Fault Simulation for Hardware Emulation

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Abstract—This paper describes the details of the research completed by the author at the University of Tennessee at Knoxville during the summer of 2016. It mainly focuses on the attempted software design during the program, including application and implementation. While this simulation had not been completed by the end of the program, many significant steps were taken toward completing the software development. The paper also discusses other work done by the student, specifically his assistance in hardware construction.

Index Terms—Faults, Fault protection, Fault transients, University of Tennessee at Knoxville, Simulink, Hardware Test Bed

1 INTRODUCTION

Every summer, the Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT) at the University of Tennessee at Knoxville takes in undergraduate college students to participate in an eight week research program. As a part of this program, the student John Curtin spent eight weeks conducting research, as well as performing other tasks. The research project assigned to the student was to create a computer program that simulates the effects of a fault on an electric power transmission system. While the end goal of this project was not met, many significant steps were taken toward the completion of the project, which will help in the eventual completion of the project.

2 BACKGROUND

This project was assigned to the student so that it could be implemented on the hardware power system simulation device called the Hardware Test Bed (HTB.) This is significant because the accurate simulation of faults would improve the overall functionality of the HTB drastically.

2.1 Faults

Faults are important to consider because the instabilities caused by faults are arguably the greatest existing threat to an electrical power grid. The damage that faults are capable of causing can easily lead to large-scale blackouts and equipment damage. This implies that, in the worst case scenario where a shunted power system fault has zero impedance, the current that passes through the fault is the parameter that protection equipment is designed around. This protection equipment, typically consisting of circuit breakers and relays, is what prevents large-scale blackouts and equipment damage. It is also worth noting that the fault current is the most significant parameter in fault calculation.

In real power systems, most faults are significant enough that they cause the protection equipment in the system to trip, preventing significant damage to the system. However, the protection equipment, consisting of relays that detect the faults and circuit breakers that open the power lines and clear the faults, takes a small amount of time to trip. In this time, the fault may have a significant effect on the power system, which the program made in this project would ideally be able to measure.

There are many different kinds of power system faults, including Line-to-Line, Line-to-Ground, Three-phase, and Double-Line-to-Ground.[1] These are the four categories of faults that have been considered in this project, and characterize many real-world power system faults. An example of one of these faults
can be seen in Figure 1, which shows the basic circuit model of a Line-to-Ground fault.

![Circuit model of a Line-to-Ground fault](image1)

**Fig 1:** Circuit model of a Line-to-Ground fault

It can be seen that this fault can be accurately characterized by a circuit model. While this is a simple concept, it is important in understanding the analysis that has been used in this project.

Another important aspect of fault analysis is the complete characteristic current waveform that is created by a typical fault. This waveform can be characterized by a DC offset current, a sub-transient and transient AC waveform, and a steady-state AC waveform. All of these components decay over time, typically very quickly, except for the steady-state AC component.[2] This can be visualized in Figure 2.

![Fault current with all components](image2)

**Fig 2:** Fault current with all components

In this figure, it can be seen that there is a large current spike at the time the fault occurs, in this case time zero, followed by a gradual decay into the steady-state stage of the waveform.

### 2.2 Hardware Test Bed

The Hardware Test Bed (HTB) is, essentially, a hardware device that is used to simulate electrical power grids. This is done using sets of three-phase AC-to-DC power converters. This works in such a way that back-to-back converters are used to simulate loads and generators. This concept can be visualized in Figure 3.

![back-to-back HTB converter model](image3)

**Fig 3:** back-to-back HTB converter model

Once the hardware is put in place, the system is controlled through software, which is written in the C programming language and programmed onto the DSP chips that control the AC-to-DC converters. This allows for control of the sending and receiving end voltages, as well as the line impedance. These values can then be used to calculate the line current, which fully parametrizes the system. This simulation method has the advantage of real-world component variation, in other words, time-variant voltages and line impedance. This is a much more accurate representation of the real power grid than a computer simulation and can also be used to test certain hardware devices to be put into the power grid. This simulation also works completely in time-domain, improving the overall accuracy.

