
Study of Electrical Power Systems Using LabVIEW Virtual Instruments (VI) Modules

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Abstract

The study of electrical power systems requires a good background on advanced mathematics. But many engineering and technology students lack this required background, and as a result, it is difficult to teach electrical power systems in these programs. A problem for electric power system students is the solution of problems in textbooks through the use of routine problem-solving techniques, such as equations and formulae. But the students' reliance on formulae and routine use of techniques in problem solving too often leads to poor performance in real-world scenarios. Also, the students' lack of comprehension of mathematical concepts results in wasted time during laboratory experiments, misinterpretations of lab data, and underachievement in standardized science and engineering tests that stress the fundamentals. This problem can be effectively addressed by improving the student's conceptual understanding and comprehension of the topics through interactive learning and teaching with a virtual instruments (VI) software package, such as LabVIEW.

This paper will discuss design and development of interactive instructional virtual instrument (VI) modules for studying (a) basic single phase circuits, (b) basic three phase circuits (Star/Delta Connections, Star/Delta Transformations and Voltage Relationships), (c) modeling of transmission lines, (d) node equations and Ybus, and (e) simple economic dispatch problems.

Introduction

The engineering, science, and technology field, at present, is very dynamic due to recent advances in computer and other technologies. These advances have resulted in numerous computer programs to solve traditional and novel problems. These programs use the computer's increased computational capabilities and assist in the design, development, and control of complex systems in a matter of minutes. Automation is becoming a part and parcel of every industry, and industries need a trained workforce to manage this new development.

As a result, engineering, technology, and science programs are under pressure to incorporate the use of computers into their curriculum so their graduates can be well-trained in the use and application of these changing technologies and serve the needs of the industrial community. This is especially true for the electric power industry. Because of the recent advances in computers and other technologies, the complexity in all areas of the electrical power industry (generation, transmission, distribution, control, protection, reliability, economics, etc.) has increased, and the graduates of engineering and technology must be well-trained to address the needs of the industry. To address this need, most of the engineering programs and some of the engineering technology programs have introduced courses, programs, and laboratories in power systems to provide the graduates with the theoretical and practical knowledge, as well as experience. The study of electrical power systems requires a good background on advanced mathematics, and since most of the engineering technology programs do not require advanced mathematics, it is difficult to teach electrical power systems in these programs.

To address this issue, many software programs are currently used in academia to design and analyze different systems. Some of these programs are text driven, where the students have to write lines of code to analyze and design systems. Sometimes, these are not user-friendly and take a longer time. With the advent of object-oriented programming, we have now programs that are interactive and user-friendly. Students do not have to write code, and the system design and analysis is achieved from the schematics of the system. Some examples of such programs are PSPICE from MicroSym Corporation and MatLab from MathWorks. Using such computer programs allows students to spend less time writing the code to solve a problem and spend more time understanding the concepts. Approximately 10 to 15 years ago, National Instruments Corporation introduced a new program called LabVIEW. The acronym stands for Laboratory Virtual Instrumentation Engineering Work Bench. Originally designed for test and measurement applications, the program has been modified over the years to design and analyze various complex systems. LabVIEW is a graphical programming environment and is based on the concept of data flow programming. The data flow programming concept is different from the sequential nature of traditional programming languages, and it cuts down on the design and development time of an application. It is widely accepted by industry, academia, and research laboratories around the world as a standard for data acquisition and instrument control software [1]. Since LabVIEW is based on graphical programming, users can build instrumentation called virtual instruments (VIs) using software objects. With proper hardware, these VIs can be used for remote data acquisition, analysis, design, and distributed control. The built-in library of LabVIEW has a number of VIs that can be used to design and develop any system. LabVIEW can be used to address the needs of various courses in a technology and science curriculum [2, 3, 4, 5, 10, 11]. The objective of this paper is to discuss the application of built-in VIs in LabVIEW to develop VI modules for use in an introductory electrical power systems course.

LabVIEW Application Areas

LabVIEW is extremely flexible and some of the application areas of LabVIEW [5] are Simulation, Data Acquisition, and Data Processing. The Data Processing library includes signal generation, digital signal processing (DSP), measurement, filters, windows, curve fitting, probability and statistics, linear algebra, numerical methods, instrument control, program development, control systems, and fuzzy logic. These features of LabVIEW will help provide an interdisciplinary, integrated teaching and learning experience that integrates team-oriented, hands-on learning experiences throughout the engineering technology and sciences curriculum, engaging students in the design and analysis process beginning with their first year.

LabVIEW can command DAQ boards to read analog input signals (A/D conversion), generate analog output signals (D/A conversion), read and write digital signals, and manipulate the on-board counters for frequency measurement, pulse generation, etc. The voltage data goes into the plug-in DAQ board in the computer, which sends data into computer memory for storage, processing, or other manipulation.

Basic Single Phase VI Module [6]

The study of electric power systems requires a good understanding of single phase and three phase circuits, and courses in electric circuits and electric machines are usually the prerequisite courses, among others, for the introductory power systems course. Almost every introductory electric power systems text provides a brief overview of electric circuits, and the instructors spend one to two weeks of their lecture time reviewing electric circuits. Depending upon the student demographics, the instructor may spend more time discussing these topics. Use of programs to display waveforms of voltage, current, and power are common in the study of electric power systems because their use enhances the instruction process and student comprehension. The VI modules presented below are developed to assist faculty and students in this process and are used in the Circuits and Power Systems course at South Carolina State University (SCSU) by this author.

