CLASSROOM LEARNING OF THE TOPICS IN ELECTRIC POWER SYSTEMS EMPHASIZED WITH THE USE OF MATLAB^{TM}, POWERWORLD SIMULATOR^{TM}, AND SIMPOWERSYSTEMS^{TM}

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Abstract

One of the most challenging aspects of engineering education is to impart an intuitive learning of the subject with abstract details to the student audience. One of the difficulties in teaching an electrical power system analysis course is that the subject involves inherently abstract concepts with no real systems and laboratory experiments. In such cases, paper-and-pencil exercises can be quite useful for highlighting the associated fundamentals, but they often fall short in imparting the desired intuitive insights. To help the students in such contexts, computer-simulated tools such as MATLAB^{TM}, PowerWorld Simulator^{TM}, and SimPowerSystems^{TM} can facilitate better learning and enable students to exercise effectively the analyses and designs of practical systems. This paper is written to outline relevant pedagogical prospects.

Introduction

There has been an increasing trend and pressure in recent years to cram more and more new topics into electrical engineering curriculums that has caused electrical machinery and power system principles to be scaled into shorter survey-type courses. The number of universities offering power engineering programs has dwindled, although the need for power engineers has increased significantly (due to the retiring workforce and expanding power utility projects). Many schools, in general, lack a complete power systems lab. Development of such a lab is comprehensive requiring high-current motors, high-current generators, high-voltage transformers, switchgears, etc. Also, a dedicated space allocation for the lab, possibly on a first floor (due to mounting of heavy equipment considerations) is required; and installation needs to be done in accordance with electrical codes and regulations including fire and safety measures. Also the high-current requirements would require special electrical installations and safety constraints. Conceiving such a lab means requiring a significant expense. Further, the effort by many schools to go more "green" should be duly considered. Under such circumstances, software-based teaching of electrical power systems and related subjects can be an option with the simultaneous ease of presenting the underlying concepts and details viably in the classroom by the instructor. Existing tools enable visualization of the electrical hardware with a dynamic demonstration of the functioning of the equipment. Hence, introducing such a software tool-based curriculum in electrical machinery and/or power systems courses can be a beneficial option for those schools without a regimented version of electrical power systems lab.

Personal computers can be used easily with the available tools so as to perform steady-state and transient analysis of large interconnected power systems. Many schools also offer "cloud" computing; and, this greatly facilitates learning. With software available to students, the course material can be made classroom efficient while preserving its essence.

Use of MATLAB^{TM} in Power Systems

MATLAB^{TM} is a matrix-based software package ideal for power system analysis. Complete solutions can be found using MATLAB^{TM}, easing the tedious aspects of the underlying mathematics. Exemplary details are as follows:

MATLAB™ solutions of power systems problems can be formulated *via* nodal equations, which can be systematically applied to circuits [1] in general. MATLAB™ exercises can generate the admittance matrix **Y** and solve for example, the unknown bus voltage vector **V** in the equation:

$$\mathbf{YV} = \mathbf{I} \qquad (1)$$

As an illustrative example shown in Figure 1, determine the node voltages V_1 and V_2 and the power delivered by each source.

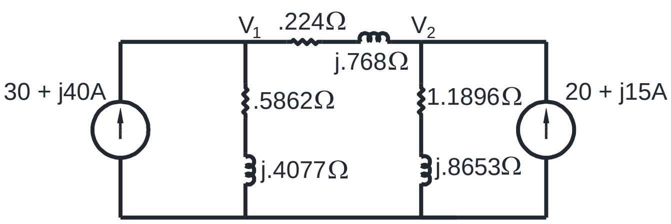


Figure 1: Illustrating Node Voltages V_1 and V_2.

The above problem can be conveniently solved using MATLAB™ as follows [2]. In Figure 1, the circuit operates in sinusoidal-steady-state; and, it has impedances specified in ohms. An algorithm for the bus admittance matrix can be formulated with MATLAB™, and it can be given to students of the power systems course to study and formulate the method of solution. The development of relevant code can be taught as follows: In the program, the line impedances are first converted to admittances. The vector **Y** is then initialized to zero. In the first loop, the line data is searched, and the off-diagonal elements are entered. Finally, in a nested loop, line data is searched to find the elements connected to a bus; and, hence the diagonal elements are formed.