It should be noted that the HTB uses the short transmission line approximation to model power systems. This approximation does not include the shunt capacitance and conductance seen in the complete transmission line model. As the name implies, this approximation is accurate for short, overhead power transmission lines. It should also be noted that the HTB is already capable of simulating open-circuit faults.
This is done simply by making the variable inductance parameter of the HTB very large, which causes the AC voltage waveform to see the inductance as an approximate open circuit.

The physical hardware configuration that makes this system possible is made up of several hardware cabinets, such as the ones shown in Figure 4.

Fig 4: Several cabinets of the HTB

The cabinets shown in Figure 4 contain many electrical components to make the power system emulation possible, such as inductors and power converters.

During his time here, the student was able to assist in the construction of one of the transmission line cabinets and the inductor cabinet that will be used in the four area configuration of the HTB. It is worth noting here that, while the program does focus largely on pure research, the skills required to build these cabinets are valuable engineering skills that are in demand in both industry and academia. These skills include metalwork, soldering, wiring, crimping, and many other fundamental hands-on skills not included in most academic engineering programs. With this in mind, incorporating more practical skills such as these is an idea worth considering for future research projects.

3 Procedure
This project was done using a step-by-step procedure. The student would begin by researching background information he needed for his project. The student would then go about putting the useful information he found into software using Simulink and testing that software to obtain the desired end results. The idea was that this Simulink software could be used as a stepping stone to write the C code that would be put into the HTB.

3.1 Background Research
The student began by finding several readings on fault analysis, as he had not taken a fault analysis course before attending the program. In his research, he found that most conventional methods of fault analysis use the phasor-domain technique of symmetrical components.[1] While this is fine for calculating the maximum possible current magnitude, it does not incorporate transient effects. This is due to the lack of a dynamic, changing frequency variable in phasor-domain analysis. As the project assigned to the student was to create a complete fault calculation model, this method would not have been suitable due to the fact that it does not include transient effects.

He also found that many assumptions and approximations in these phasor-domain analysis methods. For instance, the assumption is made that all currents other than the fault current are zero, which can be justified by saying that those currents are very small relative to the fault current.[1] These assumptions are fine for determining how to configure protection equipment, as they are made so that the equipment prepares for the worst-case scenario of a fault. However, this project requires that no assumptions are made, so that the most accurate results can be obtained. This is important for many of the research projects that the HTB is used in.

Consequently, the student proceeded to research many different areas of power systems analysis trying to find some that would help him solve his problem. These areas of analysis include d-q coordinates, the Z-bus method, and generator stability. Unfortunately, a great deal of time was spent researching these topics, which, while they are useful in certain areas, turned out to be unhelpful for the research project.

After consulting a few of the graduate students, the research student was able to obtain a
feasible method for completing the project. This method was to model the fault current using s-domain transfer functions and simulate those models using Simulink. The reason that this would work can be best explained using the characteristic equation of the s variable, shown below as Equation 1.

\[ s = \sigma + j\omega \]  (1)

In this equation, \( \sigma \) can be thought of as the amplitude variable of the signal. This means that a positive value increases the time-domain oscillation amplitude, a negative value decreases the oscillation amplitude, and a zero value causes no change in the oscillation amplitude. This is complimented by the \( \omega \) variable, which can be thought of as the angular frequency variable. This variable determines the frequency of the sinusoidal time-domain waveform. Together, these components form a variable, s, that can be used to accurately characterize the time-domain functions used in this project. The kinds of time-domain waveforms that this variable can simulate can be visualized in Figure 5, which shows the time-domain waveform of the current of a faulted power grid.

It should also be noted that use of the s variable requires that the function start at time zero and that the function is continuous. However, neither of these constraints are an issue because the initial time can be set to zero in the simulation and there is a method for digitizing the s variable known as a Z-transform.

3.2 Implementation

The student began by drawing and analyzing the equivalent circuit models that the HTB would simulate. Once these models were completed, the student would go about creating the simulation programs in Simulink. If time had permitted, the student would have used these simulations to create C code that would have been used to simulate faults on the HTB.

