AN INTERACTIVE PC-BASED ELECTRICAL POWER SYSTEM SIMULATOR FOR ENGINEERING EDUCATION

X. Ma, C. J. Taylor, M. J. Joyce

Engineering Department, Lancaster University, Lancaster UK LA1 4YR

ABSTRACT

The research scheme proposed in this article describes the development of a PC-based teaching/learning approach to power systems education. The paper describes an illustrative network system to be modelled and the software's capabilities and features, as implemented using MatLab. Simulation functions are introduced for teaching and learning purposes, in order to help students better understand complex electromagnetic transient phenomena of electrical power systems under various system fault conditions. The teaching impact of the simulator is discussed, with a focus on how students using this approach are supported with regard to developing their skill set, transferable knowledge and future career. The work demonstrates that adopting such an innovative simulation approach can allow for rapid simulation-based experimentation, and facilitates student learning in a safe and cost-effective environment, particularly where practical student experience is not otherwise feasible.

KEYWORDS

Power system modelling, digital simulation, computer programming, interactive, experiential learning

INTRODUCTION

Digital simulation has been applied in many fields e.g. aerospace [1], aeronautics [2] and chemical production [3]. A digital simulator is superior to an analogue simulator because of its high accuracy and software flexibility and also because of its low cost. Digital computer simulation is widely used in power system analysis. There have been a great number of well developed programs in various R & D and educational aspects of power systems [4 – 6].

One convenient and powerful approach is to use digital simulation tools to support teaching and learning, and to integrate these into power engineering courses. Such a power system simulation allows engineering students to understand the fundamentals of electrical power systems in an interactive way. Instead of using physical system components, the simulator configures circuit and component parameters freely, based on software models.

A Matlab-based electrical power system simulator is proposed in the paper. The simulator is designed to help students at different levels, to better understand and to provide detailed insight into complex electromagnetic transient phenomena of power systems under various fault conditions. In particular, it will provide engineering students with an effective and complementary learning method to understand power system responses and their dynamical characteristics. The paper starts with a description of an illustrative network system to be modelled and of the software's capabilities and features implemented. Simulation functions are subsequently introduced for teaching and learning purposes. The teaching impact of the simulator is discussed, with a focus on how students using this approach are supported in terms of their skill set, transferable knowledge and future career developments.

POWER SYSTEM SIMULATOR

Network Modeling

A simplified electrical power system to be simulated is shown in Figure 1. On the generation side (M) and the receiving side (N) there are two AC power sources which are connected via transformers, circuit breakers, a transmission line with local load, CTs and PTs. The current transformer (CT) and the potential transformer (PT) are instrumental devices used to measure high-range electric currents and voltages respectively, which are normally interfaced to power control equipment using signal conditioning hardware. The power sources are assumed as ideal 3-phase sources and the transformers have an ideal turn ratio with only leakage impedance being considered. The transmission line is represented by its positive-negative-zero sequence impedance by neglecting the capacity of phase-to-phase and the capacity of phase-to-ground. Nevertheless, the simplified system can adequately represent the right AC components and asymmetric DC components of voltages and currents in system fault conditions.