Power in Single-Phase AC Circuits [6]

The equations used in this VI are the following:

$$v(t) = V_m \cos(\omega t + \theta_v) \quad (1)$$

$$i(t) = I_m \cos(\omega t + \theta_i) \quad (2)$$

$$p(t) = v(t) \times i(t) \quad (3)$$

In the previous equation, $v(t)$ = instantaneous voltage, V_m = maximum value of the voltage, θ_v = angle of voltage in degrees, $i(t)$ = instantaneous current, I_m = maximum value of the current, θ_i = angle of current in degrees, and $p(t)$ = instantaneous power.

Equation (3) can be further simplified to the following:

$$p(t) = |V||I| \cos \theta [1 + \cos 2(\omega t + \theta_v)] + |V||I| \sin \theta \sin 2(\omega t + \theta_v) \quad (4)$$

$$p(t) = p_R(t) + p_x(t) \quad (5)$$

In the previous equation, $p_R(t)$ = energy flow into the circuit, $p_x(t)$ = energy borrowed and returned by the circuit, $|V|$ = RMS value of voltage, and $|I|$ = RMS value of current.

The other equations that are used in this VI are equations to calculate the RMS values of voltage and current, the maximum value of current from voltage and impedance information, and the real power (P), reactive power (Q), and total power (S).

$$|V| = \frac{V_m}{\sqrt{2}} \dots |I| = \frac{I_m}{\sqrt{2}} \dots I_m = \frac{V_m \angle \theta_v}{Z \angle \theta_z} \quad (6)$$

$$P = |V||I| \cos \theta \dots Q = |V||I| \sin \theta \dots S = P + jQ \quad (7)$$

$$\theta = \theta_v - \theta_i \quad (8)$$

The front panel of this VI consists of (a) the user inputs (controls) such as maximum voltage, angle of the voltage, impedance, angle of the impedance, starting value of the angle ωt , final value of the angle ωt , and increments and (b) the display (indicators) such as P, Q, S, and graphs such as $v(t)$ and $i(t)$, $p(t)$, $p_R(t)$ and $p_x(t)$.

This VI was simulated with the input values from an example in [6], and the results from the VI matched with the example results. The front panel of this VI is shown in Figure 1 (Figure 1A – Circuit Diagram and User Input and Figure 1B – VI Output).

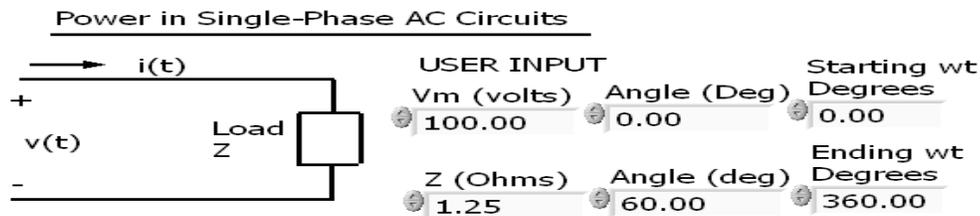


Figure 1 A – Circuit Diagram and User Input

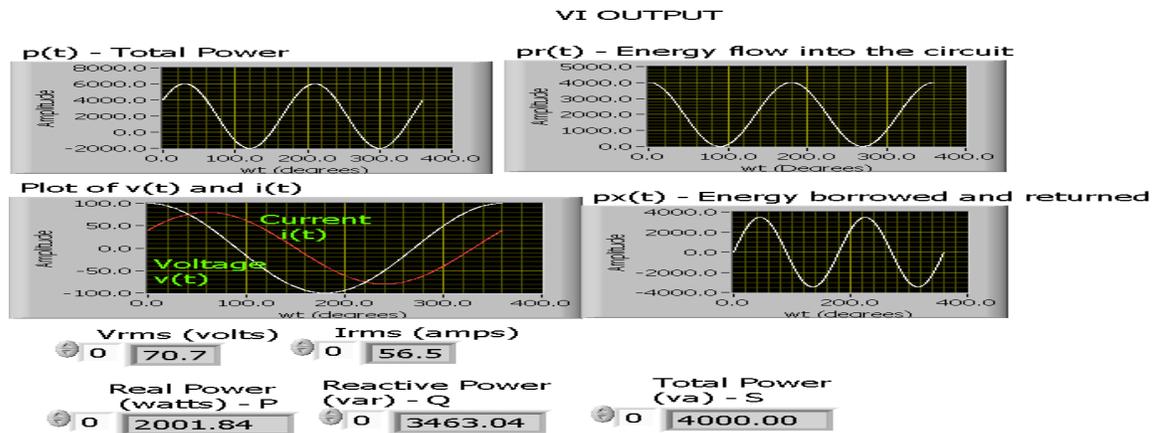


Figure 1B – VI Output

Basic Three Phase Circuits (Star/Delta Connections, Three Phase Voltage Waveforms, and Star/Delta Transformations)

VIs were developed using the equations from [6, 7, 8]. These are standard three phase equations found in any electric circuits and/or electric power systems book. This VI simulated both the Delta and Star connection and calculated the line parameters and total power from the given phase parameters. The Star/Delta VI was simulated with input values from examples in [6, 7], and the results matched the example results. The front panel of this VI consisted of controls for user input of phase parameters and load information and indicators to display calculated parameters. The diagram panel simulated various equations through the use of built-in arithmetic icons and other icons to deal with complex notations. It consisted of a case structure to decide between the type of connection (Star or Delta). The front panel of this VI indicating the simulation results of the Star connection is shown in Figure 2 below. The three phase voltage VI [8] is designed to demonstrate the voltage relationships in Star/Star connection. The diagram panel of this VI is large and difficult to fit on a standard size paper. As a result, we are presenting the front panel of this VI in Figure 3.

