Teaching electrical power systems using computer simulations

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Abstract A computer program has been developed at the Manukau Institute of Technology that can be used for teaching and researching short, medium and long overhead power lines. The program makes use of interconnected icons rather than differential equations written in computer code (text). By using programs consisting of graphical icons it is far easier for students to visualise the power line that they are studying and in addition it makes it simple for them to modify and update the program. Until recently it has been difficult to teach overhead power lines in a meaningful way because the equations modelling the transient behaviour of lines are systems of differential equations and the equations modelling the steady-state behaviour are a set of hyperbolic (or exponential) equations. Both these sets of equations are difficult for students to visualise and interpret. Furthermore, overhead line laboratory exercises that produce realistic results for students are very difficult to arrange in most university laboratories. The program developed at Manukau Institute of Technology overcomes these problems.

Keywords computer; lines; overhead; simulations; teaching

This paper is a further development of work presented at the IEE Symposium in London in 2001 and the UICEE Conference in Auckland in 1999.[6,1] At the IEE Conference programs were presented which covered the steady-state load flow and the transient analyses of small power systems. This paper covers another aspect of power systems, *viz.* short, medium and long power lines. Initially some of the problems faced by lecturers when teaching overhead power lines are explained and then the computer programs that have been developed at the Manukau Institute of Technology for overcoming these problems are described. Finally, this paper presents examples of the typical outputs that may be expected from the program for both the steady-state and transient conditions.

Difficulties encountered in teaching overhead power line theory

Until recently overhead power line theory has been difficult to teach in a meaningful way because:

(a) Three different sets of equations are used to model power lines depending on the length of the line and the accuracy of the answers required. For lines of less than about 80 km in length the capacitance of the line can usually be ignored without an unacceptable loss in accuracy. In this case, the line is modelled by a very simple model consisting of a lumped resistor and a lumped inductor. For lines of 80 km to 240 km the capacitance of the line must be included to maintain acceptable accuracy; however, lumped components may still be used. For lines in excess of 240 km lumped components can no longer be used and distributed parameters must be used to obtain acceptable accuracy. It is often difficult for students to appreciate the effects of these various model changes; in particular, students often have difficulty in interpreting hyperbolic equations. In addition, it is difficult to obtain a feeling for the increase in accuracy provided by the more complicated line models without doing many fairly complex calculations that are difficult to carry out manually.

(b) In order to model the transient behaviour of power lines, irrespective of whether the short, medium or long line models are used, systems of differential equations are required. These equations may be readily solved using computer programs and numerical techniques. The traditional methods for carrying out these solutions, however, do not make it easy for the students to develop an appreciation of how the solutions relate to the line that they are trying to solve. Furthermore, in order to obtain a deep understanding of how the different models behave under transient conditions, it would be advantageous to have a simple way of being able to make comparisons between the various models under these conditions.

(c) Because real power lines operate at dangerously high voltages it has traditionally been difficult to devise laboratory exercises that reinforce the theory covered in lectures. Some means of being able to provide meaningful simulations of power lines that could be used by students for laboratory exercises would be very useful.

Overhead power line program

Researchers at the Manukau Institute of Technology have developed a program that overcomes the above problems encountered when teaching overhead power lines. In order to develop the program the Power System Blockset (PSB) attached to the MATLAB kernel was used.[4] The PSB is a program based on graphical icons that allow the student to develop executable programs using these icons. As shown in Fig. 1, these programs, consisting of interconnected icons, appear as a modified circuit diagram of the power line that they model. Traditionally a power line was represented as a matrix of differential equations for transient analysis or, for steady-