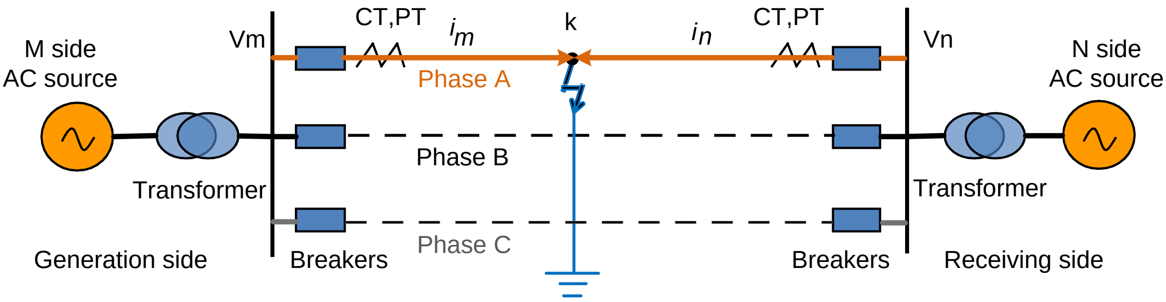


Figure 1 Simplified electrical power system

Table 1
Electrical Parameters of the Simulated System

X_{sm}, R_{sm}	Impedance of M side AC source
X_{sn}, R_{sn}	Impedance of N side AC source
X_{tm}, R_{tm}	Leakage impedance of M side transformer
X_{tn}, R_{tn}	Leakage impedance of N side transformer
X_1, R_1	Positive sequence impedance of the transmission line
X_0, R_0	Zero sequence impedance of the transmission line
E_{ma}, E_{mb}, E_{mc}, E_{na}, E_{nb}, E_{nc}	Phase voltages of power source at both sides
i_{ma}, i_{mb}, i_{mc}, i_{na}, i_{nb}, i_{nc}	Phase currents feeding from two sides of the line
V_{ma}, V_{mb}, V_{mc}, V_{na}, V_{nb}, V_{nc}	Bus voltages at both sides

The electrical parameters of the simulated system are given in Table 1. Take phase A as the example. Under normal conditions, i.e. no fault, the differential equation of phase A can be described by Eqn (1), where the boundary condition $i_{ma} = -i_{na}$ applies.

$$E_{ma} - E_{na} = \frac{X_{sm} + X_{tm} + X_1 + X_{tn} + X_{sn}}{2\pi f} \, di_{ma}/dt + (R_{sm} + R_{tm} + R_1 + R_{tn} + R_{sn}) i_{ma} \qquad (1)$$

When an AG (phase A grounded) fault occurs at location k, the electrical topology of the system changes accordingly. The differential equations of phase A can be described by Eqns

(2) – (7), where V_{m0} and V_{n0} denote the zero sequence voltage of the neutral connector of the transformers at M and N sides respectively and fault location k is represented by its percentage of the line.

$$E_{ma} + V_{m0} = \frac{X_{sm} + X_{tm} + kX_1}{2\pi f} di_{ma} / dt + (R_{sm} + R_{tm} + kR_1) i_{ma} \quad (2)$$

$$E_{na} + V_{n0} = \frac{X_{sn} + X_{tn} + (1-k)X_1}{2\pi f} di_{na} / dt + (R_{sn} + R_{tn} + (1-k)R_1) i_{na} \quad (3)$$

$$V_{m0} = \frac{kX_0}{2\pi f} di_{m0} / dt + kR_0 i_{m0} \quad (4)$$

$$V_{n0} = \frac{(1-k)X_0}{2\pi f} di_{n0} / dt + (1-k)R_0 i_{n0} \quad (5)$$

$$i_{m0} = -(i_{ma} + i_{mb} + i_{mc}) \quad (6)$$

$$i_{n0} = -(i_{na} + i_{nb} + i_{nc}) \quad (7)$$

If phases B and C work under normal conditions, their differential equations can be described similarly by Eqn (1) where only current and voltage symbols need to be replaced using those of phases B and C respectively. Therefore, three simultaneous differential equations are formed at each side with three unknown phase currents to be determined. The differential equations can be numerically solved using a suitable iterative algorithm such as a higher order RK (Runge-Kutta) method to minimise the round-off errors in calculation. Having obtained the phase currents, bus voltages can be calculated based on Eqn (8, 9) by taking phase A as the example.

$$V_{ma} = E_{ma} - \frac{X_{sm} + X_{tm}}{2\pi f} di_{ma} / dt + (R_{sm} + R_{tm}) i_{ma} \quad (8)$$

$$V_{na} = E_{na} - \frac{X_{sn} + X_{tn}}{2\pi f} di_{na} / dt + (R_{sn} + R_{tn}) i_{na} \quad (9)$$

By arbitrarily setting the initial load condition and fault situation, the system under various fault conditions can be simulated. The results show the dynamical changes of bus voltages and phase currents of the system under normal and abnormal operating conditions.

Software Implementation

A graphical user interface (GUI) which integrates with the simulation engine was developed in the MatLab programming environment. The interface allows students to configure freely initial power flows and fault conditions including location, type and status. The fault type can be one-phase grounded, two-phase short circuit, two-phase grounded, three-phase short circuit, three-phase grounded, phase breaks or complex faults. The GUI displays the steady state voltages and currents prior to the faults and their electromagnetic transient behaviours during the fault period.

The software structure is designed on a modular basis, enabling more functionality to be added to meet more flexible teaching and learning requirements. Apart from system fault simulations, the simulator also includes modules of electrical power system oscillation and harmonics analysis. The addition of new modules provides students with an improved insight into power plant response and power system dynamical characteristics.

