

Two Methods for Travelling Wave Visualization in Multi-Phase Power Systems: Painted Transients and Animated Pipes

Cansin Y. Evrenosoğlu, *Student Member, IEEE*, Ergun Akleman,
Ozan Önder Özener and Ali Abur, *Fellow, IEEE*,

Abstract—This paper presents two visualization methods, painted transients and animated pipes, for observing travelling wave transients along multi-phase transmission lines in a power system. These travelling waves may be created by various possible sources, including system faults, switching of equipment, load or generation, etc. An electromagnetic transients simulation is carried out to obtain discrete-time solution of bus voltages and then these are used to determine the voltage profile along each transmission line in the system. Once the voltage profile is obtained, different visualization methods can be applied. One way is to create a movie by using the voltage profile of a transmission line at each time step. Either phase voltage magnitudes or modal components can be used for the animation. Another way to visualize the transient phenomenon is to create color patterns using the voltage profile at each time step. Resulting images will give a better understanding of the transient behavior of the power system. Besides a by-product of these 2D images is the well-known Lattice diagram [1] which can be utilized for fault detection and fault location [2] [3]. Simulation results illustrating the appearance of Lattice diagrams are given in the paper.

Index Terms—Visualization of Power System Transients, Animated Transients, Distributed Line Model, Voltage Profiles

I. INTRODUCTION

Understanding the transient behavior of the power networks during a fault or switching is of critical importance for power system protection, control and power quality analysis. So far, studies focus on accurate modelling of various power system components such as transmission lines, transformers, switching equipment, rotating machines as well as the control systems that interact with them. Significant work also exists in the area of simulation methods, most of which are developed to be used in the time domain. The commonly used simulation tool which provides numerical solutions for power system electromagnetic transients in time domain is electromagnetic transients simulator [4]. Development and wide availability of this tool lead to better understanding

of complex transients and their effects on power system operation.

Electromagnetic transients simulators typically provide numerical solutions for the voltages at specified buses in the power system. Plotting these solutions over a time interval of interest will reveal the details of voltage transients at these buses. These plots can be described as the signatures of the travelling wave transients along transmission lines on their terminal buses. However, they do not necessarily provide the variation of the voltage along a given transmission line, i.e. its voltage profile. In principle, once the terminal voltages are known as a function of time, the voltage profile along the transmission line can be obtained by using the transmission line equations. Time variation of the travelling waves along the line can be observed by calculating this profile at discrete time steps. Such a travelling wave *movie* may not only be useful for its educational value in classroom teaching of related subjects, but it may also bring out previously unnoticed characteristics of these waves. The famous Bewley diagrams [1] can actually be considered as one of the first clever attempts to capture such behavior on paper.

Previous work on visualization of power system operation is mainly concerned about the steady state phenomena [5], [6]. Animation is used for displaying indicators such as the amount of power flows, overloaded lines, limit violations for bus voltages, etc. rather than for showing the time variation of actual voltage or current signals.

Travelling waves along transmission lines of power systems has been of interest since the last century. Having advanced simulation tools which can be executed on powerful computers allows more flexible and advanced visualization of these waves, not only along a single transmission line, but also for regions containing several interconnected lines and other equipment. Recently, readily available and flexible Java tools are used to develop web exercises demonstrating the basic behavior of travelling waves on lossless transmission lines [7]. A similar animation program, which shows travelling waves on interconnects in VLSI circuits and provides voltage-distance figures for specific RLC circuits is described in [8]. Another Java tool, which can illustrate wavelet transforms of travelling waves along a single transmission line, is presented in [9].

An early paper from 1930's by Woodruff [10] introduced transient sculptures that were ingeniously created with very limited resources. Recently, an extension of transient sculptures [10] using Computer Graphics techniques is presented in [11]. The same work also introduced one phase travelling

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C.Y. Evrenosoğlu is a graduate student in the Department of Electrical Engineering, Texas A&M University, College Station, TX, 77843, USA.

A. Abur is with the Department of Electrical Engineering, Texas A&M University, College Station, TX, 77843, USA (e-mail: abur@ee.tamu.edu).

E.Akleman is with the Department of Architecture, Texas A&M University, College Station, TX, 77843, USA.

O.Ö. Özener is a graduate student in the Department of Architecture, Texas A&M University, College Station, TX, 77843, USA.

wave animation on a power system network. The focus of these visualization methods in [11] was strictly on single phase line energization visualization and animation problem.

This paper presents two new methods for visualizing power system transients. The focus of methods presented in this paper is on visualization of fast transients which occur in three phase networks due to disturbances such as faults, switching of loads or equipment, etc. The paper is organized such that the methods are described first, followed by the results of applying them to the specific problem of transient visualization.

II. TWO METHODS TO VISUALIZE TRANSIENTS

Visualization of electromagnetic transients can facilitate better understanding of the travelling wave concepts. Visualization techniques can be used for explaining the complex time-space behavior of travelling waves during faults and other disturbances. They also constitute the basis of travelling wave based fault location methods. The details of one such travelling wave based fault location method can be found in [2] and [3]. In this paper two main visualization approaches for three phase transients are presented: (1) *Painted Transients*, and (2) *Animated Pipes*.

These methods require the calculation of the voltage profile variation along the entire line length. One simple way to obtain the voltage profile of a transmission line is to represent it as several cascaded line sections of much smaller length. Terminal buses of these small sections will serve as discrete points along the line length where voltage solution will be available by some simulation program such as the ATP-EMTP. However, an alternative, less time consuming and more accurate technique to achieve this result is presented in [12]. Once the voltages at both ends of the line are obtained by using the ATP-EMTP, these results can be used to calculate the intermediate voltages along the line by using the travelling wave equations as done in [12].

In this work a transmission line with distributed parameters is studied by using ATP-EMTP program. The line is represented by n number of sections and the simulated voltages are obtained at each section. Once the simulation results are obtained they are processed in MATLAB to create animation movies and color patterns. The image file of a voltage profile color pattern is created in MATLAB and then processed in Adobe Photoshop.

Following sections describe the methods in detail.

A. Painted Transients

This method is based on changing color patterns describing the variations of the voltage profile of a transmission line. The method is found useful in determining the type and the location of the fault by simply observing the resulting image.

An image is created by converting 3-phase transient voltage information at each section for each time step by using a transformation function:

$$f : \mathbb{R}^3 \longrightarrow [0, 255]^3 \quad (1)$$

An RGB image file consists of pixels on the 2D space while one pixel is made up of 3 colors; red, green and blue (RGB).

In this study, the 2D coordinates of one pixel is composed by treating x -axis as *time* and y -axis as *line sections* as shown in an example in Figure 1. As seen in this example, the voltage profile color pattern is obtained by transforming the voltage signals at each section for each time step to RGB values where each color value varies in the range of 0 to 255. The transformation function is different depending on the use of phase voltages or modal voltages.

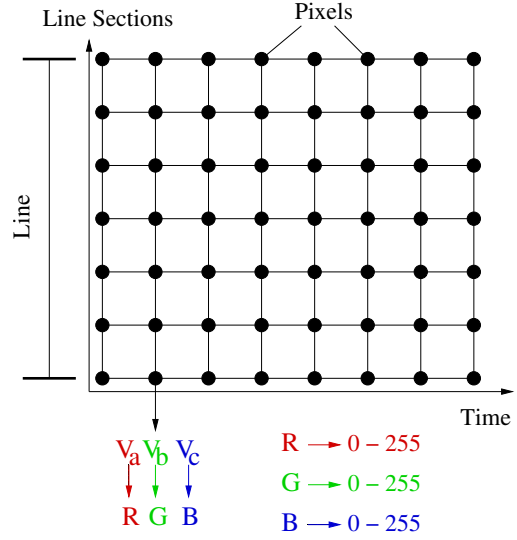


Fig. 1. An example of transformation function that converts voltage profile to an image.

B. Animated Pipes

In this method, voltage profile of a 3-phase transmission line during transients is represented as an animated pipe. The cross-sections of the pipes are changed based on voltage information. We use two types of cross-sections: Triangular for 3-phase voltages and circular for modal voltages. The voltage information is converted by using a transformation function:

$$f : \mathbb{R}^3 \longrightarrow \mathbb{R}^{+n} \quad (2)$$

where \mathbb{R}^+ represents radius (a positive real number) of the pipe in a given angle, $n = 3$ is used for triangle case and $n = 2$ for circle case. The examples of triangular and circular cross-sections are shown in Figures 2 and 3 respectively.

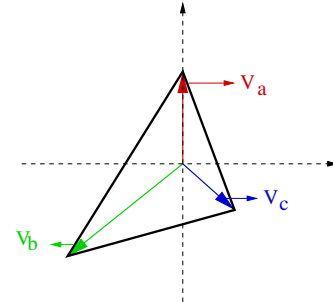


Fig. 2. Triangular representation of 3-phase voltages for one section of the transmission line

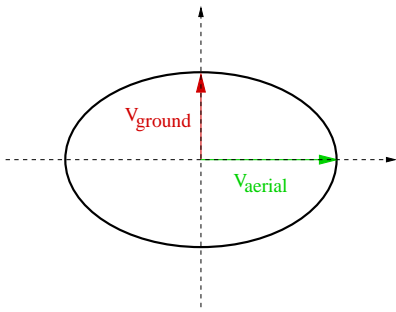


Fig. 3. Circular representation of modal voltages for one section of the transmission line

As the simulated waveforms are obtained at one end of the transmission line the voltages of intermediate points along the line are calculated. The *movie* is obtained when the voltage value of the each section is updated at each time step. Two ways of voltage profile animation is proposed using 3-phase voltage values or modal voltages.

Following section will introduce the implementation of the visualization and animation techniques along with illustrative examples.

III. IMPLEMENTATION AND RESULTS

ATP-EMTP package is used for obtaining all the simulated waveforms used by the animation and visualization techniques. A 100 mile transmission line is used throughout the simulations with a distributed line model and it is represented by 10 sections. The simulation time interval is chosen as $10\mu\text{sec}$ which is smaller than the travelling time of one section. The simulation duration is chosen to be 0.05 sec which is found to be sufficiently long to allow the dissipation of all transients. Simulated voltage signals at 10 intermediate points along the transmission line are obtained by the ATP-EMTP. The fault is assumed to be at the 8th section. Once the simulation results are obtained, they are processed in MATLAB to create the transients movie and color patterns.

A. Painted Transients

The implementation of painted transients technique is presented here for two different ways:

- 3-phase voltage signals are used
- Aerial and ground mode voltages are used

Implementation results with illustrative examples are presented in the following sections.

1) *Use of Phase Voltages:* In order to transform the 3-phase voltage information, first the voltage values are normalized and then these values are shifted upwards in the positive y direction so that the voltage signal is bounded between 0 and 1. After this operation, each discrete point of the signal is multiplied by 255. These consecutive operations define the transformation function in Equation (1).

A symmetric fault on a transmission line is simulated in ATP and one end 3-phase voltage waveforms are shown in Figure 4. At each line section for each time step the 3-phase instantaneous voltage values are extracted and used for creating pixels.

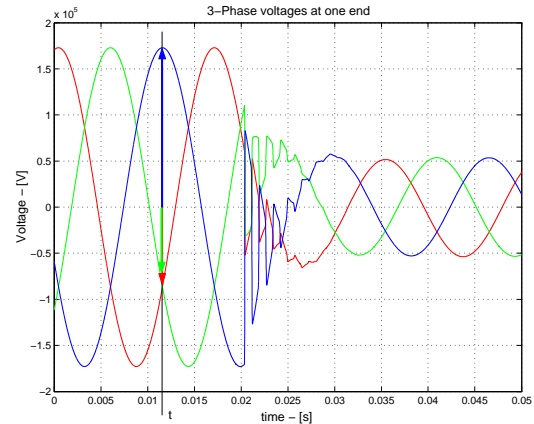


Fig. 4. Transient voltages at one end of the transmission line for a symmetric fault

Voltage profile color pattern is shown in Figure 5 when there is no fault. The pattern is created for almost one cycle.

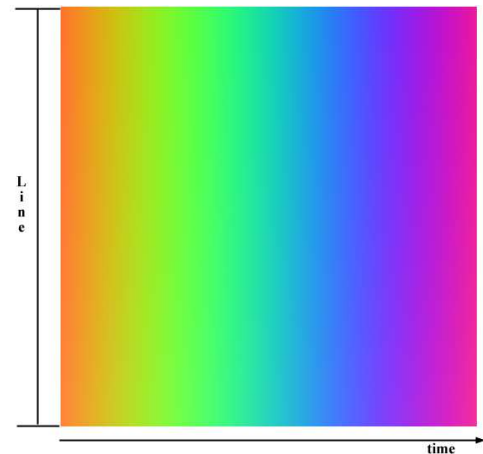


Fig. 5. Voltage profile color pattern w/o fault using phase voltage magnitudes

In Figure 6 and Figure 7, color patterns for 1-phase-to-ground and 3-phase-to-ground faults are presented. It is noted that the color patterns produced by this particular coloring approach reproduce the well known travelling wave lattice (Bewley) diagrams [1] for the simulated cases. This allows easy tracing of the time-space variation of the travelling waves initiated by the faults. The type and location of the faults can therefore be easily decoded from the resulting images.

2) *Use of Modal Voltages:* Once the simulated waveforms at each line section are obtained, Clarke transformation [13] is used in order to calculate the modal voltages. Calculated waveforms are normalized and then shifted upwards in the positive y direction so that the signal is bounded between 0 and 1. After the aerial and ground mode voltages are processed, they are used to create the color patterns. These operations define the transformation function in Equation (1).

Modal voltages are painted by choosing only one of the three RGB colors which make up a pixel. The remaining two colors are assigned null voltages.

A 1-phase-to-ground fault is simulated and only one-end

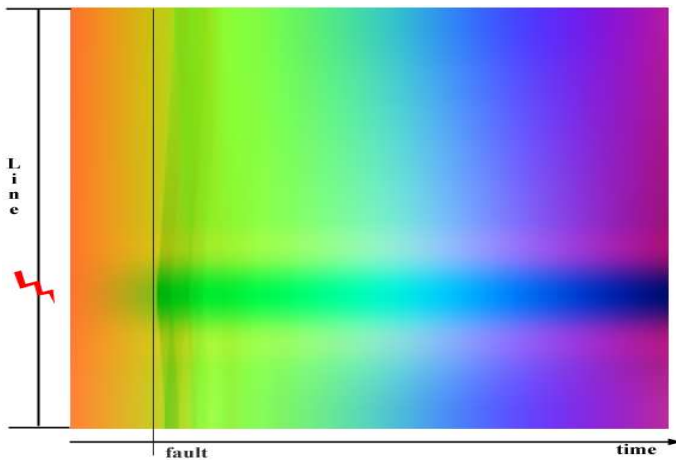


Fig. 6. Voltage profile color pattern for a 1-phase-to-ground fault using phase voltages

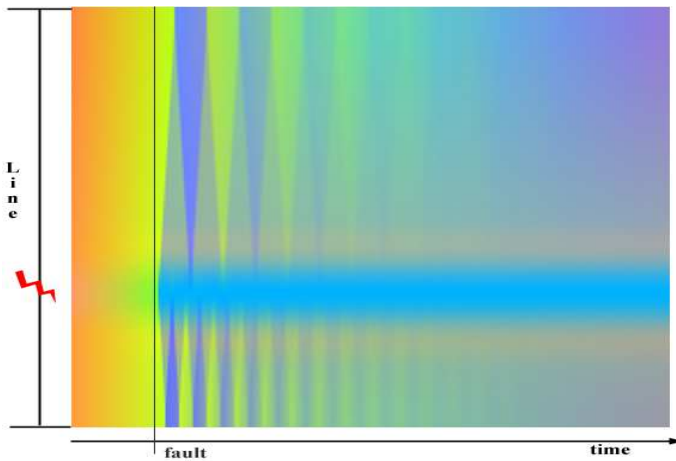


Fig. 7. Voltage profile color pattern for a 3-phase-to-ground fault using phase voltages

voltage signals are obtained as shown in Figure 8. Once the modal transformation is applied, the aerial and ground mode voltages as shown in Figure 9 are processed by normalizing, then shifting upwards in the positive y direction and finally multiplied by 255, they are used to create the color patterns.

Voltage profile color patterns for the modal components (ground or aerial) are generated using only one of the RGB colors. Red channel is assigned to the ground mode voltage, while assigning the remaining green and blue channels null voltages. Similarly, green channel is assigned to the aerial mode voltage, while the red and blue channels are assigned null voltages. Figures 10 and 11 show the aerial and ground mode color patterns respectively, for a single phase to ground fault. In case of a symmetric fault, no ground mode will be present and only the aerial mode voltage will be displayed. Figure 12 shows such a case.

B. Animated Pipes

The animation technique for 3-phase power system transients are presented for two different ways:

- Triangular representation using 3-phase voltage signals

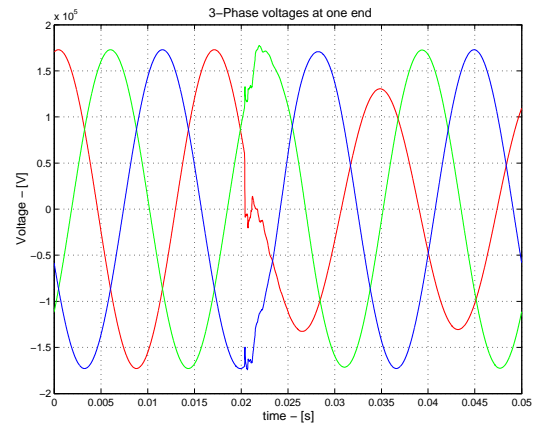


Fig. 8. Phase voltages at one end of the transmission line for a 1-phase-to-ground fault

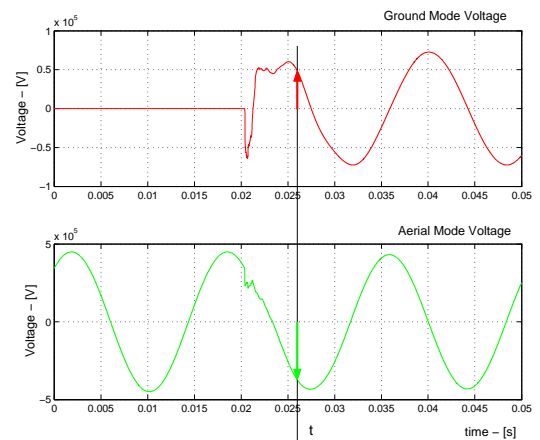


Fig. 9. Modal voltages at one end of the transmission line for a 1-phase-to-ground fault

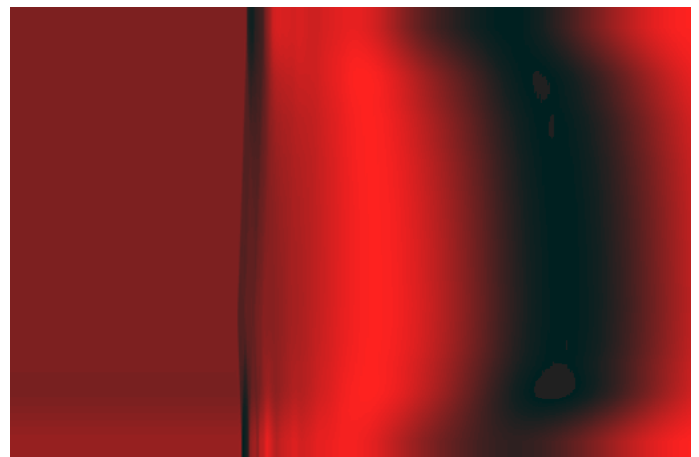


Fig. 10. