the scope without regard to the frequency of the signal there is no fixed time of occurrence of the chopping. The dashed lines therefore "slide" along the waveform rapidly and the phosphor on the screen retains its glow for some time after the beam has left it, so you usually won't see any flicker. (You may be able to see the evidence of the chopping process by observing a sine wave on two channels, offsetting them vertically, and SLOWLY changing the frequency of the signal. When the chopping frequency is some multiple of the input frequency the dashes will slow down and "kind of" stand still. (This will probably be more observable for higher signal frequencies.))

CURSORS Modern (= more expensive!) scopes provide cursors... lines either vertical for measuring times or horizontal for measuring amplitudes. This feature is available in EWB and may be available in the lab if you get the right scope. Since cursors in a simulation are simply software so cursors are provided in EWB.

COUPLING A trace may include the DC (average value) of the signal by selecting DC COUPLED for that trace OR the DC component may be blocked by a coupling capacitor so that only the AC component is observed. This is handy when a small signal of interest has been added to a relatively large DC voltage. (A small signal "riding on top of" a large DC level may not be visible because a scale large enough to show the large DC level may be too large for the small signal to be seen

INPUT IMPEDANCE

- Direct probe. A "direct" probe is basically a wire in a thin coaxial cable. When this is used to measure signals, it presents an impedance of 1 MW to DC. (Actually there is also a small capacitance, typically about 20 pF in parallel with the 1 MOhm equivalent resistance but you needn't worry about that in this lab.) This is also called a 1X (one times) probe.

- Attenuator probe. Sometimes a 1 MOhm load is too heavy for the measurement you wish to make... it changes the signal too much. An attenuator probe "looks like" a 9 MW resistor (and a small capacitor in parallel that you need not be concerned with at this time) and forms a voltage divider that attenuates the signal by a factor of 10. So it is called a "10X" or ten times probe. The vertical sensitivity of the scope is reduced by a factor of ten.

GROUNDING

- Since voltages must be measured between two points there must be a reference or ground for the scope. For safety purposes the case of the scope is "ground" and YOU ARE NOT AT LIBERTY TO PUT THE SCOPE GROUND CONNECTION AT SOME OTHER LEVEL. It would not do to have the case of the scope floating at 20 KV to make measurements of the ripple of a high voltage supply! Since there is only ONE case, you need connect only ONE lead to the reference (ground) of your circuit... not one per channel!

- EWB Ground. The scope in EWB is ASSUMED grounded, so you need not "connect" a ground lead to it in your simulations if you are measuring a node voltage with respect to ground.

Example of experiment in the lab manual (partial)

Experiment 8 (partial)

As an example of an experiment employing the stated philosophy we outline an experiment that examines the performance of an RL circuit. Since students may not have had exposure to phasors, the analysis for steady state behavior is done without resorting to this convenience. (Phasors are introduced in later experiments.) Pre-lab questions are designated PL while those associated with the experimental portion of the lab are labeled with an L. Normally the answers for the pre-lab questions would be given on a page immediately to the right of the document and labeled APL, i.e. the answer to question PL N is APL N. The circuits are drawn in MULTISIM which is then used also to obtain simulation results.

Experiments 8. RL Circuits, Sinusoidal Excitation (Steady State)

All the voltages and currents (in steady state) in a linear time invariant circuit excited by a sinusoidal source must be sinusoidal and have the same frequency as the source . Only the magnitude and phase may be changed. Consider the RL circuit shown in Figure 1.

SUMMING THE VOLTAGE RISES AROUND THE LOOP WE HAVE

$$VP\cdot\cos(\omega 0\cdot t) - i(t)\cdot R - L\cdot\left(\frac{d}{dt}i(t)\right) = 0 \quad \text{(SUM OF LOOP VOLTAGES)}$$

ASSUMING THAT THE FORM OF i(t) IS $i(t) := IP\cdot\cos(\omega 0\cdot t + \Phi)$ THEN $\frac{d}{dt}i(t) :=$

$$\frac{d}{dt}(IP\cdot\cos(\omega 0\cdot t + \Phi)) \to -IP\cdot\sin(\omega 0\cdot t + \Phi)\cdot\omega 0 \quad = \quad -IP\cdot\omega 0\cdot\sin(\omega 0\cdot t)\cdot\cos(\Phi) - IP\cdot\omega 0\cdot\cos(\omega 0\cdot t)\cdot\sin(\Phi)$$

SO THAT THE EQUATION FITS ON ONE LINE LET C = cos(ω0*t) AND S = sin(ω0*t)

$$VP\cdot C - R\cdot IP\cdot C\cdot\cos(\Phi) + R\cdot IP\cdot S\cdot\sin(\Phi) + L\cdot IP\cdot\omega 0\cdot S\cdot\cos(\Phi) + L\cdot IP\cdot\omega 0\cdot C\cdot\sin(\Phi) = 0$$

$VP - R\cdot IP\cdot\cos(\Phi) + L\cdot IP\cdot\omega 0\cdot\sin(\Phi)$ coefs of cos(ω0*t)

BOTH COEFS MUST BE 0.
IP CAN NOT BE ZERO, SO DIVIDE sin(ω0*t) COEFS BY IP.

$R\cdot IP\cdot\sin(\Phi) + L\cdot IP\cdot\omega 0\cdot\cos(\Phi)$ coefs of sin(ω0*t)

$R\cdot\sin(\Phi) + L\cdot\omega 0\cdot\cos(\Phi)$ coefs of sin(ω0*t) / IP FROM COEFS OF sin(ω0*t)

WE CAN GET THE PHASE FROM THE EQUATION ABOVE:

THE PHASE OF THE CURRENT WITH RESPECT TO THE SOURCE IS

$$\Phi(\omega 0, R, L) := \operatorname{atan}\left(\frac{-L\cdot\omega 0}{R}\right) \quad \text{PHASE (RADIANS) OR} \quad \Phi D(\omega 0, R, L) := \operatorname{atan}\left(\frac{-L\cdot\omega 0}{R}\right)\cdot\frac{180}{\pi} \quad \text{(DEG)}$$

NOW WE NEED THE MAGNITUDE, IP, WHICH WILL "COME FROM" THE COEFFICIENTS OF cos(ω0*t). FIRST SOME HANDY TRIG IDENTITIES:

$\tan(\Phi) := \frac{-L\cdot\omega 0}{R}$ IF TAN(Φ)=Y / X THEN SIN(Φ)=Y/(X^2 +Y^2)$^{1/2}$ AND COS(Φ) = X/(X^2 +Y^2)$^{1/2}$

WITH Y = $-L\cdot\omega 0$ AND X = R $\quad \sin(\Phi) := \frac{-L\cdot\omega 0}{\left[R^2 + (L\cdot\omega 0)^2\right]^{0.5}} \quad \cos(\Phi) := \frac{R}{\left[R^2 + (L\cdot\omega 0)^2\right]^{0.5}}$

1

USING THESE IN

$$VP - R\cdot IP\cdot\cos(\Phi) + L\cdot IP\cdot\omega0\cdot\sin(\Phi) = 0 \qquad \text{(coefs of cos(}\omega0\text{*t))}$$

WE HAVE

$$VP - R\cdot IP\cdot\frac{R}{\left[R^2 + (L\cdot\omega0)^2\right]^{0.5}} + L\cdot IP\cdot\omega0\cdot\frac{-L\cdot\omega0}{\left[R^2 + (L\cdot\omega0)^2\right]^{0.5}} = 0$$

WHICH WE SOLVE FOR IP

<u>MAGNITUDE OF IP</u>

$$IP(VP,\omega0,R,L) := \frac{VP}{\left(R^2 + L^2\cdot\omega0^2\right)^{\frac{1}{2}}}$$

SO THAT THE CURRENT IS

$$i(t,VP,\omega0,R,L) := \frac{VP}{\left(R^2 + L^2\cdot\omega0^2\right)^{\frac{1}{2}}}\cdot\cos\left[(\omega0)\cdot t + \operatorname{atan}\left(\frac{-L\cdot\omega0}{R}\right)\right]$$

AND THE VOLTAGE VR IS

$$VR(t,VP,\omega0,R,L) := \frac{VP\cdot R}{\left(R^2 + L^2\cdot\omega0^2\right)^{\frac{1}{2}}}\cdot\cos\left[(\omega0)\cdot t + \operatorname{atan}\left(\frac{-L\cdot\omega0}{R}\right)\right]$$

AND VL IS

$$VL(t,VP,\omega0,R,L) := \frac{-\omega0\cdot L\cdot VP}{\left(R^2 + L^2\cdot\omega0^2\right)^{\frac{1}{2}}}\cdot\sin\left(\omega0\cdot t + \operatorname{atan}\left(-L\cdot\frac{\omega0}{R}\right)\right)$$