A MATLAB™ function file to build the bus admittance matrix is as follows:

```
function [ Y ] = ybus( zdata )
n1= zdata(:,1);
nr = zdata(:,2);
R = zdata(:,3);
X = zdata(:,4);
Nbr = length(zdata(:,1));
nbus = max(max(n1),max(nr));
% branch impedance
Z = R + j*X;
% branch admittance
Y = ones(nbr,1)./Z;
% initialize Y to zero
Y = zeros(nbus,nbus);
% formation of the off diagonal elements
for k =1:nbr;
   if n1(k) > 0 & nr(k) > 0
      Y(n1(k),nr(k)) = Y(n1(k),nr(k)) - y(k);
      Y(nr(k),n1(k)) = Y(n1(k),nr(k));
   end
end
% formation of the diagonal elements
for n = 1:nbus
   for k = 1:nbr
      if n1(k) == n | nr(k) ==n
         Y(n,n) = Y(n,n) + y(k);
      else,end
   end

end
```

The above function file can be called from within a script file to solve for the admittance matrix **Y** and the voltages V_1 and V_2 in Figure 1:

```
% From  To     R        X
z = [0     1     .5862     .4077;
       0     2    1.1896    .8653;
       1     2    .224       .768];
   Y = ybus(z)
   Ibus = [30 + j*40; 20 + j*15]
   V=Y\Ibus
```

The program as above leads to results for the circuit of Figure 1 as follows:

$$Y = \begin{bmatrix} 1.5 - j2.0 & -.35 + \mathrm{j}1.2 \\ -.35 + j1.2 & 0.9 - \mathrm{j}1.6 \end{bmatrix} S \qquad (2)$$

$$V = \begin{bmatrix} 3.5902 + 35.0928j \\ 6.0155 + 36.2212j \end{bmatrix} \quad (3)$$

The complex power of each source is given by **S** = **VI***, and the following program is written using MATLAB[TM] to yield solutions for **S**:

```
J= sqrt(-1)                          %Define j
I=[30 + j*40; 20 + j*15] %node current phasors
%Define complex admittance matrix Y
Y=[1.5 - j*2  -.35 +j*1.2; -.35+j*1.2  .9-j*1.6]
Disp('The solution is')
V = inv(Y) * I
S=V.*conj(I)
```

The solution is:

$$S = \begin{bmatrix} 1511.4 + 909.2j \\ 663.6 + 634.2j \end{bmatrix} VoltAmps \quad (4)$$

Modern computers have sufficient storage and speed to compute efficiently the voltage magnitudes, phase angles, and transmission-line power flows accommodating as large as 100,000 buses and 150,000 transmission lines. Exposing power engineering students to similar programs like MATLAB[TM] and solving relevant problems prepares them to enter the power industry confidently and with ample prior knowledge on power systems.

Another application of MATLAB[TM] for use in power systems is to find the exact ABCD parameters of a transmission line. A power transmission line, in general, is a 3-phase balanced system; and, as such, it can be represented in terms of a two-port single-phase network as shown in Figure 2.

The following equations give the ABCD parameters of the line in Figure 2 in a matrix format as follows:

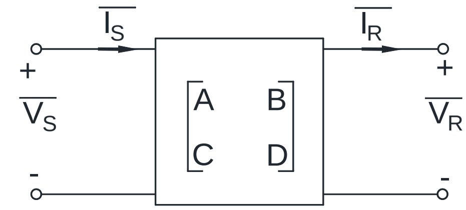


Figure 2:
Transmission Line Single-Phase Equivalent.

$$\begin{bmatrix} \overline{V_S} \\ \overline{I_S} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \overline{V_R} \\ \overline{I_R} \end{bmatrix} \quad (5)$$

where

$\overline{V}_s$ = sending-end voltage

$\overline{I}_s$ = sending-end current

$\overline{V}_R$ = receiving-end voltage

$\overline{I}_R$ = receiving-end current

$\overline{z}$ (Ω / m) = series-impedance (per length valued)