To conduct various analyses, the source and load must be of same type (Star/Star or Delta/Delta). However, sometimes the source and load may not be of the same connection type, and a transformation must be carried out to convert both the load and source to the same type using standard equations. Figure 4 and Figure 5 present front panel (simulation results) of this VI [8].

VI Front Panel (Star Connection)

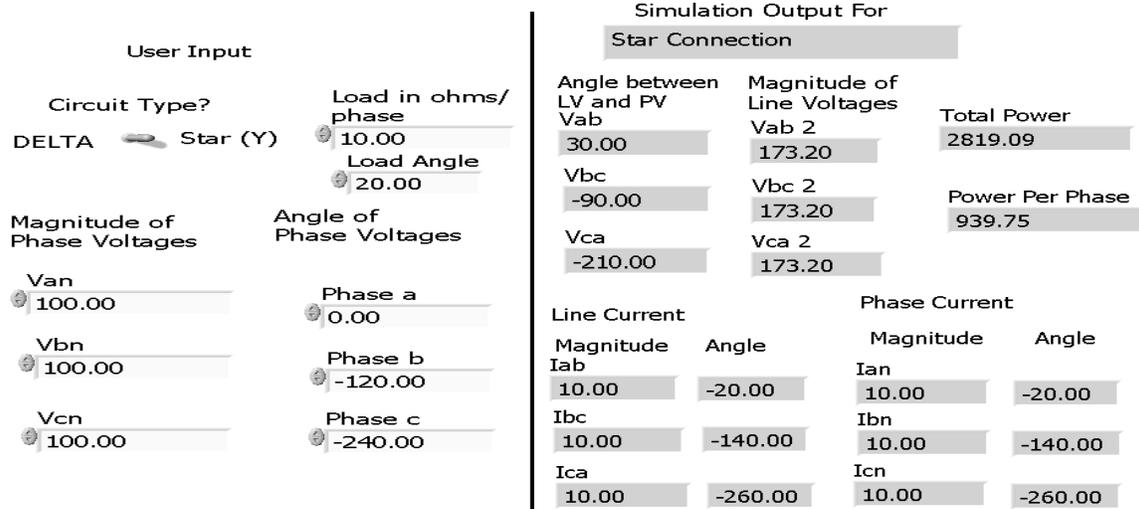


Figure 2 – Front Panel of Balanced Three Phase (Star/Delta) Circuit VI

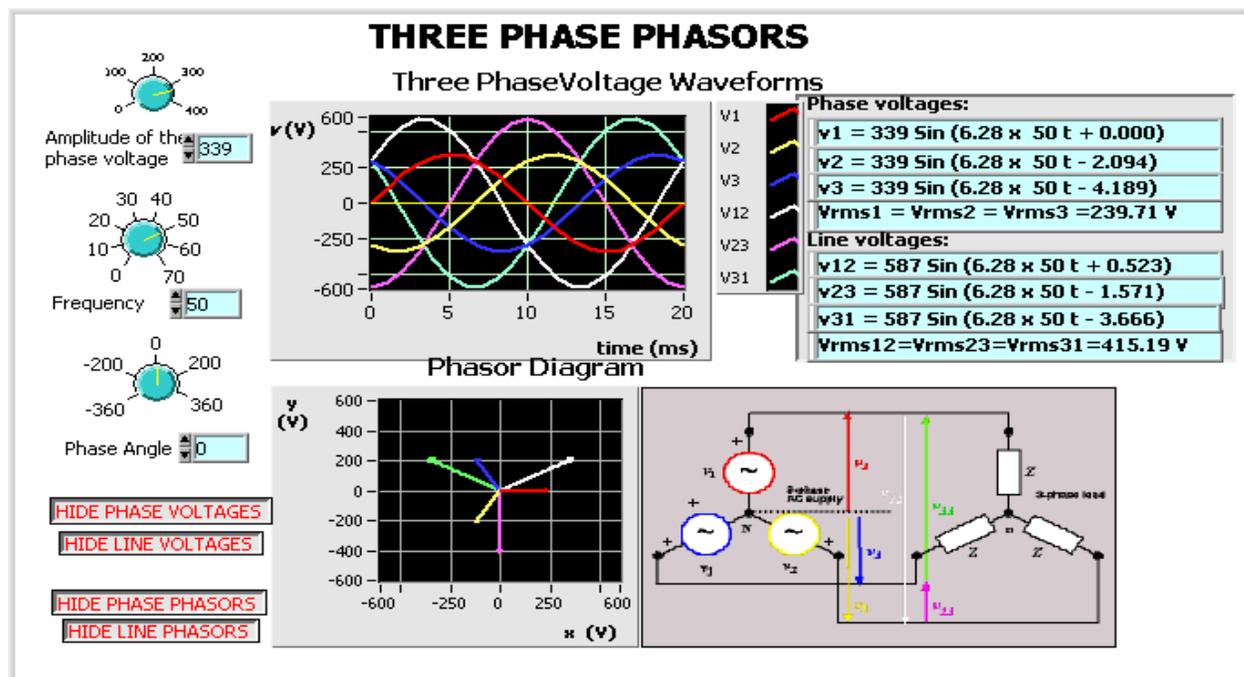


Figure 3 – Front Panel of Three Phase Voltage VI

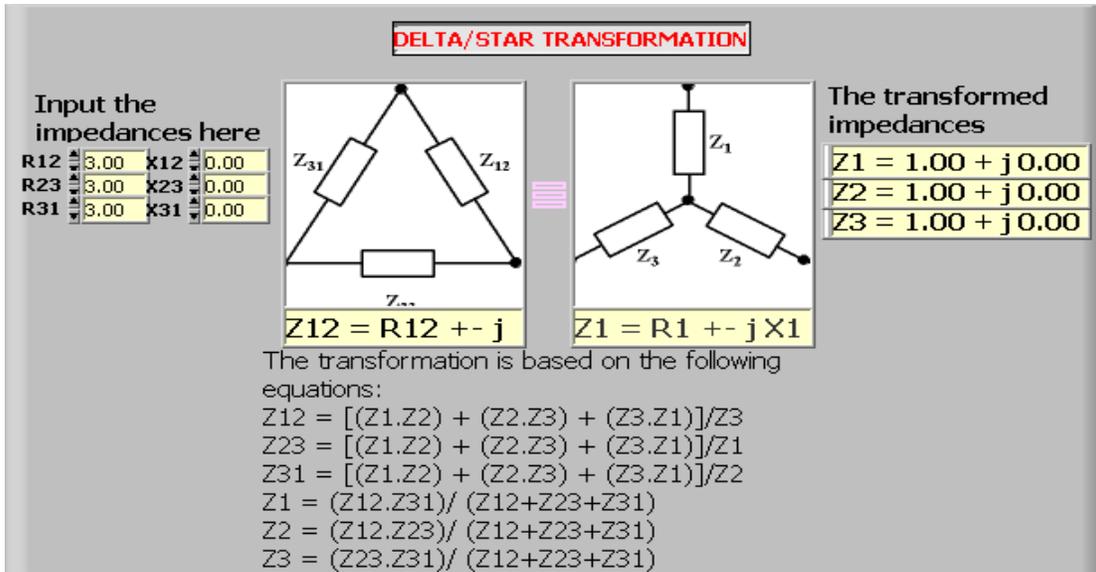


Figure 4 – Front Panel (Results of Delta/Star Transformation)

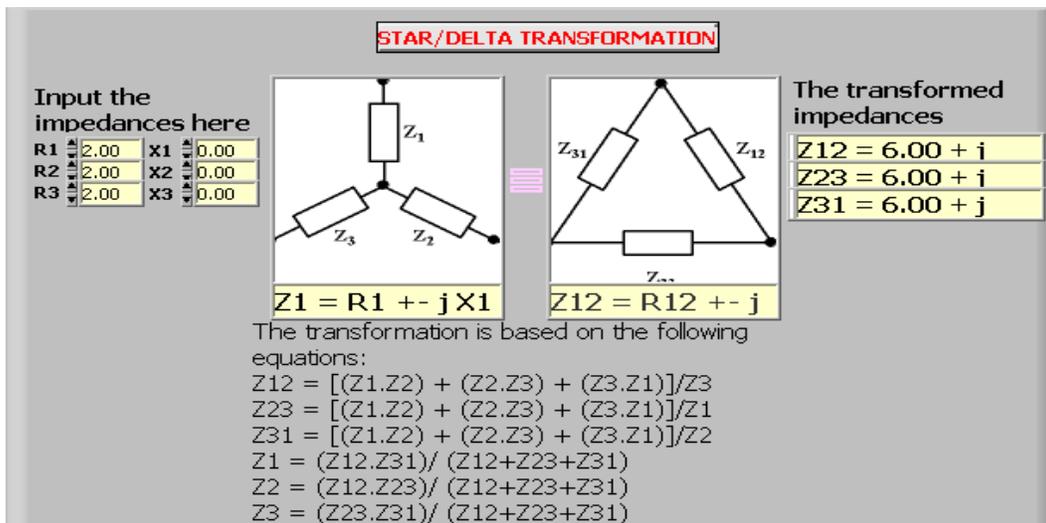


Figure 5 – Results of Delta/Star Transformation

VI to Model Transmission Line

One of the requirements of the operation of any power system is the maintenance of the voltage within specified limits at various points in the system [7]. This requires understanding the mathematical model of the transmission line and solution of various equations used to calculate voltage, current, and power at various points of a transmission line. The exact analysis of the transmission line involves a distributed parameter analysis, as the parameters of the line (series capacitance, shunt capacitance, inductance, and resistance) are uniformly distributed over the length of the line. The exact analysis is complicated and

time consuming. Fortunately, depending on the length of the line, some of these parameters can be lumped, resulting in a simplified model with reasonably accurate results.