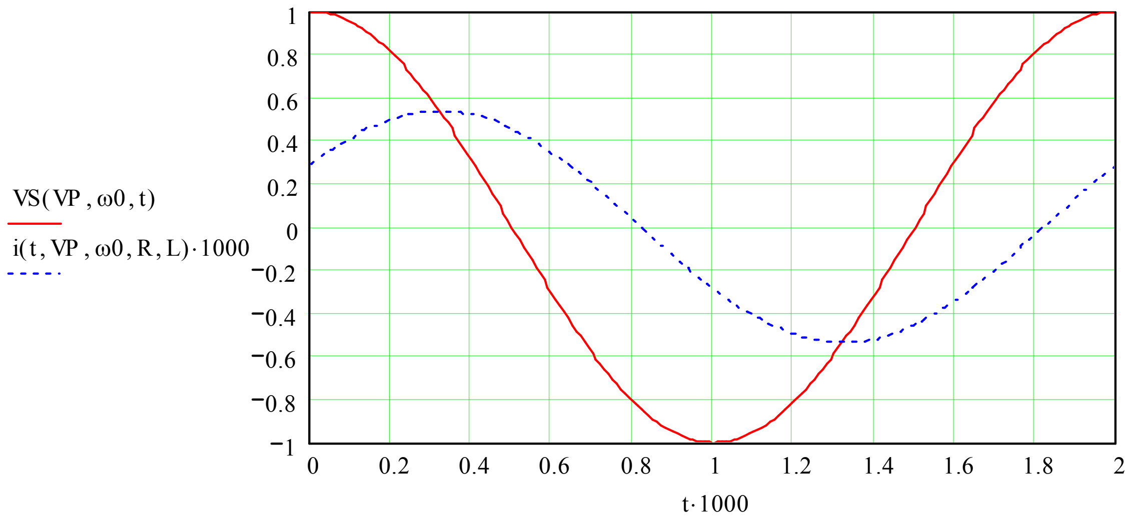
2

AS AN EXAMPLE, GRAPH THE SOURCE VOLTAGE FOR ONE CYCLE AND i(t), VR(t), VL(t):

FOR f0=500 Hz 1 kΩ H V

$t := 0, 10^{-5} \ldots .002 \quad f0 := 500 \quad \omega 0 := 2 \cdot \pi \cdot f0 \quad R := 1000 \quad L := 0.5 \quad VP := 1 \quad VS(VP, \omega 0, t) := VP \cdot \cos(\omega 0 \cdot t)$

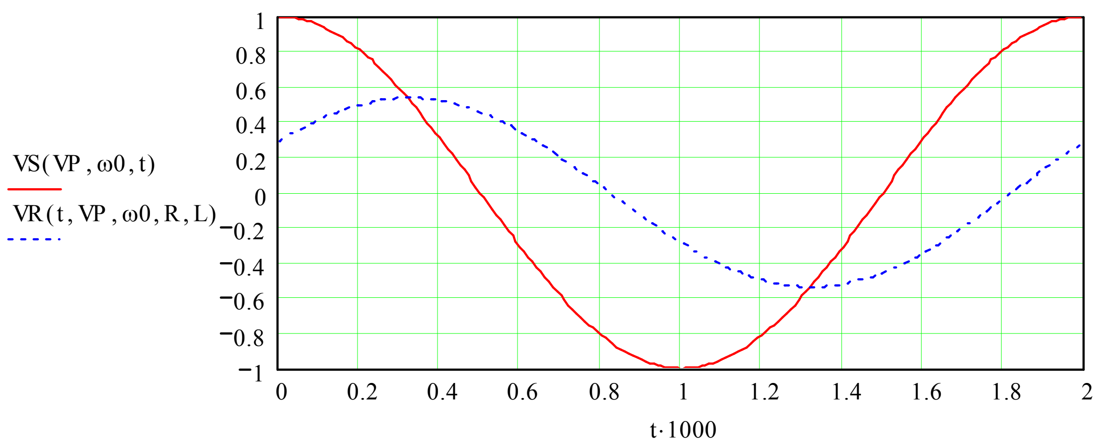
LF1. SOURCE VOLTAGE (V) AND CURRENT (mA) AS A FUNCTION OF TIME (ms), RL CIRCUIT



PL1 DOES THE CURRENT LEAD OR LAG THE APPLIED VOLTAGE IN AN RL CIRCUIT?

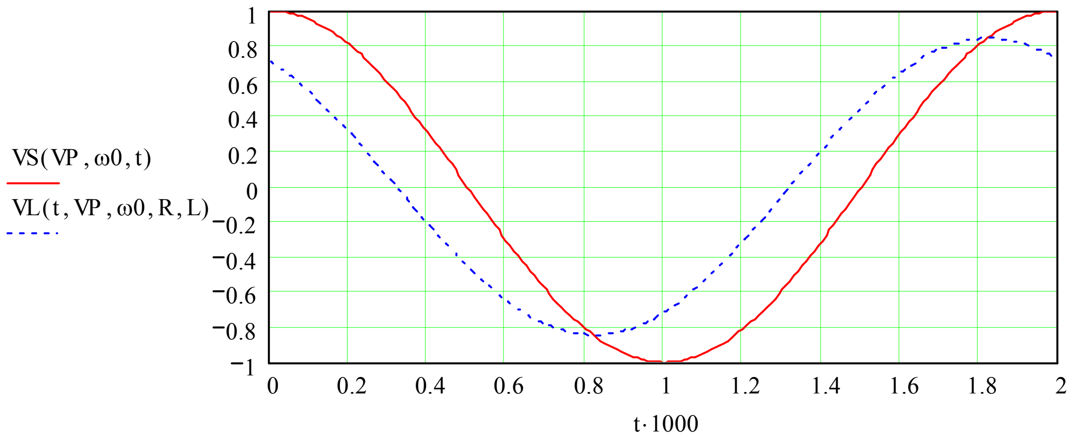
PL2 WHAT IS THE PHASE OF i WITH RESPECT TO VS? (IN DEGREES)

LF2 SOURCE VOLTAGE (V) AND VR (V) AS A FUNCTION OF TIME (ms), FOR RL CIRCUIT



PL3 WHAT IS THE PHASE SHIFT OF VR WITH RESPECT TO VS?
PL4 HOW DOES IT COMPARE WITH THE PHASE SHIFT OF i WITH RESPECT TO VS? 3

LF3 SOURCE VOLTAGE (V) AND VL (V) AS A FUNCTION OF TIME (ms), FOR RL CIRCUIT



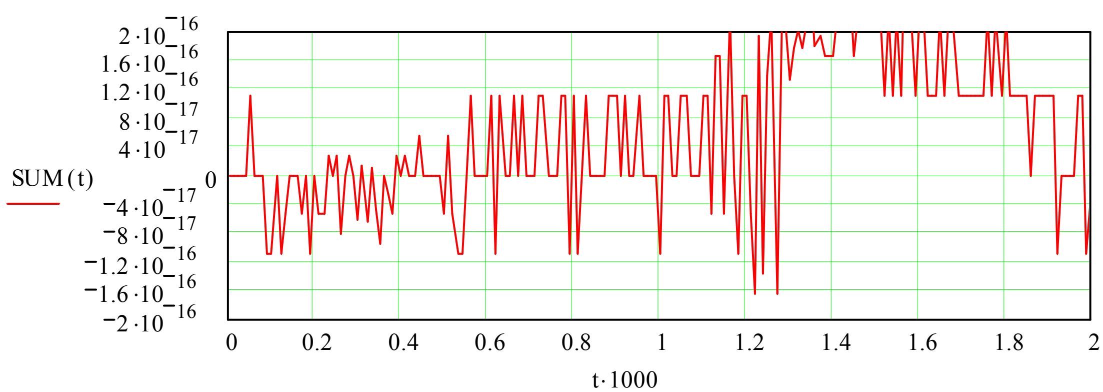
PL5 DOES THE INDUCTOR VOLTAGE LEAD OR LAG THE APPLIED VOLTAGE IN AN RL CIRCUIT?

PL6 WHAT IS THE PHASE OF VL WITH RESPECT TO VS? (IN DEGREES)

THE SUM OF THE VOLTAGES VR + VL SHOULD BE THE SOURCE VOLTAGE AND SHOULD BE 0 IF OUR ANALYSIS IS CORRECT. LET'S GRAPH THIS SUM

$$SUM(t) := VS(VP, \omega 0, t) - VR(t, VP, \omega 0, R, L) - VL(t, VP, \omega 0, R, L)$$

LF4 SUM OF LOOP VOLTAGES (V) AS A FUNCTION OF TIME (ms)



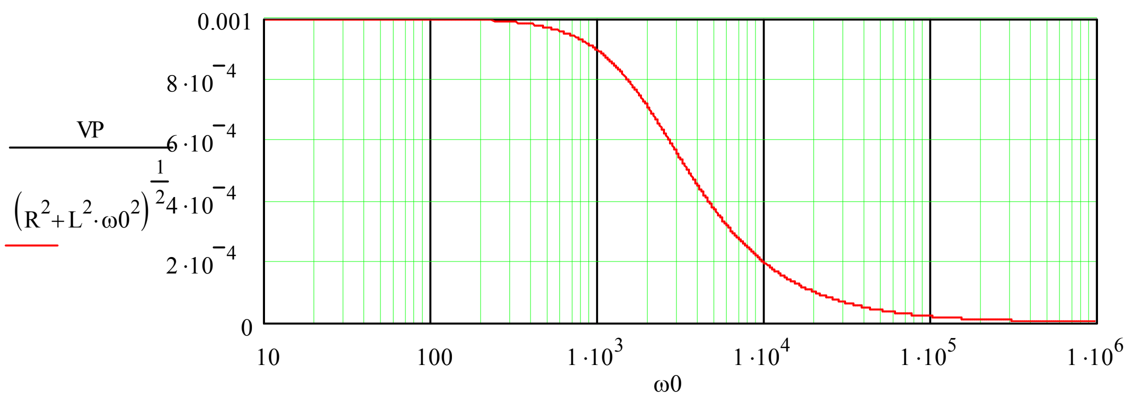
PL7 IS THE SUM OF THE LOOP VOLTAGES A MATHEMATICAL ZERO? AN ENGINEERING ZERO?

NOW LET'S GRAPH THE PEAK MAGNITUDE AND PHASE OF i, VR, AND VL AS A FUNCTION OF FREQUENCY (**NOT TIME!**)

SET A RANGE OF FREQUENCIES (IN RADIANS/s) $\omega 0 := 10, 20 .. 1000000$

SINCE THIS IS A RANGE OF FIVE ORDERS OF MAGNITUDE, WE'LL USE A LOG SCALE FOR ω.

LF5 MAGNITUDE OF i (mA)

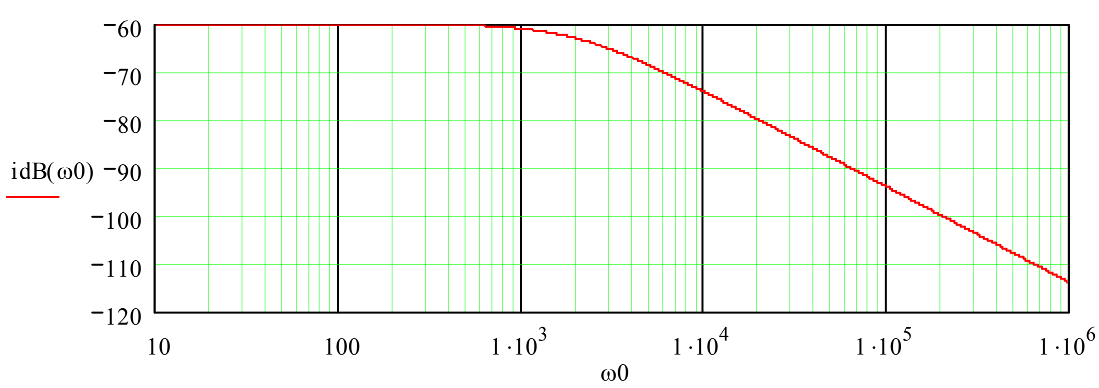


HMM. THE AMPLITUDE CHANGES BY ORDERS OF MAGNITUDE ALSO. LET'S USE A FORM OF A LOG SCALE ON THE AMPLITUDE. DEFINE idB (FOR DECIBEL) FUNCTION:

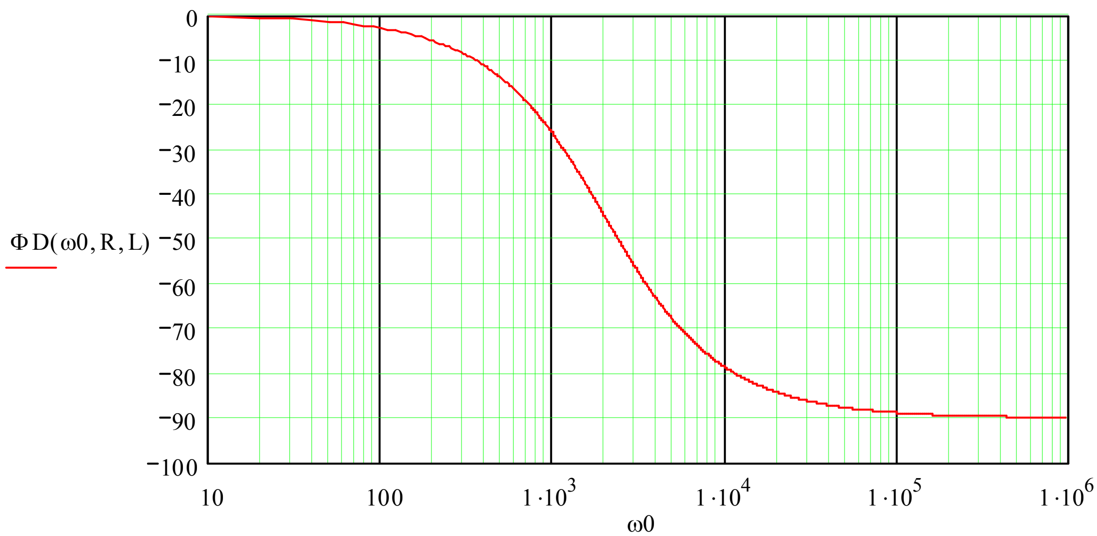
$$idB(\omega 0) := 20 \cdot \log\left[\frac{VP}{\left(R^2 + L^2 \cdot \omega 0^2\right)^{\frac{1}{2}}}\right]$$