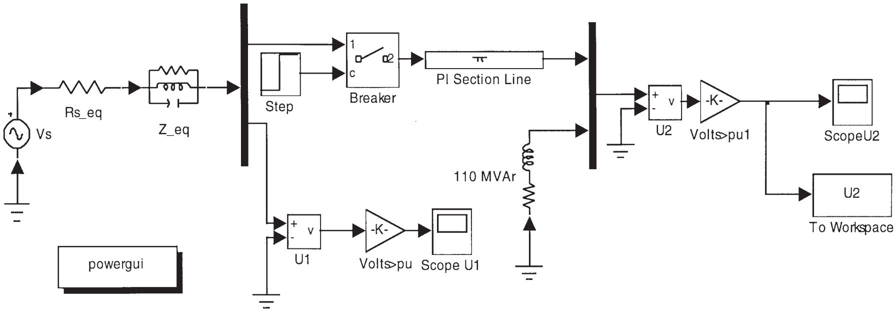

Fig. 1 *Power line program.*

state analysis, as a set of hyperbolic equations that made interpretation and visualization of the total system difficult.[2]

The interconnected icon approach to programming has a number of significant advantages. The most important of which is that it is easy to visualise the power line being programmed because the executable computer program looks similar to a circuit diagram of the line. It is not made up of lines of computer code (text) that, without careful examination, makes one listing of computer code resemble any other listing of computer code. This in turn makes it difficult to relate the code to the physical system being analysed.

A second advantage is that changes to the program may be easily made using the icon-based system. For example, an overhead line model may be easily changed from the short line model to the medium or long line model without re-writing the program or following a special data input procedure. Further, it is clear with an icon-based system where the new component has been added and whether or not it is correct.

A third advantage is that by using these icon-based programs, laboratory exercises may be developed which produce realistic results as shown in the diagrams below. Hydro Quebec in Canada who were the project managers that developed the PSB have thoroughly tested the program to make sure that it produces realistic results.[4] In addition, the Manukau Institute of Technology is running a research project to confirm that the outputs of the programs are realistic.

A fourth advantage is that the programs that have been developed enable research students to do 'what if' analyses on power lines. This is particularly useful if a number of different transient modes of power lines are being studied, for example, the switch on transients under different load conditions or when comparisons are being made of the accuracy of different line models.

Examples of the teaching programs developed

To illustrate the didactic usefulness of the programs developed at the Manukau Institute of Technology two examples are given. The first example is a program that may be used for teaching overhead power line behaviour when the line is being initially energised. The second example is a set of outputs from the program under steady-state conditions which allow the steady-state behaviour to be analysed in detail.

Example a: Overhead power line program

When teaching power lines three different models of a power line are used depending on the length of the line under consideration and the accuracy of the results that are required. The simplest model consists of one resistor and one inductor in series; and the second model, which is slightly more complex and hence more accurate, consists of resistance, inductance and capacitance in a Π or a T configuration.[2] The most complex model involves modelling the power line using distributed circuit parameters in differential equations that have hyperbolic functions for their solutions. It is usually quite difficult to give students a sound appreciation of the differ-

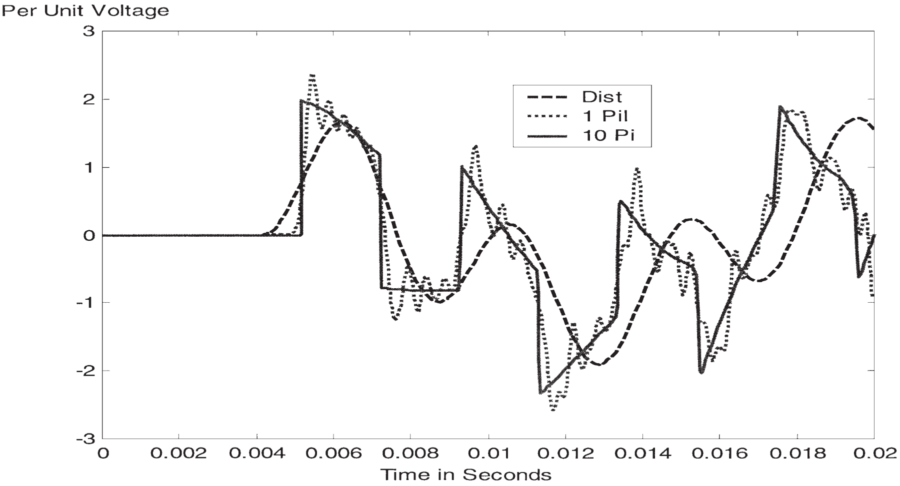

Fig. 2 *Output of the power line program.*

ence between these three models and the sorts of errors that would result if an inappropriate model were used. This is particularly difficult under the transient conditions that occur when a power line is initially energised.

Fig. 1 shows the executable icon-based program that was used to model the three types of power lines. Fig. 2 shows the output of this program for the first few seconds after each of the three line models has been energised. For the reasons given above it would be difficult to teach these effects in any other way than by using computer simulation. The advantage of the icon-based executable program is that the students can easily relate to and visualise the system being investigated. They can then spend time analysing and explaining the results without being distracted by the underlying mathematics.

The program shown in Fig. 1 has also been used as part of a laboratory exercise. The exercise comprised modelling a power line and then investigating its response under steady-state and transient conditions; something that is not easy to replicate using hardware in the laboratory.

Example b: Steady-state long line behaviour

In order to teach the behaviour of power lines under steady load conditions it is necessary to be able to show how the voltage is distributed along the length of a line and how the phase of the voltage changes. Similarly, it is necessary to be able to do the same analysis for the current distribution along the line. This last point can be particularly difficult for students to comprehend because the line at first sight appears not to adhere to Ohm’s Law. However, once the effect of the line capacitance is appreciated it becomes clear that the basic laws of physics have not been contradicted in anyway. The above programs are particularly useful in getting points such as these across to students.

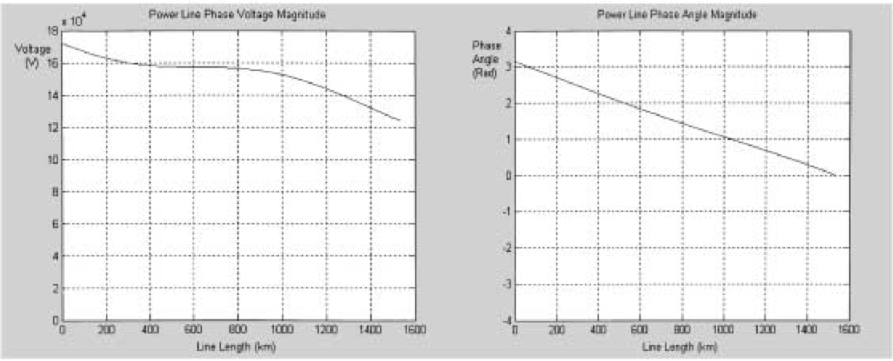

Fig. 3 *Voltage characteristics.*

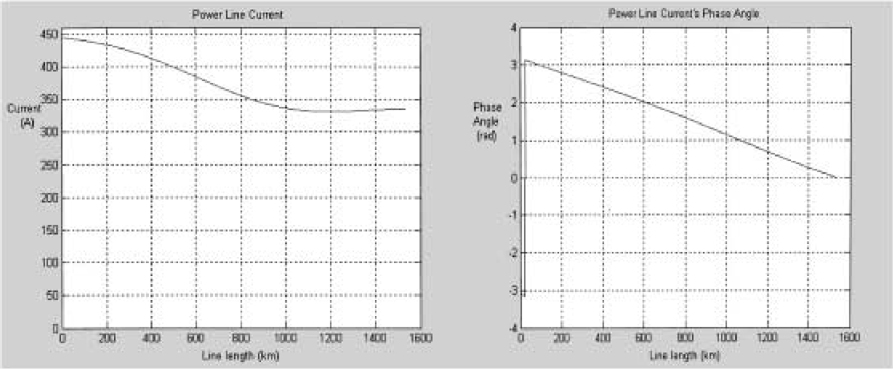

Fig. 4 *Current characteristics.*

As an illustration of the outputs of the steady-state version of the program a 1533 km long, 60 Hz power line constructed from Rook conductor and connected to a 125 MW, 215 kV, unity power factor load has been used. The following graphs were calculated using phase voltages and line currents.