Simulation results can be exported into a file format which can be further processed by programs such as Excel. The data files can also be downloaded into a digital storage oscilloscope (DSO) via an internet link for waveform replay when required.

SIMULATOR FUNCTIONS FOR TEACHING DELIVERABLES

System Operation and Fault Analysis

The main function of the simulator is to simulate various types of short circuit fault occurring in the transmission line including faults evolving from a simple one to a more complex one. Fault location k can be set arbitrarily at any position on the line. The fault can be transient or permanent. The fault resistor can be zero (directly grounded) or a specific value that is defined by program.

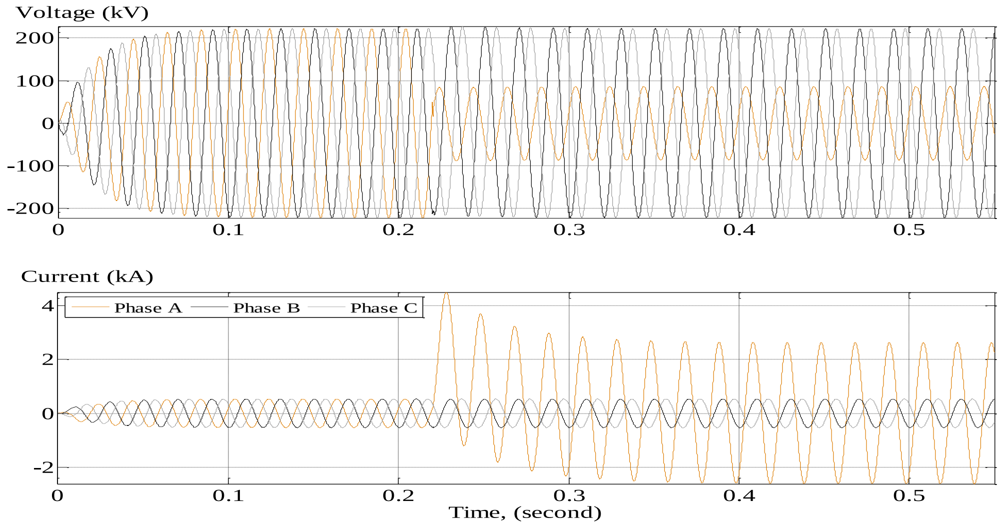
A case study is considered in this paper to simulate two substations connected via one 100 km transmission line. Table 2 gives the main parameters used to configure the case study system. Two fault positions are chosen; k1 is defined as midpoint on the line whereas k2 the point between transformer and breakers at M side. Breakers at both sides are independently timed controlled and default status is closed. System voltage of 275 kV is chosen since this is a popular voltage level in the UK transmission system. By adjusting phase angle between two power sources, the correct power flow can be obtained. In this case, M side power source leads N side 20 °, which means that substation M is a generation side and substation N is a receiving side.

Table 2
Case Study System Configuration

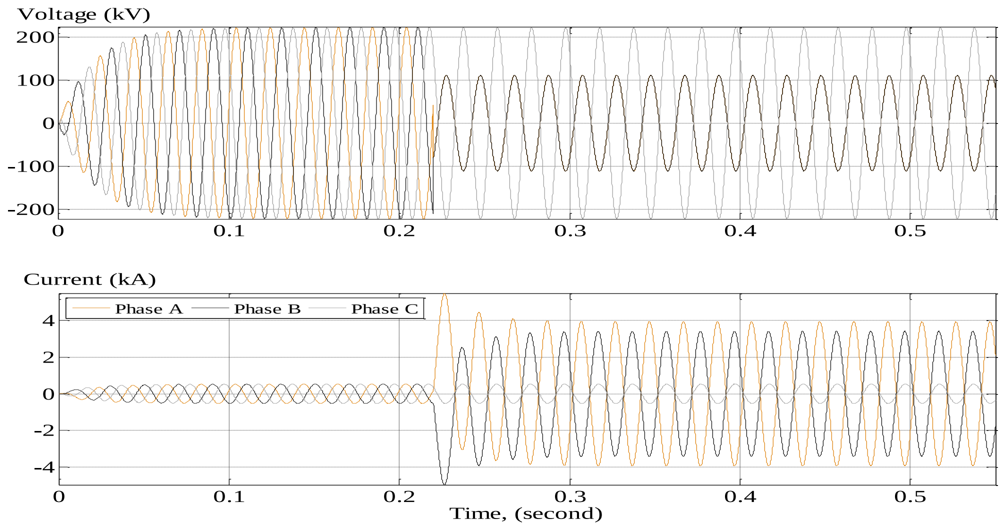
	Substation M	Substation N
Power source	100 MVA, 275 kV, 20°, 50 Hz	100 MVA, 275 kV, 0°, 50 Hz
Voltage setup time	0.2 s	0.2 s
R_s, X_s	1 Ω, 0.1 Ω	1 Ω, 0.1 Ω
R_t, X_t	1 Ω, 0.1 Ω	1 Ω, 0.1 Ω
Breaker	Default is closed	Default is closed
AG	Phase A grounded fault	
AB	Short circuit fault between phase A and phase B	
ABCG	Three-phase grounded fault	