$\overline{y}$ (S / m) = shunt-admittance (per length valued)

$\gamma =$ propagation constant = $\sqrt{\overline{z}\,\overline{y}}$ m^{-1}

$\overline{Z}_c$ = characteristic impedance = $\sqrt{\dfrac{\overline{z}}{\overline{y}}}$ Ω

$A = D = \cosh(\gamma l)\, per\ unit$

$B = \overline{Z}_c \sinh(\gamma l)\ \Omega$

$C = \dfrac{1}{\overline{Z}_c} \sinh(\gamma l)$ S

Because the propagation constant γ is a complex quantity with real and imaginary parts, computing the ABCD parameters given in the form as above, is not straightforward with conventional calculators. However, MATLAB[TM] can be adopted to easily solve for these parameters. For example, suppose the A,B,C, and D parameters are to be calculated for a 368 km long line in which, $z = 0.8\angle 80^{\circ}\ \Omega / km$ and $y = 10^{-7}\angle 90^{\circ}\ S / km$.

Relevant MATLAB™ code is as follows:

```
%Program to compute ABCD parameters of a
transmission line
%Define j
j = sqrt(-1)
L = input('length of line in kilometers= ');
zmag = input('series-impedance magnitude
(ohm/kilometer)');
zphase = input('series-impedance angle in
degrees');
ymag = input('shunt-admittance magnitude
(Siemens/kilometer)');
yphase = input('shunt-admittance angle in
degrees');
%Convert degrees to  radians
zphaser = zphase*pi/180;
yphaser = yphase*pi/180;
realz = zmag*cos(zphaser);
imagz = zmag*sin(zphaser);
z = realz + j*imagz;
realy = ymag*cos(yphaser);
imagy = ymag*sin(yphaser);
y = realy + j*imagy;
Zc = sqrt(z/y);
Gamma = sqrt(z*y);
gammaL = gamma*L;
AR = cosh(gammaL);
DR = AR;
BR = Zc*sinh(gammaL);
CR= sinh(gammaL)/Zc;
[ABCD] = [AR  BR; CR  DR]
disp('The magnitude of A is')
AMAG = abs(AR)
disp('The angle of A is')
ANGLEAR = angle(AR);
ANGLEAD = ANGLEAR*180/pi
disp('D=A')
disp('The magnitude of B is')
BMAG = abs(BR)
disp('The angle of B is')
ANGLEBR = angle(BR);
ANGLEBD = ANGLEBR*180/pi
disp('The magnitude of C is')
CMAG = abs(CR)
disp('The angle of C is')
ANGLECR = angle(CR);
ANGLECD = ANGLECR*180/pi
```

The solutions obtained are:

$$A = D = 0.9947\angle 0.05^o \ per\ unit$$

$$B = 293.82\angle 80.02^o\ \Omega$$

$$C = 3.673X10^{-5}\angle 90.02^o S$$

Apart from the use of MATLAB™ to solve typical power systems problems, other software also exist that are extremely useful for similar applications. One such software is PowerWorld Simulator™ discussed next.

Use of PowerWorld Simulator™ in Power Systems Calculations

PowerWorld Simulator™ can be used to integrate computer-based examples, problems, and design projects in any power systems course. It is a viable software tool for more realistic design projects, and provides experience on a commercial grade power systems analysis package.

For example, Figure 3 represents a simple power system [1] in which a generator is supplying power to a load through a 16 kV distribution feeder. In PowerWorld™, the power flows can be visualized appropriately with arrows superimposed on the generators, loads, and transmission lines. The size and speed of the arrows indicates the direction of flow. Further, PowerWorld™ has the ability to animate the power systems.