Fig. 3 shows the steady-state voltage profile and the voltage phase angle change along the line. Figure 4 repeats the data in Fig. 3 but for the current profile and the phase change of the current along the line.

It should be noted that the load phase voltage is 124.1 kV and the load current is 335.7 A as expected. It is also worth noting that the phase angle of the voltage and the current at the load are both zero as would be expected with a unity power factor load. However at the sending end of the line the voltage and current are much larger in order to allow for the regulation of the power line. Also for a 1533 km line the phase change of both the voltage and current is 180° or π radians.

It should be noted that the above graphs show the root mean square (rms) voltage and current distributions along the line. The voltage is also a function of time and

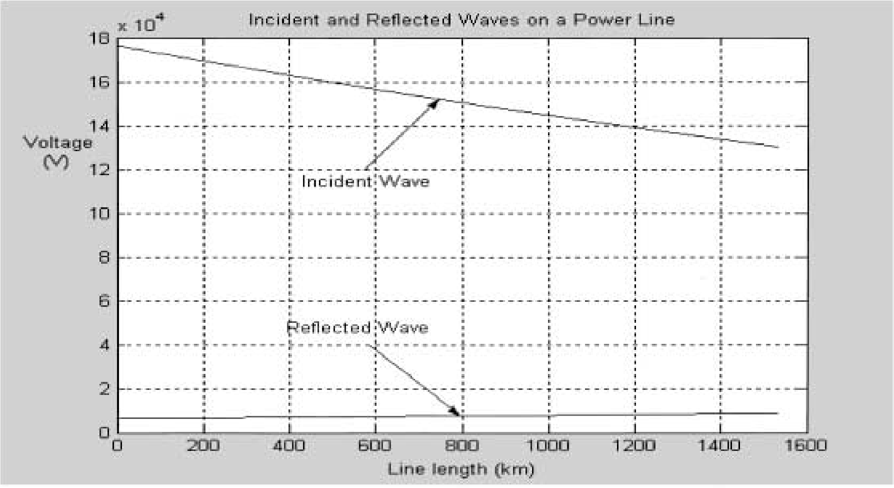

Fig. 5 *Incident and reflected voltage waves.*

this is not shown in the above graphs. It is not necessary to show the time variation because it is obvious that the voltage magnitude shown in these graph oscillates sinusoidally at 60 Hz about zero.

A further interesting use for the steady-state output of the power line program is to illustrate to students that the steady-state voltage along a power line may be thought of as two separate standing waves: an incident wave and a reflected wave. The actual voltage on the line is then the phasor sum of these two waves. Fig. 5 shows these two voltage waves.

In Fig. 5 the line is terminated in a load that is not the characteristic impedance of the line that results in the incident voltage at the load being of a very different value to the reflected voltage wave.

Conclusion

As in reference [5] this paper has further emphasised that complex engineering systems can be taught in a meaningful way by using the latest programming tools. Again, the modern icon-based programming tools allow students more easily to visualise the system they are trying to analyse without being swamped by the mathematics involved. More time can then be dedicated to interpreting and explaining the results of the analysis rather than doing arithmetic.

Students should, therefore, gain a deeper appreciation for real power lines, the various models used to model the lines, and how these complex systems behave under steady-state and transient conditions.

Again, as in reference [6], it must be emphasised that an understanding of the underlying mathematics behind the analysis of complex systems is important or should be understood by the students. A deep understanding of mathematics and its applications is essential for modern engineering; however, large amounts of manual arithmetical processing should be avoided if possible. The program described above should be used only once the students have sufficient mathematical background to appreciate the numerical processing that is taking place in order to produce the results. In other words, the above program is a tool that may be used to avoid large amounts of manual arithmetic but should not be used as a means of avoiding the use and understanding of fundamental mathematics.

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