OR, IN GENERAL $dB(X) := 20 \cdot \log(|X|)$

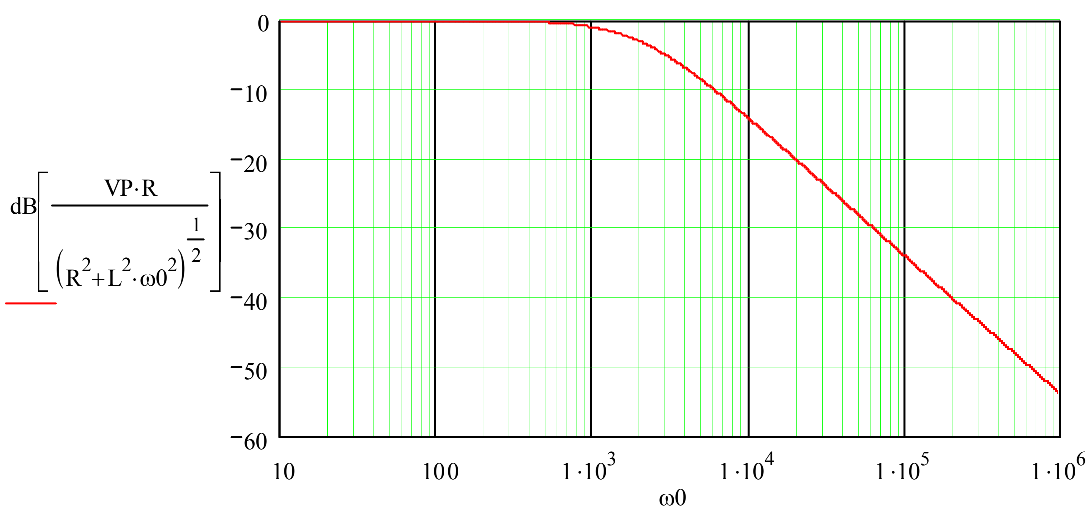
LF6 MAGNITUDE OF i (IN dB)



LF7 PHASE OF i (IN DEGREES)



LF8 MAGNITUDE OF VR (V, IN dB)



THE PHASE OF VR IS THE SAME AS THE PHASE OF i...THE VOLTAGE AND CURRENT ARE IN PHASE FOR A RESISTOR.

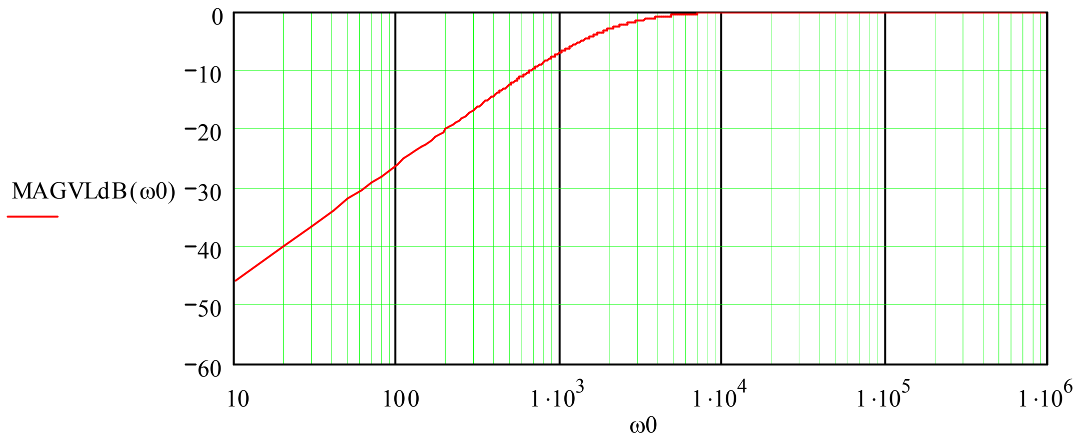
NOW WE'LL DO VL.

$$VL(t, VP, \omega0, R, L) := \frac{-\omega0 \cdot L \cdot VP}{\left(R^2 + L^2 \cdot \omega0^2\right)^{\frac{1}{2}}} \cdot \sin\left(\omega0 \cdot t - \operatorname{atan}\left(L \cdot \frac{\omega0}{R}\right)\right)$$

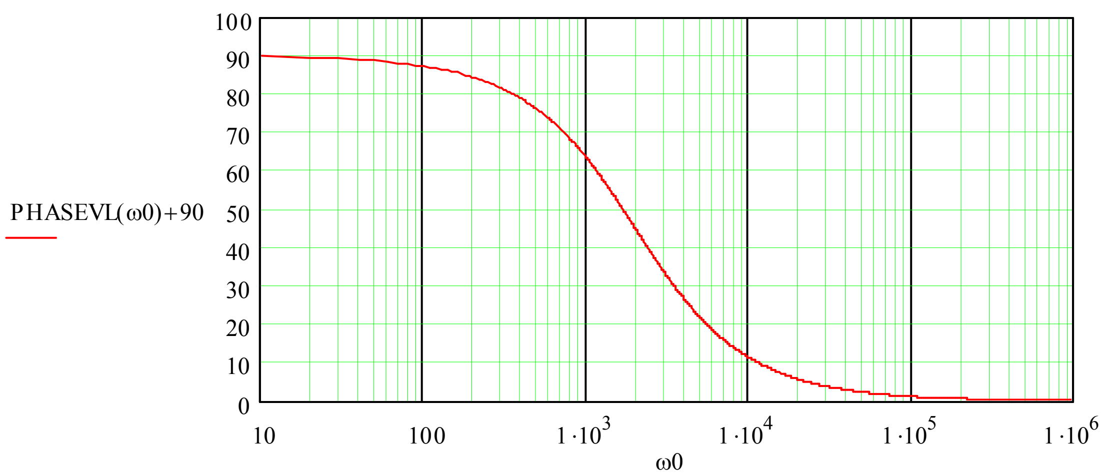
$$MAGVLdB(\omega0) := dB\left[\frac{-\omega0 \cdot L \cdot VP}{\left(R^2 + L^2 \cdot \omega0^2\right)^{\frac{1}{2}}}\right]$$

$$PHASEVL(\omega0) := \operatorname{atan}\left(-L \cdot \frac{\omega0}{R}\right) DEG$$

LF9 MAGNITUDE OF VL (V, IN dB)



LF10 PHASE OF VL (DEG)



7

PL8 AT WHAT FREQUENCY (IN RADIANS/s) IS THE PHASE SHIFT OF THE CURRENT WITH RESPECT TO THE SOURCE VOLTAGE - 45 DEGREES? (PLEASE REFER TO FIGURE LF7.)

FOR OUR EXAMPLE THE ELEMENT VALUES ARE $R = 1000$ Ω $L = 0.5$ H

IF YOU WERE BACK DOING A FIRST ORDER STEP RESPONSE EXPERIMENT YOU WOULD BE INTERESTED IN THE TIME CONSTANT OF THE CIRCUIT.

PL9 WHAT IS TC, THE TIME CONSTANT OF THE CIRCUIT?

WE KNOW THAT FREQUENCY IS DIMENSIONALLY THE RECIPROCAL OF TIME.

PL10 WHAT FREQUENCY IS 1/TC? _________ R/s

PL11 DO YOU SEE ANY SUBTLE RELATIONSHIP BETWEEN THE TIME CONSTANT OF THE CIRCUIT AND THE FREQUENCY AT WHICH THE PHASE SHIFT OF THE CURRENT IS -45 DEGREES (FOR A SINE WAVE)?

PL12 WHAT IS THE AMPLITUDE OF VL AT THIS FREQUENCY (IN dB)?

LET'S CALL THIS FREQUENCY $\omega 3$. THIS IS OFTEN A FREQUENCY AT WHICH "THINGS BEGIN TO HAPPEN" SO WE WILL TAKE DATA "AROUND" THIS POINT, SAY FOR A FACTOR OF 10 HIGHER (OR SO) OR A FACTOR OF 10 LOWER (OR SO). IF WE WANT THE DATA POINTS TO BE EVENLY SPACED ON THE FREQUENCY AXIS WE HAVE TO REMEMBER THAT THIS IS A LOG SCALE. POINTS WHICH ARE EVENLY SPACED ON A LOG SCALE FORM A GEOMETRIC SERIES. IF WE WANT FIVE POINTS PER DECADE, THE RATIO OF THE ADJACENT FREQUENCIES MUST BE

$RAT := 10^{\frac{1}{5}}$ TO COVER TWO ORDERS OF MAGNITUDE WE WILL HAVE 11 POINTS. (INCLUDING THE END POINTS)

$PTNO := 1..11$

THE STARTING FREQUENCY WILL BE $\omega LO := \frac{\omega 3}{10}$

AND THE MEASUREMENT FREQUENCIES WILL BE $\omega_{PTNO} := \omega LO \cdot RAT^{PTNO-1}$

PL13 WHAT IS THE RATIO OF THE GEOMETRIC SERIES (NUMERICALLY)? WHAT ARE THE FREQUENCIES AT WHICH WE WILL MAKE MEASUREMENTS?