Students can use PowerWorld™ to interactively learn the power system functions. MATLAB™ code can also be used in conjunction on the same system to compare methods and results. That is, for the transmission-line shown with a resistance of 0.768 Ω and a reactance of 1.536 Ω , it can be found that the generator delivers 5.0805 MW and the line and load absorb 0.0775 MW and 5.0030 MW respectively, *via* Matlab™ and PowerWorld™ tools.

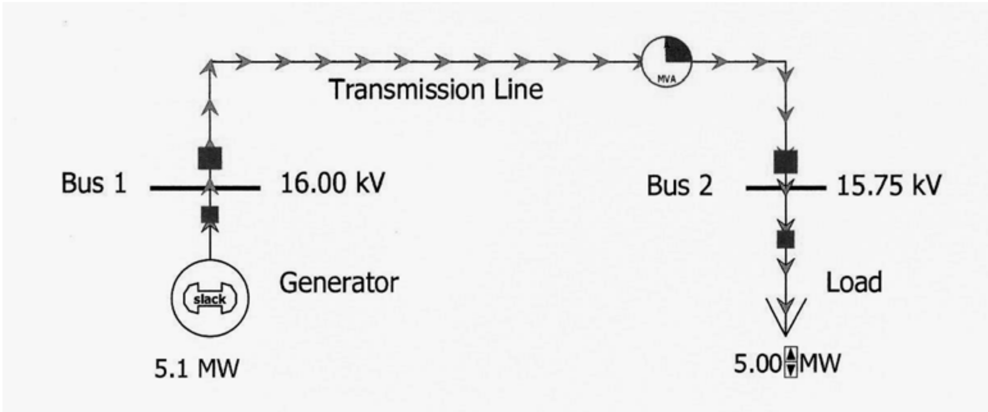


Figure 3: Two Bus Power System.

PowerWorld Simulator™ can also be used to simulate balanced and unsymmetrical faults. This is extremely important in selecting, setting, and coordinating the protective equipment such as circuit breakers, fuses, relays, and instrument transformers. Without such software, it would not be easy for the underlying calculations to be done in a timely manner. Thus, use of software such as PowerWorld Simulator™ calculates the results so that students will be able to learn the design aspects of selecting appropriate circuit breakers and fuses. Students will have more time to concentrate on the design of such systems because relevant calculations concerning possible fault currents, etc. are in hand, thanks to the simulations.

Further, PowerWorld Simulator™ can be used to solve for balanced and for unsymmetrical faults. Once the diagram is drawn (as shown in Figure 4) with the machine, line, and transformer data being entered, just right-click on the bus symbol corresponding to the fault location. This displays the local menu. Select "**Fault**" to display the fault dialog. Verify that the correct bus is selected, and then set the Fault Type field to "Single Line-to-Ground" for this type of fault. Click on **Calculate** to determine the fault currents and voltages. As an example, PowerWorld Simulator can be used to solve for a bolted single line-to-ground fault at bus 2 in the above example given in Figure 4. The results are shown in the following screen shot of the table (Figure 5).

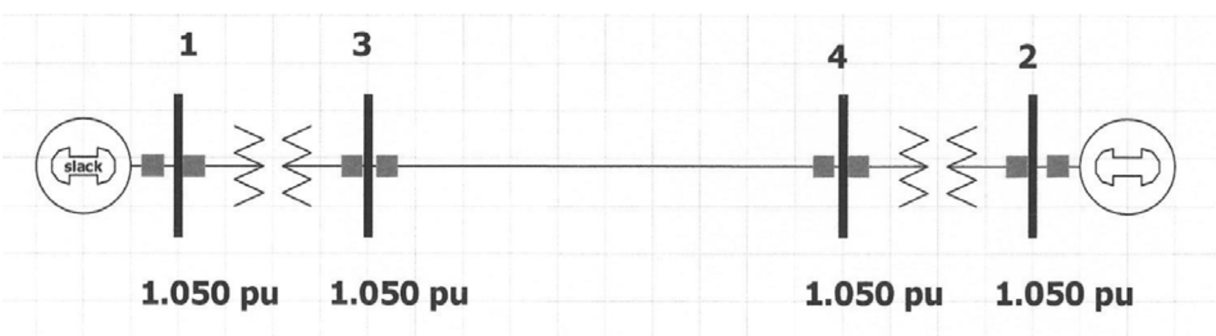
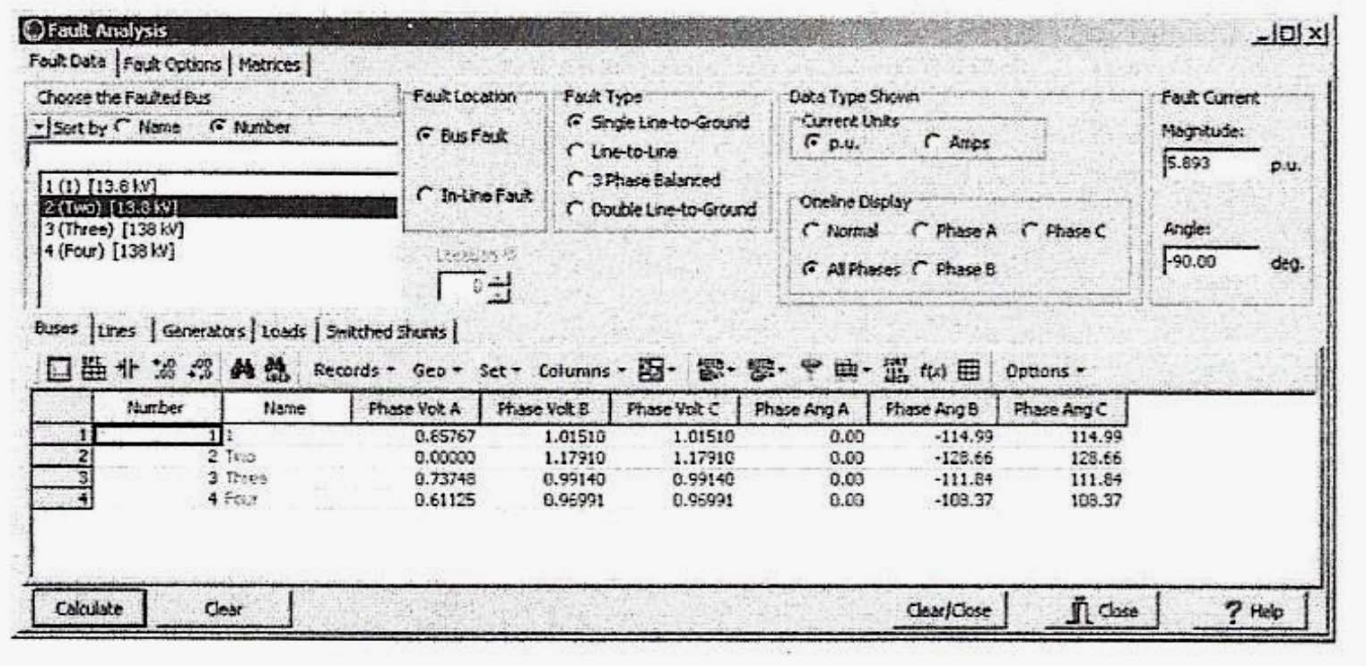


Figure 4: PowerWorld Simulator™ Drawing of Example Power System.



	Number	Name	Phase Volt A	Phase Volt B	Phase Volt C	Phase Ang A	Phase Ang B	Phase Ang C
1	1	1	0.65767	1.01510	1.01510	0.00	-114.99	114.99
2	2	Two	0.00000	1.17910	1.17910	0.00	-128.66	128.66
3	3	Three	0.73748	0.99140	0.99140	0.00	-111.84	111.84
4	4	Four	0.61125	0.96991	0.96991	0.00	-108.37	108.37

Figure 5: Screen For PowerWorld™ Example.

Using SimPowerSystems™ in Power Systems Calculations

Another useful software available for modeling and simulation of electric power systems is SimPowerSytems™, which provides component libraries and analysis tools. An advantage of using this software is that models of electrical power systems are built using physical connections. These models closely resemble the network they represent, and are easy to understand and share. SimPowerSystems™ can be used for a wide variety of practical applications such as modeling renewable energy systems and performing tests such as injecting a single-line-to-ground fault.