Short Transmission Line Model

If the length of the line is less than or equal to 50 miles, then a Short Transmission Line model is used for analysis [7]. In this type of modeling, the capacitances have negligible effect, and they are ignored. The resistances and inductances are lumped and represented by single units. The per-phase model of the line is basically a series circuit with a much simpler voltage, current, and power equations. Figure 6 represents the diagram of such a line.

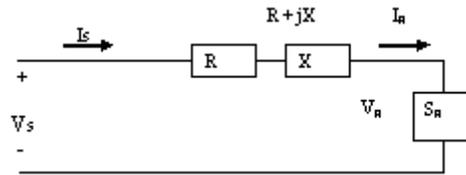


Figure 6 – Short Transmission Line Model

The line equations are as follows [6]:

$$Z = (r + j\omega L)l = R + jX \quad (9) \quad I_R = S_{R(3\phi)}^* / 3V_R \quad (10)$$

$$V_s = V_R + Z \times I_R \quad (11) \quad I_s = I_R \quad (12)$$

$$\%VR = ((|V_{R(NL)}| - |V_{R(FL)}|) / (|V_{R(FL)}|)) \times 100 \quad (13)$$

$$S_{s(3\phi)} = 3V_s I_s^* \quad (14) \quad S_{L(3\phi)} = S_{s(3\phi)} - S_{R(3\phi)} \quad (15)$$

$$\eta = (P_{R(3\phi)}) / (P_{s(3\phi)}) \times 100 \quad (16)$$

In the previous equation, Z = impedance of the load, I_R = receiving end current, V_s = voltage at the sending end, I_s = current at the receiving end, $\%VR$ = percentage voltage regulation, $S_{s(3\phi)}$ = sending end power, $P_s + jQ_s$, $S_{L(3\phi)}$ = total line loss, and η = transmission line efficiency.

Medium Transmission Line

If the length of the line is greater than 50 miles and less than or equal to 150 miles, then a Medium Transmission Line model is used for analysis [7]. In this type of modeling, the shunt admittance, usually pure capacitance, is included in the calculations. If the total shunt capacitance is divided into equal parts placed at the sending end and receiving ends of the line, the circuit is called a nominal π . On the other hand, if all of the shunt admittance of the line is lumped in the shunt arm of the T and the series impedance is divided equally between the two series arms results in the nominal T, the per-phase model of the line is basically a series-parallel circuit with simpler voltage, current, and power equations. Figure 7 represents the nominal π model of such a line.

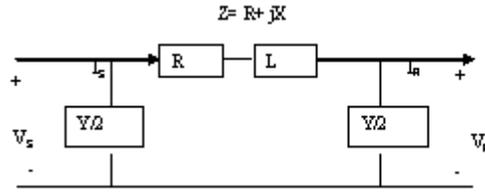


Figure 7 – Nominal π Model

The voltage and current equation of the nominal π model is as follows [7]:

$$V_s = AV_R + BI_R \quad (17) \quad I_s = CV_R + DI_R \quad (18) \quad A = D = \frac{ZY}{2} + 1 \quad (19)$$

$$B = Z \quad (20) \quad C = Y\left(1 + \frac{ZY}{4}\right) \quad (21)$$

$$\%VR = \left(\frac{|V_s|}{|A|} - |V_{R(FL)}|\right) / (|V_{R(FL)}|) \times 100 \quad (22)$$

Long Transmission Line

The exact solution of any transmission line and one required for a high degree of accuracy in calculating 60-Hz lines more than approximately 150 miles long must consider the fact that the parameters of the line are not lumped but are distributed uniformly throughout the line [6]. The per phase circuit of this line is shown in Figure 8.

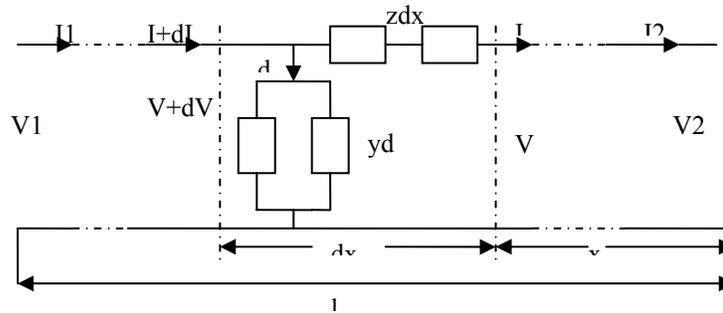


Figure 8 – Transmission Line

The hyperbolic form of voltage and current equations for this line are [6]:

$$V_R = V_S \cosh \gamma l - I_S Z_C \sinh \gamma l \quad (23)$$

$$I_R = I_S \cosh \gamma l - \frac{V_S}{Z_C} \sinh \gamma l \quad (24)$$

where

$\gamma = \sqrt{yz}$ and is called propagation constant and

$Z_C = \sqrt{\frac{z}{y}}$ and is called characteristics impedance

Two VIs were developed using the equations for (a) the Short Transmission Line and (b) the Long Transmission Line. The VIs were simulated with the input values from a short transmission line example [6] and a long transmission line example [9], and the results from the VI matched with the example results. The front panel for the short transmission line simulation is shown in Figure 9, and the long transmission line is shown in Figure 10.