As an example, Figure 2 shows bus voltages and phase currents at M side when a permanent AG fault at position k1, AB fault at position k2, and ABCG fault at position k1 occur respectively. The waveforms of the first 0.1 second simulate the time duration for the system to stabilise, which is determined by the source voltage setup time configured for the system. The faults start at 0.22 s as controlled resulting in a significant change in both voltages and currents on fault phases. The voltages become small whereas the currents are larger due to the short circuit nature compared to their steady state levels prior to the fault.

The fault can be transient, which implies that it disappears after a time period. Figure 3 shows the voltages and currents of the examples given in Figure 2 with a fault time duration of 0.15 s being applied. After the fault varnishes at 0.37 s, the levels of voltage and current on fault phases return to the steady state levels after stabilisation.



(a)



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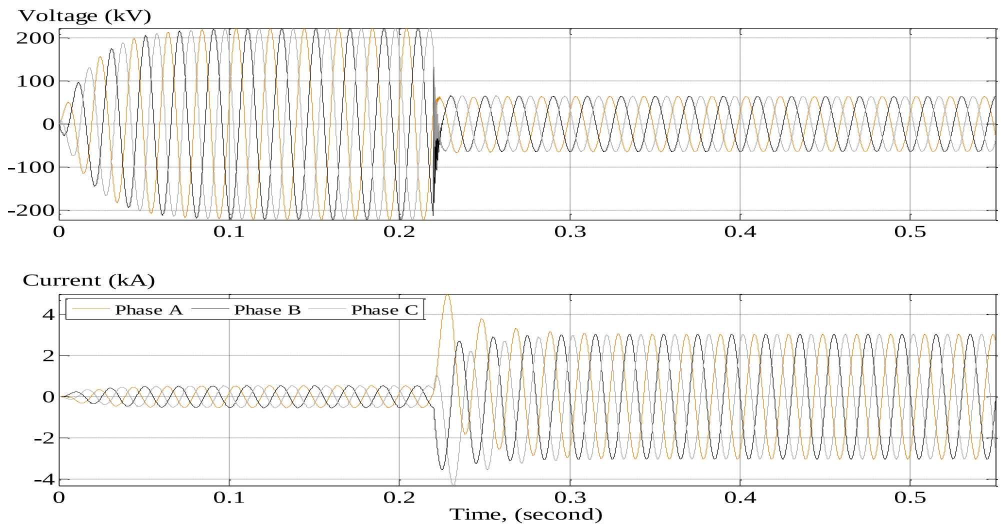
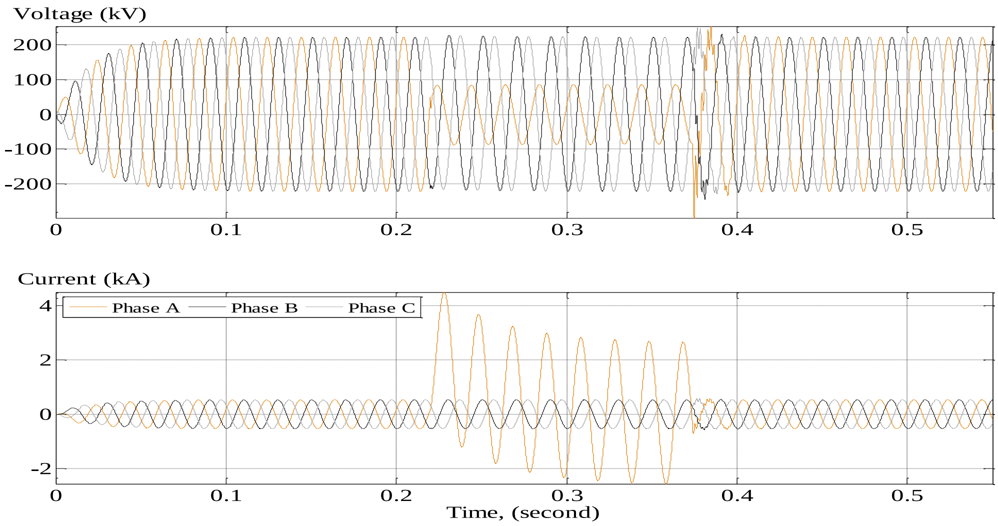


(c)

Figure 2 Voltages and currents under permanent faults (a) AG at K1, (b) AB at K2, (c) ABCG at K1



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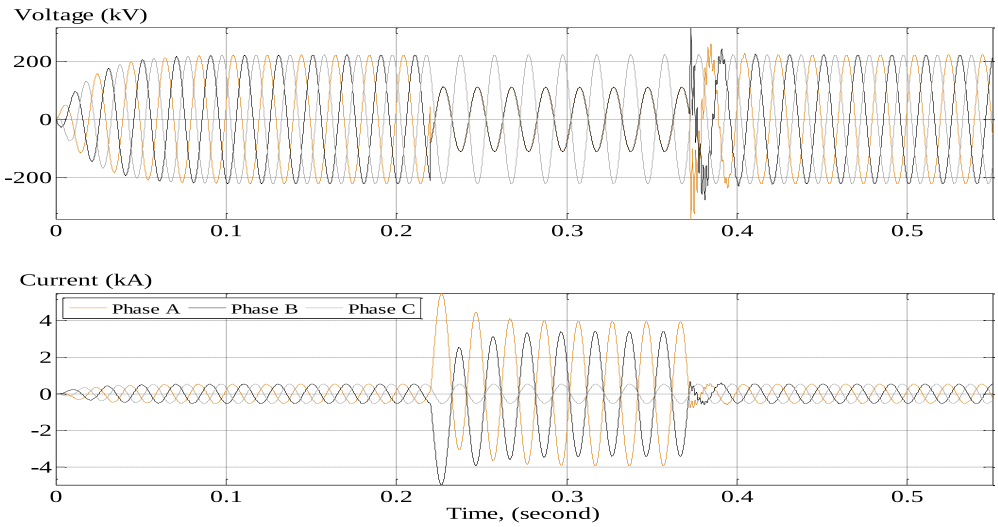

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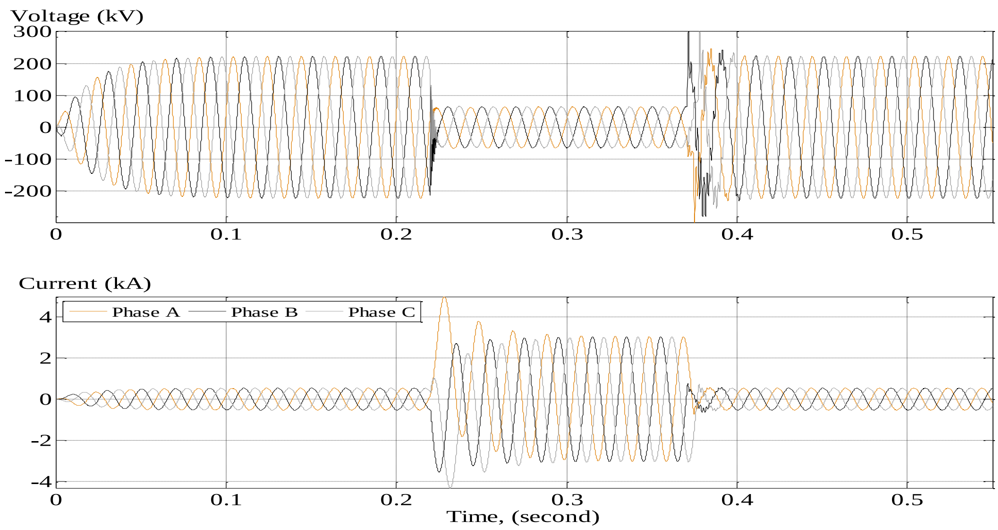


(c)

Figure 3 Voltages and currents under transient faults (a) AG at K1, (b) AB at K2, (c) ABCG at K1

Power System Protection

An accumulation of faults can lead to catastrophic failure and hence cause outages with serious health and safety, environmental and economic consequences. Therefore, the protection of electrical power systems will be essential. This can be realised by setting breaker clearing time and reclose time to reflect the on / off state of the circuit breakers in each phase. Figure 4 shows the voltages and currents under breaker controls where the breakers are controlled to trip off at 0.33 s and reclose at 0.38 s. In this case, circuit breakers trip off after the fault lasts for 0.11 s since initiated; the fault is cleared when circuit breakers reclose at 0.38 s. Breaker clearing time and reclose time can be adjusted in the simulations if needed.