That is, SIMULINK™ now has expanded to include SimPowerSystems™. SIMULINK™ provides a graphical user interface for constructing block diagram models using "drag-and-drop" operations [2]. A system is configured in terms of a block diagram representation from a library of standard components. Figure 6 shows an example of the use of SimPowerSytems™ to model three sinewaves going through a gain device. The output is shown on the scope and given in Figure 7.

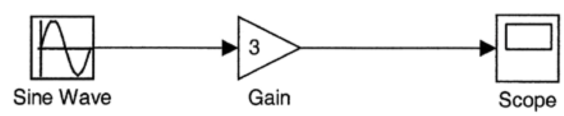


Figure 6: Example of a Block Diagram Using Simulink™ .

Parameters can be assigned to each of the components by double clicking on each block and entering the appropriate value. To obtain the result on the Scope, run the simulation, double click on the Scope, click on the Auto Scale, and the result is displayed as shown.

Figure 8 is an example of a single phase transmission line connected with a voltage source and a load constructed using SimPowerSystems™. There are two measurements, namely current and voltage. Currently, the Simulink Block Library has been expanded to include blocks used to solve and simulate Electrical Power Systems through SimPowerSystems™. The Parameters of the components are set before the simulation is run.

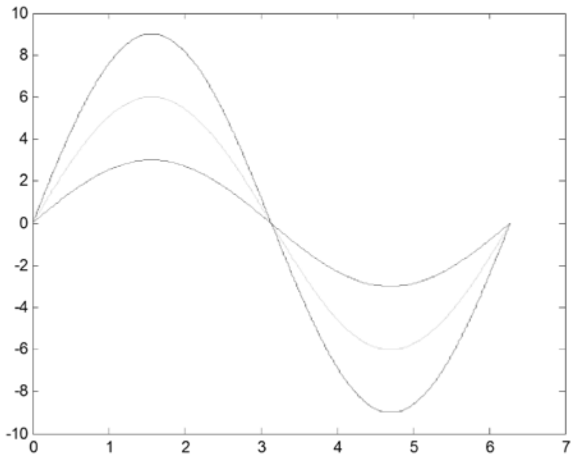


Figure 7: Output Result Versus Time.

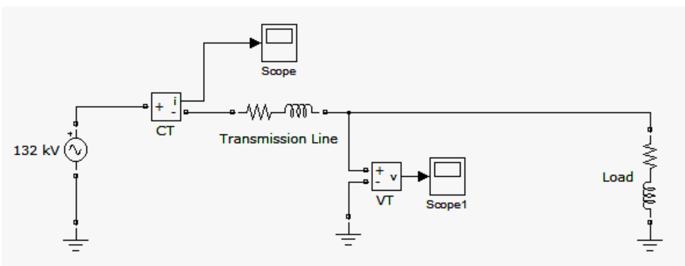


Figure 8: SimPowerSystem™ Drawing of a Single Phase Transmission Line Connected with a Voltage Source and a Load.

Depending on the relevant parameters chosen for the transmission line and load, the scope would display the corresponding sinusoidal waveforms.

For example, considering a frequency of 50 Hz, an input voltage of 132 KV, transmission line 9.89Ω in series with inductor 0.1142H, load 643.33Ω in series with inductor 7.43 H, Figure 9 and Figure 10 represent the output current and output voltage respectively given by SimPowerSystems™.

Students can also be encouraged to solve such a problem by hand, and compare the results with the SimPowerSytems™ solution.

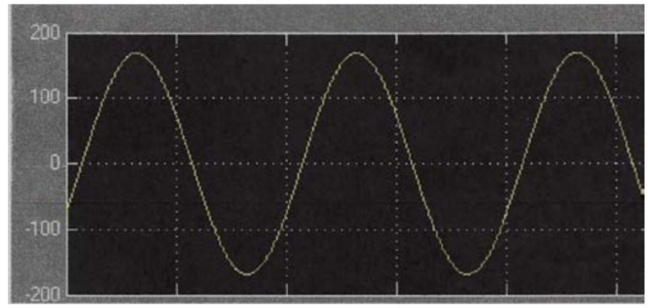


Figure 9: Output Current *Versus* Time.