NOW WE QUICKLY DASH TO THE LAB AND TAKE DATA AT THESE FREQUENCIES.

GEE. THAT DIDN'T TAKE LONG. WE EVEN CONVERTED IT TO dB FORM AND GRAPHED IT

8

Since no reader is actually taking this laboratory course for credit, we truncate this example at this point, deleting about six pages of the write up of the experiment.

Answer key. The answer key for the experiment is in the instructor's manual on pages immediately to the right. Page numbers are indicated using RPN to indicate Right Page N. RPN is the companion page to the right of LPN. Many of the right pages are empty because the corresponding left pages require no response. Sometimes the right hand pages are used as a scratch pad. The answer key is updated automatically whenever the parameters are changed in the students' manual.

$$\frac{VP}{\left(R^2+L^2\cdot\omega 0^2\right)^{\frac{1}{2}}}\cdot\cos\left[(\omega 0)\cdot t+\operatorname{atan}\left(\frac{-L\cdot\omega 0}{R}\right)\right]$$

$$\frac{-\omega 0\cdot L\cdot VP}{\left(R^2+L^2\cdot\omega 0^2\right)^{\frac{1}{2}}}\cdot\sin\left(\omega 0\cdot t-\operatorname{atan}\left(L\cdot\frac{\omega 0}{R}\right)\right)\cdot\omega 0$$

2

$T := \frac{1}{f0}$ $T = 0.002$ $DEG := \frac{180}{\pi}$ $R = 1000$ $L = 0.5$

PHASE SHIFT FROM GRAPHS

$TVS0 := .0004$ Given $VS(VP, \omega 0, TVS0) = 0$ $TVS0 := Find(TVS0)$

$TVS0 = 0.0005$

$TI0 := .0008$ Given $i(TI0, VP, \omega 0, R, L) = 0$ $TI0 := Find(TI0)$

$TI0 = 0.00082$

$\Delta T := TVS0 - TI0$ $\Delta T = -0.00032$ (LAGGING) **APL1**

PHASE SHIFT FOR i(t) $\Phi i := \frac{\Delta T}{T}\cdot 360$ $\Phi i = -57.518365 DEG$

CHECK:

$\operatorname{atan}\left(\frac{-L\cdot\omega 0}{R}\right)\cdot DEG = -57.518363$ OK LAG **APL2**

APL3, 4 VR IS IN PHASE WITH i(t), SAME PHASE SHIFT

3

$TVL0 := 0.0002$ Given $VL(TVL0, VP, \omega 0, R, L) = 0$

$TVL0 := Find(TVL0)$

$TVL0 = 0.00032$

APL5, 6 LEADS $\frac{0.5 - 0.31}{2} \cdot 360 = 34.2$

$atan\left(\frac{-L \cdot \omega 0}{R}\right) \cdot DEG + 90 = 32.481637$

CHECK

APL7 NO. YES.

4

APL8 $PHASEVL(2000) = -45$ i. e. **AT 2000 R/s**

APL9 $TC := \frac{L}{R}$ $TC = 0.0005$

APL10 $\frac{1}{TC} = 2000$

APL11 DUH!

APL12 $MAGVLdB(2000) = -3.0103$

$\omega 3 := 2000$

APL13 $RAT = 1.584893$

$\omega =$

	1
1	200
2	316.978638
3	502.377286
4	796.214341
5	1261.914689
6	2000
7	3169.786385
8	5023.772863
9	7962.143411
10	12619.14689
11	20000

$e := 2$ MAX

ERROR: 2 dB
UNIFORM RV

$E := runif(11, -e, e)$

"DATA"

$DATA := \overrightarrow{MAGVLdB(\omega) + E}$

8

END OF ANSWER KEY EXAMPLE

Conclusions As of this date the lab manual generated using this philosophy has been used twice. It seems to have been well received by the students and I feel that they have learned more about basic topics in electrical engineering and have developed much more skill in using software useful to them in future work.

The course continues to evolve and more experiments will be added. The approach cited will be extended to other laboratory courses.

Acknowledgements

I would like to thank Professor Nash Younis for encouraging me to document our efforts in developing this lab manual and for the support of Dean Gerard Vorland. Much of the work done to develop the approach cited in this paper was done during a sabbatical leave which was supported by the University and Academic Vice Chancellor Susan Hannah. I would also like to thank my co-author Bill Westrick for his contributions to the success of this manual and his excellent help in formatting this paper.