3.2.1 Modeling

The circuit models used in this project, as mentioned before, use the short transmission line approximation. This means that, in each branch of the circuit, there will only be a series resistance and inductance. While the line impedance of a short transmission line is still a distributed parameter, this can easily be remedied. This is done by using the line length and the location of the fault. Any phases that the fault does not directly impact will have their distributed impedance multiplied by the total line length. Similarly, the phases that are directly impacted by the fault will have their sending end impedance multiplied by the length of the line from the sending end to the fault. Likewise, their receiving end impedance multiplied by the length of the line from the receiving end to the fault.

This causes what could be complicated transmission line models to become simple circuits, which can be analyzed using simple circuit analysis techniques. For example, the circuit model of a typical Line-to-Ground fault is shown below in Figure 6.
It should be noted that in this figure, the sending and receiving ends of the circuit are connected to ground, as they are in the HTB. The receiving end voltage is also modeled as a voltage source, just as it is in the HTB.

Using this circuit model, equations for the post-fault sending and receiving end currents can be derived. The resultant equations for this case can be seen in Equations 2 and 3.

\[
i_A = \frac{V_A (Z_a + Z_f) - V_a Z_f}{Z_A Z_f + Z_a (Z_A + Z_f)}
\]

\[
i_a = \frac{V_A + Z f - V_a (Z f + Z_A)}{Z_A Z_f + Z_a (Z_A + Z_f)}
\]

Equation 4 can then be used to find the fault current.

\[
i_f = i_A - i_a
\]

In order to find the pre-fault current, one simply takes the fault branch out of the circuit and analyzes that new circuit. The resulting line current for this case can be seen in Equation 5.

\[
i_A = \frac{V_A - V_a}{Z_A + Z_a}
\]

This modeling process was done for each of the previously mentioned fault cases. Once this was done, it was appropriate to begin simulating these models in Simulink.

### 3.2.2 Simulation

In order to create a complete model for the line and fault current that can be used for the HTB, it is necessary to include all of the previously mentioned transition states of the current. These states are the pre-fault steady-state, transient state, and post-fault steady-state. The student consequently decided to create different simulations until this result was achieved.

The student first attempted to use the static transfer function blocks, as well as the typical sinusoid and mathematical operator blocks available in Simulink. The idea behind this method is that one can initially run the simulation using the pre-fault transfer function. Then a switching mechanism can be used to switch from the pre-fault transfer function to the post-fault transfer function at the time of the fault. Unfortunately, while this method can give accurate results for the pre-fault and post-fault current, it does not give the transient effect. This can be seen visually in Figures 7 and 8.
Figures 2 and 5. After several attempts with this method, it was determined that the use static transfer function blocks would not work.

It was then decided that the use of a dynamic transfer function, with variable coefficients, would be necessary. These kinds of transfer functions are commonly used in adaptive control systems, but can be used for this model as well. There are several methods for implementing this kind of transfer function in Simulink, which can be found on various locations on the Internet.

One such method is to use a Simulink block called “Time Fcn Direct Form II Time Varying,” which allows the user to input the coefficients of the transfer function as a vector.[3] The block will use linear interpolation between the indexes of the vectors to create varying coefficient values. By using large vectors with many indexes, one can create approximate step functions that can be used to switch the coefficients at the time that the fault occurs with minimal error. If successful, this method would produce the desired result of a complete time-domain current waveform. However, it is worth noting that this is a fairly high-level Simulink block, so translating it into C code for the HTB might be difficult. Unfortunately, as the student was investigating this method and trying to implement it, he ran out of time and had to do the final documentation for the program.

4 CONCLUSION

While the project was not finished, many steps were taken toward completing it. In future attempts at doing this project, it is recommended that dynamic transfer functions be looked into, for the reasons mentioned earlier. This was an overall enjoyable experience for the student, which he would recommend to other students in the future.

ACKNOWLEDGMENTS

The author would like to thank the Department of Energy (DOE) and the National Science Foundation (NSF) for providing funding to this summer research program. He would also like to thank the University of Tennessee at Knoxville for hosting him during this program. Additionally, he would like to thank the following people, who continuously helped him throughout the summer with any questions he had. These people are: Dr. Fred Wang, Dr. Kevin Tomsavic, Dr. Gerald Selvaggi, Geoffrey Laughon, Bo Liu, Yiwei Ma, Jessica Boles, and Shouting Zhang.

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