

MATLAB/SIMULINK SIMULATION OF ARC FAULTS

Amir Khan, California State University Fresno; Nagy Bengiamin, California State University, Fresno

Abstract

Many models have been developed to characterize electric arcs in the computer simulation software package, Electromagnetic Transients Program—Alternative Transients Program (EMTP/ATP). EMTP/ATP software has traditionally been the preferred simulation tool for electric power applications. However, Matlab/Simulink has been gaining popularity among researchers and engineers for its versatility and ease of use. In this paper, the software tools (Simulink and EMTP/ATP) are compared for their abilities and viability to simulate arc models. The Cassie arc model was simulated in two circuit schematics using identical settings in both software tools. The arc voltages produced by both tools were compared in the time and frequency domains. It was shown that Simulink provides the needed computational capability to model arcs accurately; as compared to the results of EMTP/ATP.

Introduction

Power system protection schemes have traditionally focused on bolted fault-current protection, such as protection against phase-to-phase faults or line-to-ground faults. Recently, fault research has shifted to studying arc faults. These faults also occur from phase-to-phase or line-to-ground, but the current conducts through air. The conductance through air causes several complexities that are of particular interest to researchers. Because of the impedance of the arc, these currents are often smaller than bolted faults. As a result, their currents sometimes are not immediately detected by protection devices. Furthermore, if the arc experiences a high enough current, it can produce a flash of high-temperature plasma and pressure, otherwise known as an arc flash.

The voltages and currents measured from arcs are often multifaceted and complex. Many black-box models have been created to characterize arcs. The digital simulation of these arc models gives researchers a way to study arc characteristics without creating an actual high-energy arc experimental setup. The long-established program used to simulate arcs is EMTP/ATP, a program often used to study transients within power systems. A popular preprocessor of EMTP is a program named ATPDraw. This program integrates a visual circuit designer and plotting tools with the EMTP program.

In recent years, Simulink has expanded its library to include actual circuit components for simulation. As a result, it has been used more widely as an alternative to EMTP in simulating arc faults [1]. In this study, the authors attempted to compare the simulations from both programs in order to investigate whether Simulink is a suitable alternative in the simulation of arc faults, which can compare two situations involving an arc using identical settings in Simulink and ATPDraw. Their characteristics were then compared in time and frequency. Lastly, any software limitations from either program were evaluated.

Simulation of the Cassie Model in a Simple Circuit

It is preferable to represent arcs as electrical elements in a circuit [2]. Equation (1) shows how the Cassie model defines arc conductance [3]:

$$\frac{dG}{dt} \frac{1}{G} = \frac{d(\ln(G))}{dt} = \left(\frac{1}{\tau}\right) \left(\frac{u^2}{u_c^2} - 1\right) \quad (1)$$

where, G is the arc conductance; τ is the time constant associated with the arc; u is the arc voltage; and, u_c is the average arc voltage.

The model assumes that the power loss of the arc is constant and due to “deformation processes” [3, 4]. It also assumes that the arc voltage is constant and best used to represent the arc during most of the current-carrying period [3]. This model was first implemented in series with one resistor and a power supply, uS . Both programs were set to a fixed-step of $1 \mu s$ and sampled for 0.2 seconds. The following parameters were used in both programs:

$$uS = 12kV, R = 200\Omega, u_c = 3.850KV, \tau = 5 \times 10^{-5} s$$

Software Implementation

ATPDraw opens in an interface in which circuit components can be put together visually, similar to circuit simulation programs like PSIM and Multisim. The arc can be represented as either a time-varying resistance, R(TAC) Type 91, or a time-varying voltage source (TACS Source). That time-varying component is then defined using a MODEL block. This model defines the time-varying component through each iteration, and it can read voltages or currents from the circuit as inputs. The actual language and syntax

used to code these models are defined in the ATP Rule Book. Figure 1 shows the schematic used in this study. Figure 2 shows the content of the MODELS block. Part of the code was influenced by the work of Kizilcay and Hoidalen [5]. A time-varying resistor was used to define the arc.

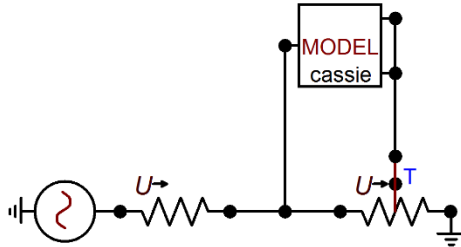


Figure 1. The Cassie Model Implemented in ATPDraw Using a Time-Varying Resistor

```

MODEL CASSIE
DATA tau,uc
INPUT v2
OUTPUT o1,g
VAR o1,g,G1,i1
HISTORY i1 {dflt: 0}
G1 {dflt: 0}
g {dflt: 10000}
INIT
G1:=0
ENDINIT
EXEC
  if t=0 then
    g:=10000
  else
    COMBINE ITERATE AS group1
      i1:=v2*g
      G1 := (i1*v2) / (uc**2)
      LAPLACE (g/G1) :=1.0|/(1.0|+tau|S)
    ENDCOMBINE
  endif
  o1 := recip(g)
ENDEXEC
ENDMODEL

```

Figure 2. Contents of the MODEL Block that Define the Time-Varying Resistance According to the Cassie Model

The Cassie model was implemented in Simulink using the same parameters. The overall circuit was implemented using only mathematical blocks; no components from SimPowerSystems were used in this case. Figure 3 shows the schematic for this block diagram.

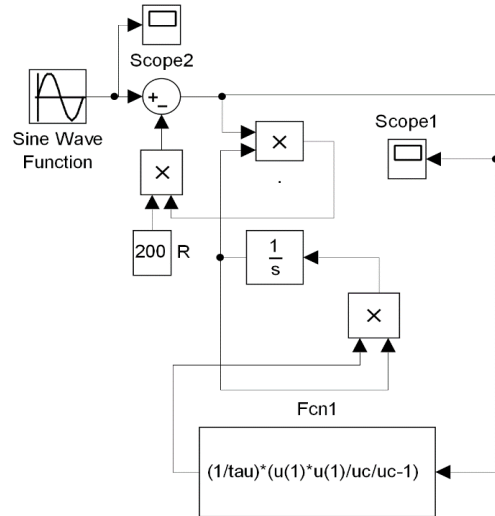


Figure 3. Cassie model implemented in Simulink

Results and Comparisons in the Time Domain

Figures 4 and 5 show the results from both programs. Figure 6 shows the two voltages from both programs on the same plot.

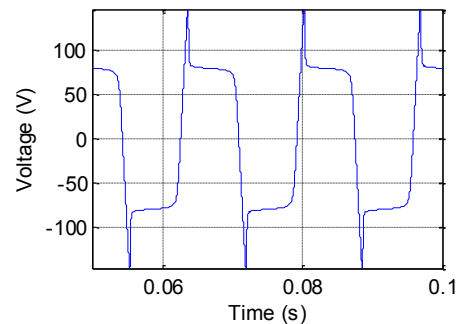


Figure 4. Simulink-Generated Arc Voltage for the Cassie Arc Model

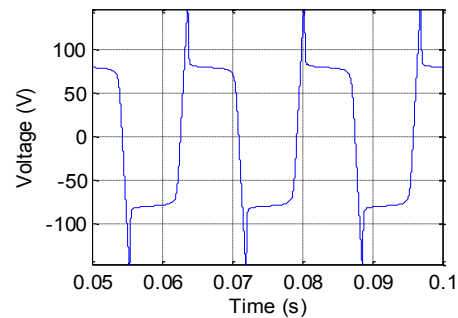


Figure 5. ATPDraw-Generated Arc Voltage for the Cassie Arc Model

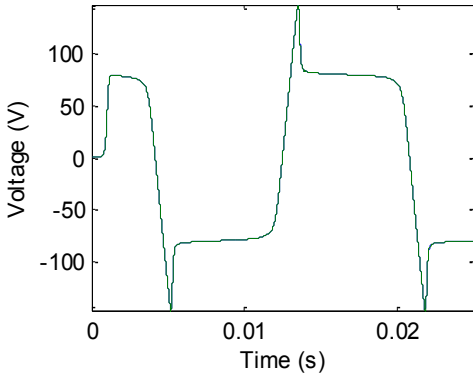


Figure 6. Two Overlapping Signals

The two signals in the time domain were compared within Matlab by calculating their cross-correlation using the `xcorr` command. This command takes two matrices as inputs and continually shifts the second matrix across the first. For each time shift, the two signals are multiplied and the sum of those array elements is calculated. The highest value of this array indicates the point in time in which the two signals are most similar.

However, the shifting in time is not of importance, because the signal from Simulink and the signal from ATPDraw will already be in-phase. Of greater interest is the actual maximum cross-correlation value, which would be the two signals multiplied together and then all array elements summed together, when the two signals overlap. This value can be compared to the individual energies of both signals to determine signal similarities. If both signals are identical, this maximum cross-correlation value should be equal to the individual energies of the two signals.

Since the signals had identical time steps, a new array was created that calculated the difference between the two signals for every array element. From this array, the maximum difference between any two individual array elements was identified, and the total number of array values that had a difference of 5% or less was calculated as a percentage of the total number of array elements. Table 1 presents those findings.

The maximum of the cross-correlation indicated that the two signals were nearly identical, since its value was equal to energies of each individual signal. Furthermore, the maximum difference between any two points was very small relative to the maximum and minimum values that the signals reach. Most notably, no array value ever exceeded a difference greater than 5%. The time domain information from Table 1 indicates that the signals were not significantly different.

Results and Comparisons in the Frequency Domain

The frequency spectra were plotted using the FFT command in Matlab. Figures 7 and 8 show the spectra for the arc voltages from the two programs. Similar comparisons were again made in Table 2. Since the signals were virtually identical in the time domain, it was predicted that they would be similarly identical in the frequency domain. Table 2 shows that to be true. The percent difference in the maximum values between the two in the frequency domain was 0.00269%. The maximum difference between any two array values was 0.0050, and the maximum of the cross-correlation, when compared to the energies of each individual signal, indicated that they were virtually identical. Only 0.04% of the frequency array values differed by more than 5%.

Table 1. Comparison of Two Signals in the Frequency Domain

	ATPDraw Voltage	Simulink Voltage
Minimum value	- 147.2625 V	- 147.1222 V
Maximum value	147.2625 V	147.2222 V
Energy	1.2733×10^9 J	1.2733×10^9 J
Maximum of cross-correlation	1.2733×10^9 J	
Maximum difference between any two array elements	0.3346 V	
Percentage of array elements in which signals differ by 5% or less	100.00 %	

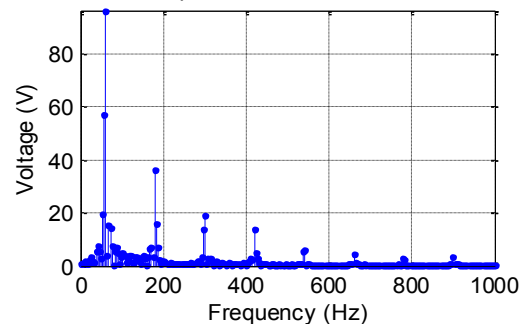


Figure 7. Frequency Spectrum for Arc Voltage Produced by ATPDraw

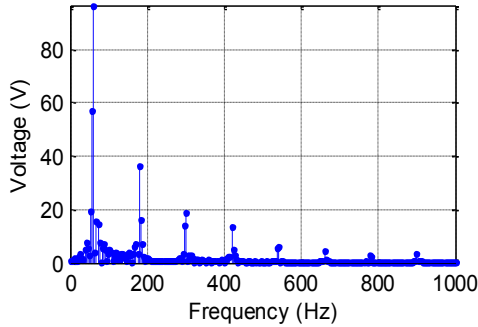


Figure 8. Frequency Spectrum for Arc Voltage Produced by Simulink

Table 2. Comparison of Two Signals in the Time Domain

	ATPDraw Voltage	Simulink Voltage
Maximum value	96.4789 V	96.4815 V
Energy	8.3445×10^3 J	8.3445×10^3 J
Maximum of cross-correlation	8.3445×10^3 J	
Maximum difference between any two array elements	0.0050 V	
Percentage of array elements in which signals differ by 5% or less	99.96 %	

Comparisons in the time and frequency domains demonstrated that this simpler schematic with a voltage source, resistor, and the Cassie arc model produced nearly identical results. Subsequently, a more elaborate circuit schematic was developed using the same arc model, and the performance of the arc simulations in both programs was compared.

Simulation of the Cassie Model and Time Domain Analysis

The same Cassie arc model was placed inside of another circuit that was more reflective of an actual transmission line. Figure 9 portrays that schematic. This circuit was replicated from the block diagrams previously produced by Schavemaker and Van der Sluis [6]. Figure 9 defines the Cassie model. The content of the MODELS block is identical to the code used in Figure 2. A time-varying resistor was used to define the arc. The system was simulated and then exported to Matlab for further analysis.

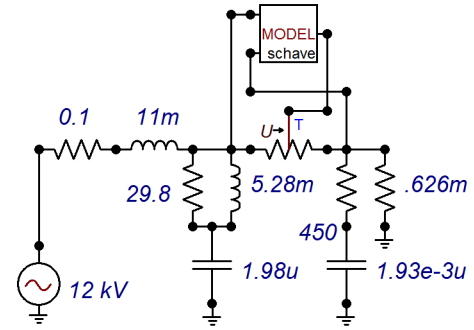


Figure 9. New Schematic for the Cassie Model in ATPDraw

The model was created in Simulink using the same parameters. The circuit was implemented using SimPowerSystems, a toolbox that allows the simulation of actual electrical components. Figures 10 and 11 show the Simulink schematic for this block diagram. Figures 12 and 13 show the arc voltage results from both programs. Figure 14 shows the results from both programs on the same plot for the first few cycles. The blue signal is ATPDraw and the green is Simulink. The two signals appear to be very similar. The same characteristics from Table 1 were calculated for these two signals. Table 3 shows the results. The maximum of the cross-correlation indicated that the two signals were extremely similar. Its value differed from the ATPDraw signal's energy by 0.020%, and from the Simulink signal's energy by 0.017%. The energies of the ATPDraw signal and the Simulink signal differed by only 0.0034%. Only 4.73% of the array indexes differed by more than 5%. The maximum difference calculated between array elements was a large value, but it was misleading in comparing the two signals.

This large value was a result of an apparent time delay between the two signals that was only apparent at the first falling edge and first rising edge of the arc voltage. The reason for this time shift was not identified; however, since this was not evident in the previous schematic, it was likely associated with how each individual program processes inductors and capacitors, not the arc modeling. The voltage sources of each program did not contain this characteristic when overlapped with one another. Figures 15 and 16 show these. In those figures, the dashed red line is the Simulink signal; the solid green dotted line is the ATPDraw signal; and the solid blue line is the difference between the two.

After about two cycles, the two signals were in-phase, so it is safe to assume that this occurrence does not appear in steady state values after a few cycles have passed; this is evident in Figure 13. However, the width of the time shift is not significant in changing the characteristics of the signal.

Neglecting the first few cycles, the maximum difference between the two signals in each array element then becomes 270.89 V, and this occurs at one of the sharp peaks of the arc voltage. This value is very close to the difference in the maximum values of the two signals, which is about 212.9 V. The value of 270.89 V is about 4.64% of the maximum value. The information from Table 3 and Figure 14 demonstrates that the signals were virtually the same in the time domain.

Table 3. Comparison of Two Signals in the Time Domain

	ATPDraw Voltage	Simulink Voltage
Minimum value	-6.0750×10^3 V	-5.8652×10^3 V
Maximum value	6.0450×10^3 V	5.8321×10^3 V
Energy	2.9488×10^{12} J	2.9487×10^{12} V
Maximum of cross-correlation	2.9482×10^{12}	
Maximum difference between any two array elements	2.2533×10^3 V	
Percentage of array elements in which signals differ by 5% or less	95.272 %	

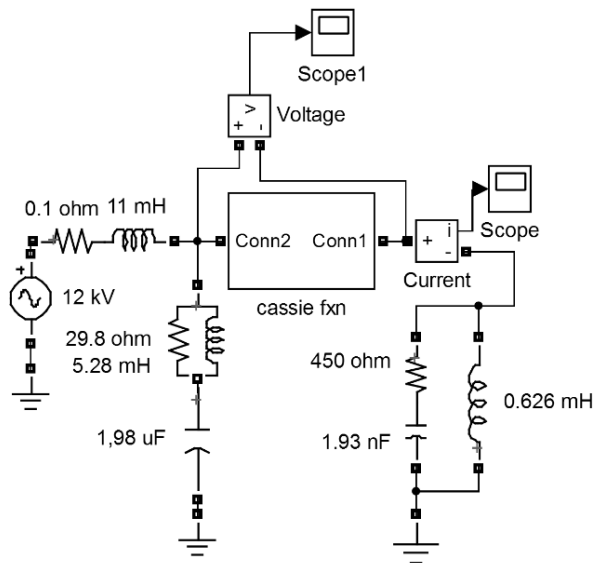


Figure 10. Block Diagram for a New Model in Simulink

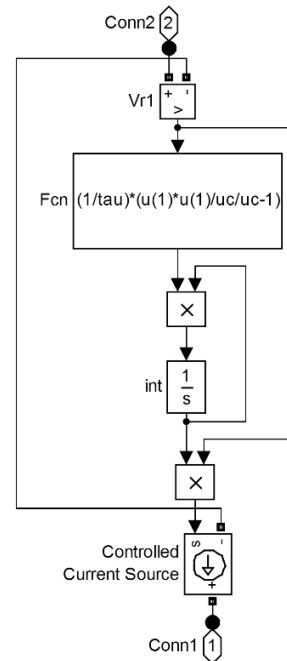


Figure 11. Sub-model from Figure 10 that Defines the Arc as a Controlled Current Source

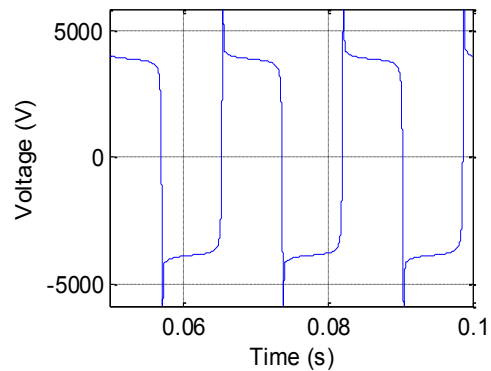


Figure 12. Simulink-Generated Arc Voltage for Schematic 2

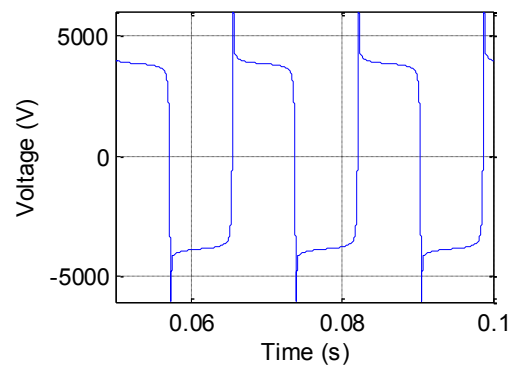


Figure 13. ATPDraw-Generated Arc Voltage for Schematic 2

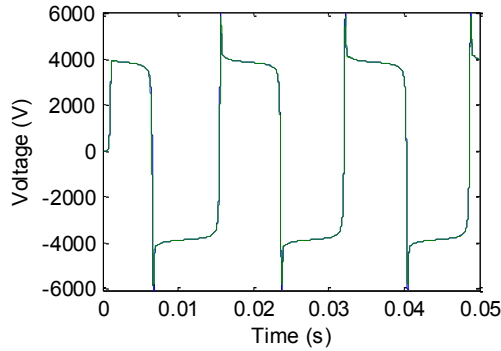


Figure 14. Output Voltage from Both Programs on the Same Plot

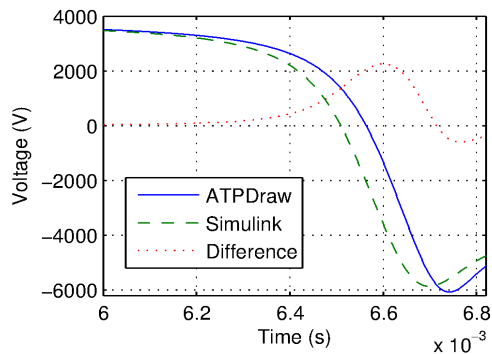


Figure 15. Demonstration of Time Shift on the First Falling Edge

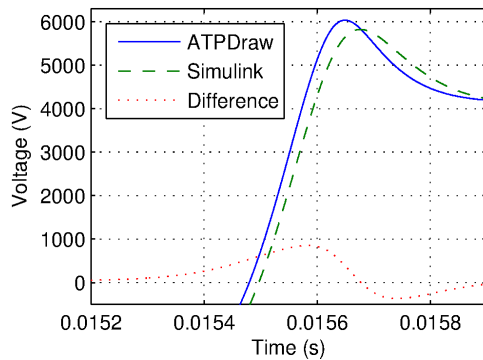


Figure 16. Demonstration of Time Shift on the First Rising Edge

Frequency Domain Analysis

The frequency spectra were plotted using the FFT command in Matlab, similar to what was done for the previous schematic. Figures 17 and 18 show the spectra for the arc voltages from the two programs. Table 4 presents a comparison of the two. The percent difference in the maximum values between the two in the frequency domain was 0.0343%.

The maximum difference between any two array values was 0.1565, and the maximum of the cross-correlation was extremely close to the powers calculated from the frequency domain. Only 1.85% of the total array indexes differed by greater than 5%. All of these features demonstrate that both programs produce indistinguishable frequency spectra for the arc voltage.

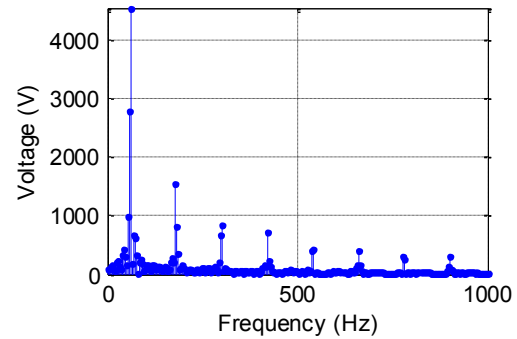


Figure 17. Frequency Spectrum Produced by ATPDraw

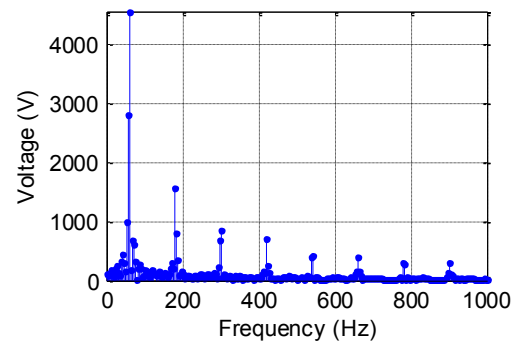


Figure 18. Frequency Spectrum Produced by Simulink

Table 4. Comparison of Two Signals in the Time Domain

	ATPDraw Voltage	Simulink Voltage
Maximum value	$4.5563 \times 10^3 \text{ V}$	$4.5545 \times 10^3 \text{ V}$
Energy	$1.9325 \times 10^7 \text{ J}$	$1.9324 \times 10^7 \text{ J}$
Maximum of cross-correlation	1.9323×10^7	
Maximum difference between any two array elements	5.1275	
Percentage of array elements in which signals differ by 5% or less	98.05 %	

Limitations of Simulink and ATPDraw

Arc models in ATPDraw/EMTP are represented as time-varying resistors or controlled voltage sources. In Simulink, the arc is represented as either a controlled current source for series arcs, or controlled voltage sources for parallel arcs. However, using a controlled current source in Simulink does prevent the use of inductors in series with these current sources. This is due to the inductor having its own current characteristic that is dependent on the voltage across it. ATPDraw does not encounter this problem in modeling an arc. As a result, modifications need to be made in Simulink models to bypass this limitation. Furthermore, EMTP is restricted to a fixed time-step solver, while Simulink has the ability to use a fixed or variable time-step with multiple solvers. This gives Simulink an advantage in debugging solver issues. Although ATP is widely used as a standard for arc model simulations, the ATPDraw software has much more limited support in comparison to Simulink. ATPDraw has a small forum community on its website, and EMTP has a mailing list, where users can ask other licensed users questions. However, responses to queries are not guaranteed. Simulink, on the other hand, has a large community of users and an extensive help service. For software issues, more assistance is available for Simulink than ATPDraw.

Conclusions

Based upon the similarities that ATPDraw and Simulink produced in the arc model simulations in this study, the authors concluded that Simulink is a suitable alternative to EMTP in the study of arc faults. The characteristics of the arc in the time and frequency domain were consistent in both programs, and both could be used to model an arc to a similar precision. In the second circuit schematic that was modeled, a small phase difference was found in the time domain during the first two cycles. However, this was likely due to differences between the two programs in their modeling of capacitors and inductors rather than differences in their abilities to model arcs. Although a small time shift was identified between the two, its duration was negligible, and it did not change the characteristics of the model in the time domain. This time shift was not caused by the actual arc model, but rather the passive components external to it. The frequency domain characteristics for both comparisons were also similar for signals from both programs. Thus, both programs produce results that are similar in both the time and frequency domains. Therefore, either program can be used to simulate and study arcs in the time and frequency domains.

References

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Biographies

AMIR KHAN earned his MS degree in engineering, Electrical Engineering Option, in 2016, from California State University, Fresno. He earned his BS degree from the University of California, Davis. His interests include power and control systems. He may be reached at amir454@mail.fresnostate.edu

NAGY BENGIAMIN is a professor of electrical engineering at California State University, Fresno. He holds an MEngr degree in systems engineering (1976) from Carleton University and PhD in electrical engineering (1979) from The University of Calgary, Canada. Dr. Bengiamin's current interests include power systems, power electronics, and control systems. Dr. Bengiamin is a senior member of IEEE and may be reached at bengiami@csufresno.edu