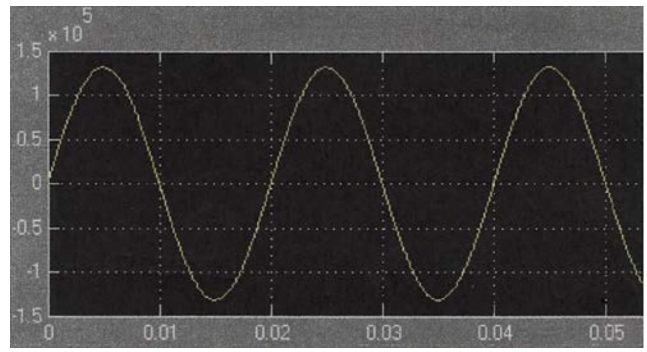


Figure 10: Output Voltage *Versus* Time.

The power system shown in Figure 8 can be solved by hand using voltage divider and Ohm's law as follows:

$$\overline{V}_{out} = \frac{132{,}000 < 0^o \text{ V x } (643.33 + j371.43)\Omega}{[(9.89 + j5.71) + (643.33 + j371.43)]\Omega}$$
$$= 130{,}000 < 0^o \text{ Volt} \quad (6)$$

Thus, $V_{out}(t) = 130{,}000 \cos(314t + 0^o)$ Volt.

$$\bar{I} = \frac{(132{,}000 < 0^o - 130{,}000 < 0^o) \text{ Volt}}{(9.89 + j5.71)\Omega}$$
$$= 175{,}000 < -30^o \quad \text{Amp} \quad (7)$$

And, $I_{out}(t) = 175.000 \cos(314t-30^o)$ Amps

It can be seen that these results agree with the SimPowerSystems™ solution.

Thus, SimPowerSytems™ can be used in the classroom to stimulate interest in power systems by using it to solve realistic, interesting, and exciting problems such as modeling renewable energy systems.

Conclusion

The present study illustrates the use of MATLAB^{TM}, PowerWorld Simulator^{TM}, and SimPowerSystems^{TM} in obtaining solutions for basic power systems analyses required in an undergraduate Electrical Power Systems course. Such computer-based solutions, in essence, yield visual details in addition to knowing other pertinent circuit information such as voltages and currents. Further, relevant efforts can be carried out fast and in a less tedious manner. Solving *via* paper-and-pencil such problems *sans* modern computer software deprives the designer of valuable insights into the behavior of the power system being designed. Also invaluable clues on how to improve the system performance quickly are lost without the use of software on the design details. By resorting to the use of computer software exemplified, more visual aspects of elements and the associated details are captured.

The efficacy of the methods described in this study is reflected in the class-room efforts pursued by the author. Relevant strategy of pedagogy described was adopted at the junior level in the Department of Computer and Electrical Engineering and Computer Science at FAU. The general feedback and learning experience indicated by the students has been encouraging. More exercises and design problems are being planned in the near future. Specifically, use of MATLAB^{TM}, PowerWorld Simulator^{TM} and SimPowerSystems^{TM} cohesively in similar analyses and design problems (involving electric power systems) is planned. This will provide the context for the selection of the appropriate computational tool for the task at hand. It is expected that such exposures will enhance the learning potential and fastness in obtaining solutions together with the advantage of visualizations. Classroom learning can be conveniently coordinated with practical design experiments, also.

Bibliography

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2. Hadi Saadat, Power System Analysis, 2010, PSA Publishing

Biographical Information

Dr. Dolores De Groff is an Associate Professor in the Department of Computer and Electrical Engineering and Computer Science at Florida Atlantic University. She has twenty-two years experience teaching in laboratories and in the classroom and in doing research. She has received several teaching awards.