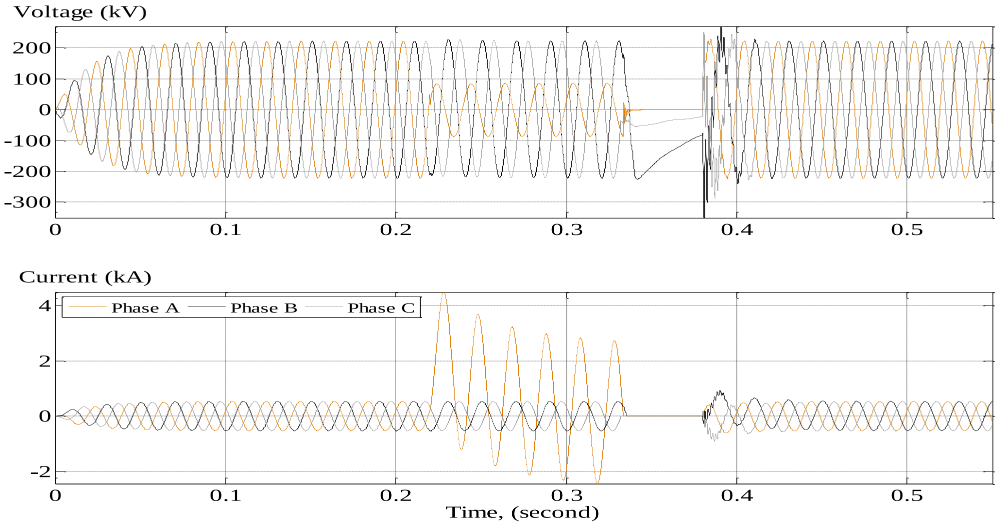
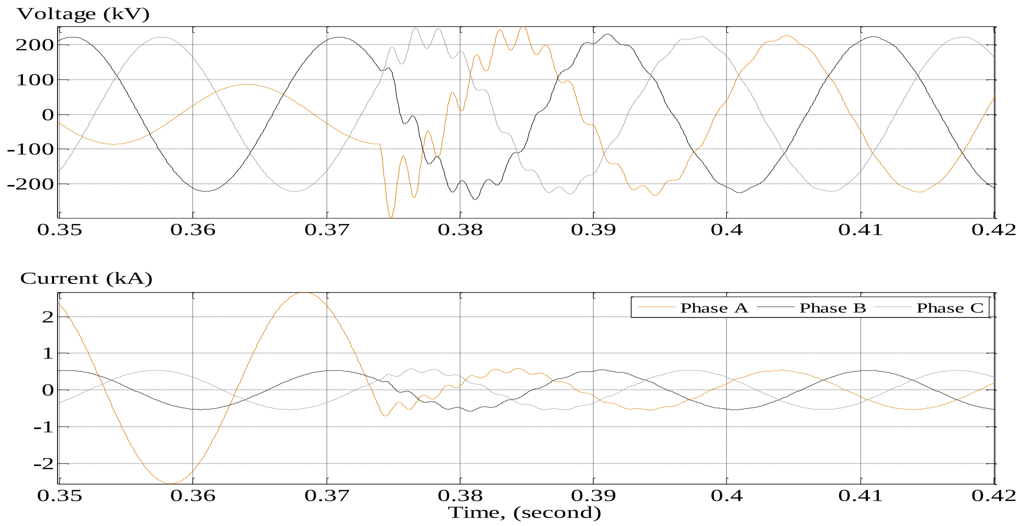