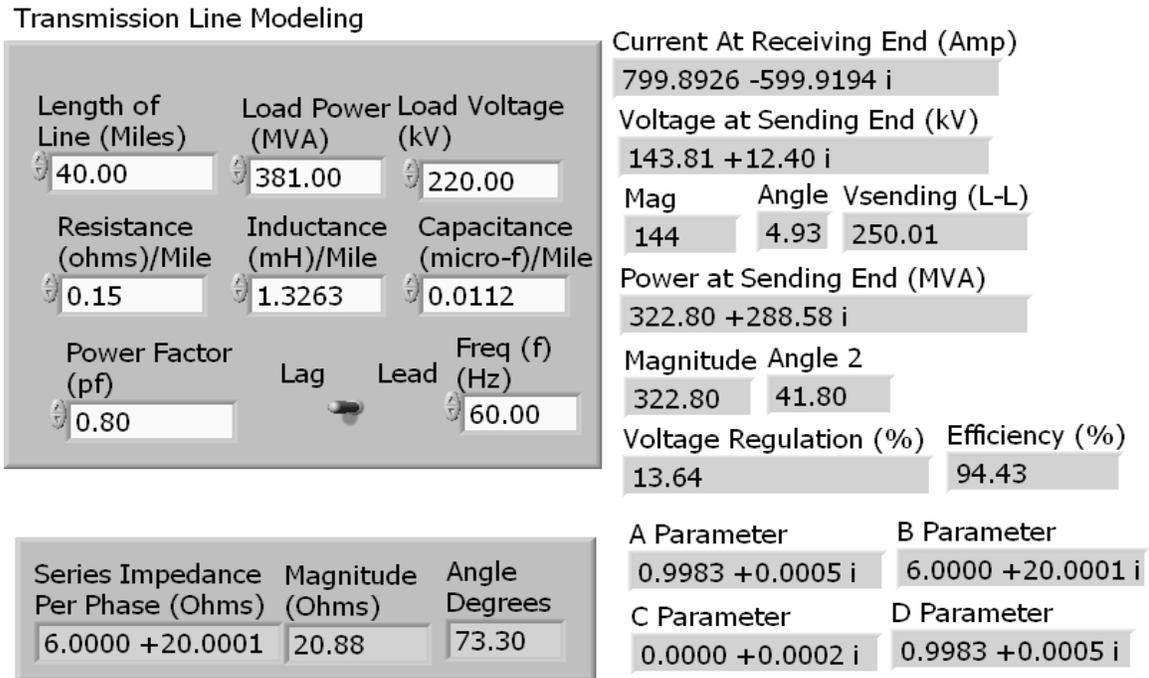


Figure 9 – Front Panel of Short Transmission Line Simulation VI

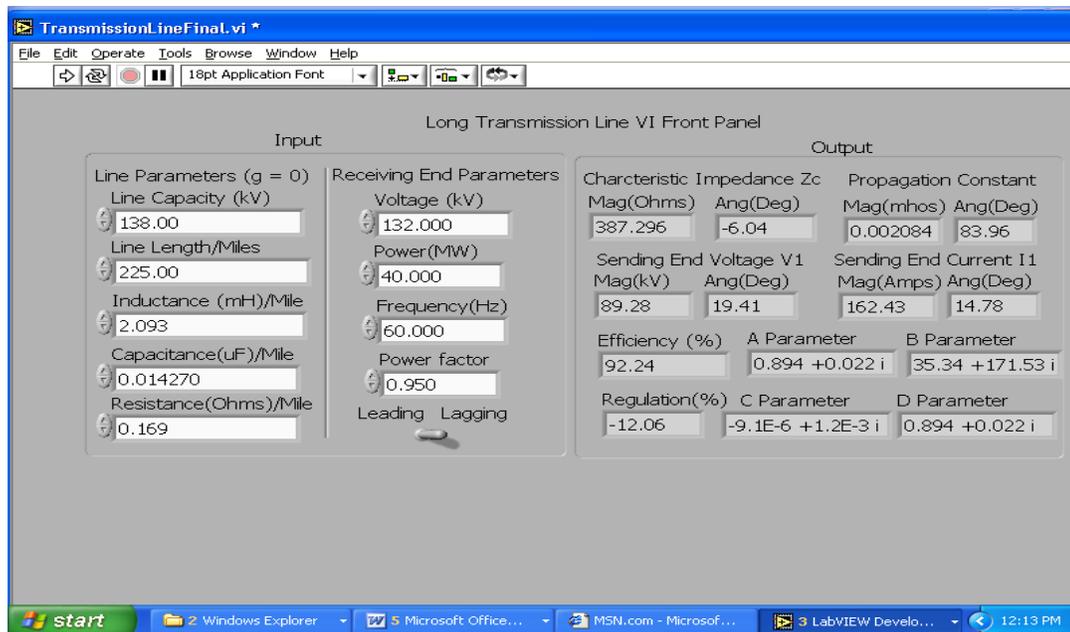


Figure 10 – Front Panel of Long Transmission Line VI

Economic Dispatch (distribution of load between units in a plant) [7]

Economic Dispatch is an important area of study in a power systems course because it deals with practices to achieve maximum efficiency of operation. This, in turn, helps to maintain a reasonable relation between cost to a consumer and the cost to the company delivering the power in the face of constantly rising prices for fuel, labor, supplies, and maintenance. The Economic Dispatch study provides solutions for operating the system for any load condition with a minimum cost for delivered power and determines the contribution from each plant and from each unit within a plant. Economic Dispatch is a complex topic and covers topics, such as distribution of load between plants, transmission loss as a function of plant generation, distribution of load between plants, penalty factors and loss coefficients, and automatic generation control. Understanding of these topics requires knowledge in load flow, parameter optimization with inequality constraints, and higher level calculus.

The simplest economic dispatch problem is the case when transmission line losses are neglected. The model does not consider system configuration and line impedances. In essence, the model assumes that the system is only one bus, with all generation and loads connected to it.

The Economic Dispatch problem dealing with the distribution of loads between units in a plant uses the incremental fuel cost methodology. If F_n = input to unit n, dollars per hour, P_n = output of unit n, MW, then dF_n/dP_n is the incremental fuel cost of the unit in dollars per megawatt hour.

The Economic Dispatch VI presented in this paper uses the incremental fuel cost methodology for allocating load between two units. It simulates an example in [7] successfully. The VI can be extended to handle more than two units. The incremental fuel costs are as follows:

$$dF1/dP1 = 0.0080P1 + 8.0 \dots \text{and} \quad dF2/dP2 = 0.0096P2 + 6.4 \quad (25)$$

Both the units are operating at all times, and the total load varies from 250 to 1250 MW. The maximum and minimum loads on each unit are 625 and 100 MW, respectively. The objective is to determine the allocation of loads and plant incremental fuel factor.

The incremental fuel cost is calculated at minimum load. The unit having the minimum incremental fuel cost supplies the additional load until its incremental fuel cost becomes equal to the other unit. After that the load distribution is solved, assuming equal incremental fuel cost for both units. The simulation results clearly indicate that.

The front panel of this VI is shown Figures 11A through 11G below.

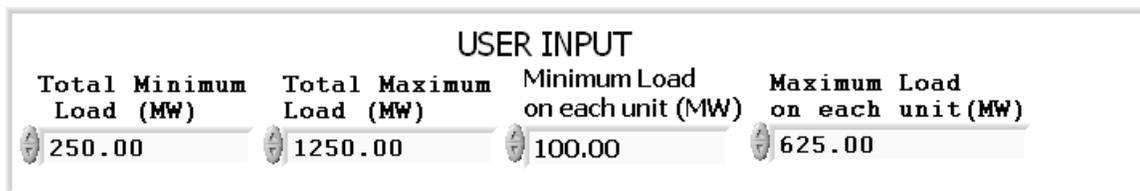


Figure 11A – VI Front Panel Depicting User Input

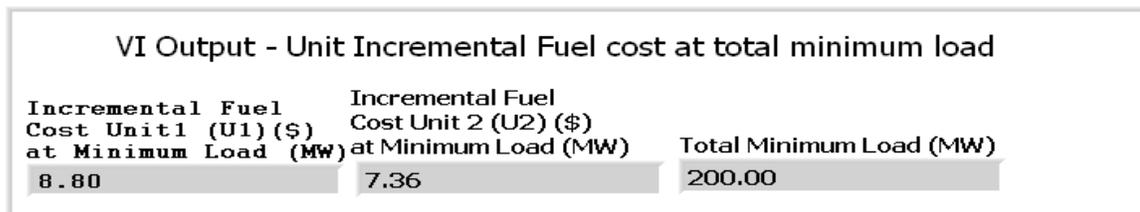


Figure 11B – VI Output Depicting Unit Incremental Fuel Cost at Minimum Load

Distribution of load between units for Plant Output of 250 MW

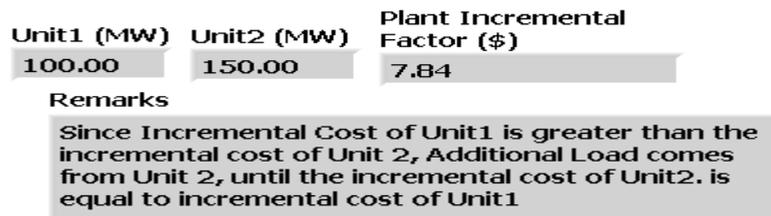


Figure 11C – VI Output for Distribution of Load for Plant Output of 250 MW

Calculation of incremental fuel cost of each unit at maximum load

Incremental Fuel Cost Unit1 (U1) (\$) at Maximum Load (MW)	Incremental Fuel Cost Unit2 (U2) (\$) at Maximum Load (MW)	Total Maximum Load (MW)
13.00	12.40	1250.00

Distribution of load for Plant Output = 1250 MW

Unit1 (MW)	Unit2 (MW)	Remarks
625.00	625.00	Since incremental cost of Unit1 is greater than the incremental cost of Unit2, additional load comes from Unit 2 until the incremental costs are equal.
Plant Incremental Factor (\$)	13.00	

Figure 11D – VI Output for Distribution of Load for Plant Output of 1250 MW

Load distribution as a factor of plant incremental factor - Results from VI

ICP (\$)	P1(MW)	P2(MW)	PT (MW)
7.84	100.00	150.00	250.00
8.36	100.00	203.75	303.75
8.87	109.00	257.50	366.50
9.39	173.50	311.25	484.75
9.90	238.00	365.00	603.00
10.42	302.50	418.75	721.25
10.94	367.00	472.50	839.50
11.45	431.50	526.25	957.75
11.97	496.00	580.00	1076.00
12.48	560.50	625.00	1185.50
13.00	625.00	625.00	1250.00
0.00	0.00	0.00	0.00

Figure 11E – Distribution of Load as a Factor of Plant Incremental Factor

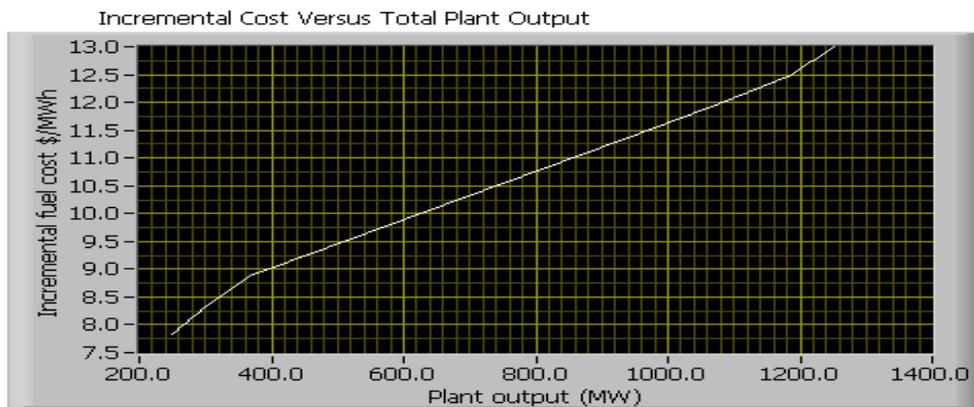


Figure 11F – Plot of Incremental Fuel Cost versus Total Plant Output

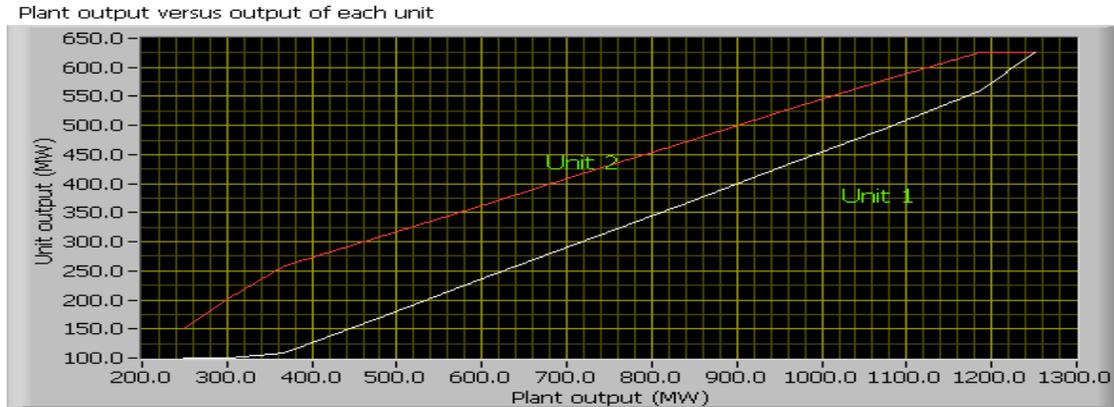


Figure 11G – Plot of Plant Output versus Output of Each Unit

Node Equations and Ybus

This VI is designed to calculate the Ybus matrix from the user input of reactance between various nodes in a system. The VI was tested for a four-node system and worked satisfactorily. Because of the page limitations, we are unable to provide the simulation results of this VI.

Conclusions

The VI modules presented in this paper are tested with the input values from various examples in textbooks and results matched with the results of the examples. The modules presented in this paper are developed using simplified models. Although this is sufficient for introducing the concepts, elaborate models must be incorporated into the modules to address the complex real world situations. A number of software packages are currently being used in engineering, technology, and sciences curriculum. While some of them require a programming background, others are designed for specific course requirements. LabVIEW has features and built-in virtual instrument modules identical to most of the features found in all these software packages. MATLAB is extensively used for studying circuits and power systems, and a number of books and literature are available on this topic. MATLAB requires writing codes. LabVIEW on the other hand, provides a graphical environment to solve complex problems. No or minimal programming knowledge is necessary to design and develop the VI modules. LabVIEW has provision to transfer data between LabVIEW, Excel, and MATLAB and call MATLAB and Excel from the LabVIEW environment. Therefore, one can use LabVIEW to address the needs of various courses. This will be beneficial for students and faculty and introduce standardization across the curriculum.

Acknowledgement

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Biography

Nikunja K. Swain is a Professor at the South Carolina State University. Dr. Swain has more than 25 years of experience as an engineer and educator. He has more than 50 publications in journals and conference proceedings; has procured research and development grants from the NSF, NASA, DOT, DOD, and DOE; and reviewed multiple books on computer-related subjects. He is also a reviewer for ACM Computing Reviews, IJAMT, CIT, ASEE, FIE, JET, IAJC, and other conferences and journals. He is a registered Professional Engineer in South Carolina.

James A. Anderson's areas of specialization are in electro-optics, solid-state devices/microelectronics, and microwave and optical communications. He has performed research and design at various industries, worked as a consultant and professional engineer, and has been a university professor and Dean of the School of Engineering Technology and Sciences (SETS) at South Carolina State University. Currently, he serves as Professor and Manager of HBCU/UP grant at South Carolina State University.

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