Figure 4 Voltages and currents under breaker controls under AG at K3

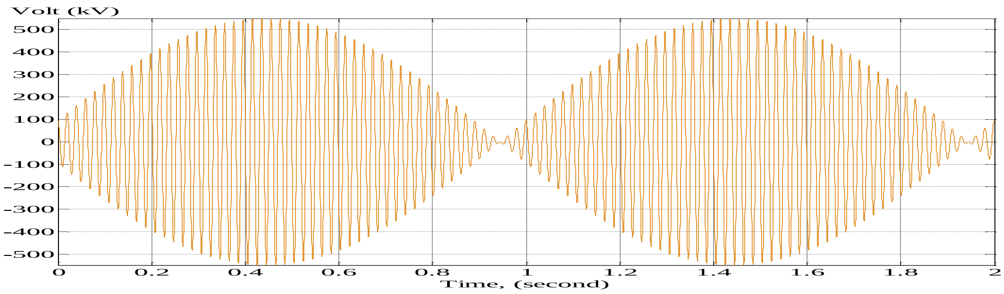
Power System Oscillation

A fault on a transmission line may excite oscillations due to the external disturbances it causes [7]. The voltages at the fault are small indicating active power transformed on the line is decreased. In reality, this will cause the generators that are unable to deliver power to speed up and, therefore, swing against the rest of the system. The oscillations are mitigated in the simulations because the dynamics of generators are simplified with ideal AC power sources. However, fault controls and the operation of circuit breakers still can interact with the system giving rise to voltage and current oscillations, which can be seen from the transient behaviours in Figure 3 and Figure 4. Figure 5(a) illustrates an enlarged section of Figure 3(a) after the AG fault is cleared showing the oscillation frequency is approximately 2.5 Hz before stability reaches.

If the power source at M side is set purposely to swing against the N side, for example at 1.0 Hz, the system yields unstable oscillations leading to an out-of-step event. This can be illustrated in Figure 5(b), where the oscillations behave like AC signals but are modulated by the swing frequency in the magnitude. Unstable oscillations may lead to rapid system collapse if proper measures are not taken.



(a)



(b)

Figure 5 Power system oscillations (a) stable oscillations, (b) unstable oscillations

TEACHING IMPACT

Skill Sets

The simulator can be used by a wide range of students, including: (i) students seeking ways in which to better understand difficult classroom concepts in power engineering; (ii) students trying to learn and enhance their skills in a more interesting context; (iii) students looking for ways to improve their numerical analysis skills in solving real-world differential equations that are dealt with in calculation; and (iv) students wishing to apply computer programming skills to the GUI design of the simulator.

The multidisciplinary approaches involved in the simulator require that students should have fundamental skills relating to objectives and schedules, analysing problems, understanding the structure and performance of the simulator, gathering and processing useful information from simulation data. These skill sets can be achieved by taking university courses such as computers and control, elementary calculus dealing with differential equations, and the fundamentals of power energy systems. The simulator is essentially designed to aid classroom teaching and learning of major courses in electrical power engineering. It can be a platform for the students to continuously develop their skill sets from the use of the simulator during their course of learning.

Transferable Knowledge

The simulator provides the students with an illustrative tool to help them bridge the gap between theory and the practical operation of a power system. Students can effectively interact with the electrical power system modelled by the simulator. It is difficult for students to operate a real power system to understand the system's response characteristics. Therefore, it is important to analyse a system's behaviour in order to understand the system's capability and limits using simulation.

As with most toolboxes developed for use in MatLab, the simulation programs are open to learning from the students. For example, a toolbox is designed in the simulator which allows students to configure the system including fault type, location, duration and development, and to understand how the system responds to the settings, with various combinations of the actions from circuit breakers. Mathematical solutions to the differential equations of the modelled system can be offered with different numerical methods in addition to the RK method. Students can be challenged by selecting different methods for in-depth analysis of the system in terms of minimising round-off errors and the length of time needed to complete all calculations. By taking advantage of modular basis design, more functionality can be added in the simulator to meet changing teaching and learning requirements. The simulator can be interfaced with large power simulation tools such as PSCAD/EMTDC by which students gain the knowledge about the dynamics of a more complex power system if needed. Students are also encouraged to return information regarding the use of the simulator to the tutor, so that the simulation programs can be improved, particularly with regard to their ease of use and flexibility.

Career Developments

One of the possible careers available to engineering students is a power system analysis engineer. In this regard, the simulator is an ideal demonstration and learning tool to show simulation techniques, power system dynamics and operation. By being trained on the simulator with a number of case studies, the students gain insight into the system operation in an interactive learning environment where they are an active part of the simulation.

Another relevant career would be protective relay engineers. As described above, power system protection is simply modelled by setting the on/off state of the circuit breakers on the transmission line. In reality, on/off state of circuit breakers is controlled by a protective relay installed at either end of the line and connected to CTs and PTs at its side. Figure 6 shows a schematic arrangement of protective relay connected to the simulated system. Briefly, the simulated bus voltages and phase currents are sent to the relay. The relay operates if the fault location is within the protection zone and relay signals are fed back to affect the simulation by opening and reclosing breakers. The main components of relay equipment can be simulated and integrated into the simulator, including signal processing to extract fundamental magnitude and phases, and typical protection schemes such as distance protection and over-current protection. The use of this approach would enable students climb the career ladder as potential protective relay engineers if they wish.

The knowledge and expertise gained from this simulation program may also help the students into another career ladder as system simulation engineers. The simulator can be easily developed into a real-time one if it performs on a high-speed computer. True close-loop simulation can be achieved if the simulator is equipped with a suitable hardware I/O interface. This would be beneficial for those students who want to develop their careers beyond power engineering such as industrial process applications and even in the creative game industries.

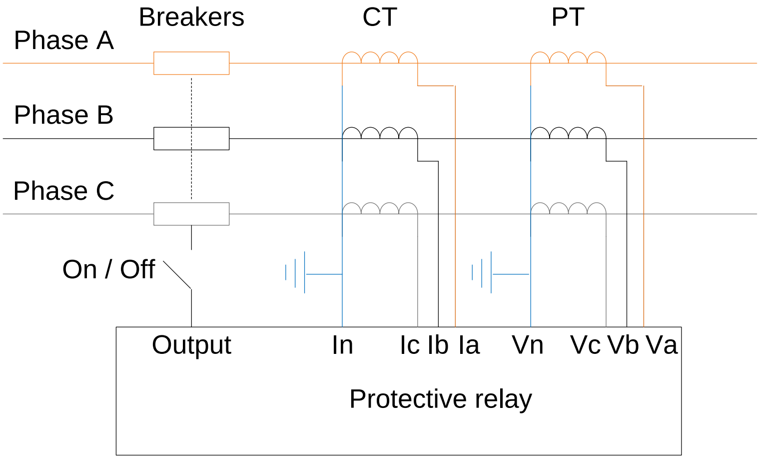


Figure 6 Schematic arrangement of protective relay

CONCLUSIONS

This paper has presented a modular simulation software framework, which is intended for educational use in power engineering. The study has shown that difficult concepts in power engineering can be effectively addressed in an interactive way, thus sustaining and increasing the students' learning interests. The simulation programs have been designed to accommodate representative types of unhealthy conditions of electrical power systems, including various types of fault situation and system oscillations. The proposed simulator can be effectively used to support power engineering education, coursework or projects.

The desire for cost-effective teaching is balanced by the ideal of giving students the opportunity to solve real design problems. Since its inception, the teaching goals of the Engineering Department at Lancaster University have focused on a multidisciplinary approach to real world applications. To this end, the Department puts great effort into the development of stimulating research and industry-based projects applicable to all parts of the degree scheme. However, these projects are supported by the use of innovative simulations tools such as the package described in the paper, which allow for rapid simulation-based experimentation, and facilitates student learning in a safe and cost-effective environment or where practical student experience is not feasible.

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Biographical Information

Xiandong Ma is a Lecturer for the Engineering Department at Lancaster University, and for the CDIO Initiatives at Lancaster. His current scholarly interests are sustainable power energy and health condition monitoring of power plant.

James Taylor is a Senior Lecturer in the Engineering Department at Lancaster University. He works on both theoretical and application aspects of computer-aided control system design, with earlier projects funded by the EPSRC, European Community and the Highways Agency. Applications of this research include nuclear decommissioning robots and environmental control systems; and the development of a Captain Toolbox for time series analysis.

Malcolm Joyce is a Full Professor in Nuclear Engineering and Head of Engineering at Lancaster University, UK. He specialises in the research and development of nuclear instrumentation, especially for fast, digital, mixed-field analysis and has pedagogical interests across electronics, safety engineering and nuclear engineering. He holds a National UK Teaching Prize from the Royal Academy of Engineering (2005) and a Lancaster University Commercialisation Staff Prize and is a Chartered Engineer, Chartered Physicist and a Fellow of the Nuclear Institute and of the Institute of Physics.

Corresponding author

Dr. Xiandong Ma
Engineering Department
Lancaster University
Lancaster
UK LA1 4YR
44-1524-593700
xiandong.ma@lancaster.ac.uk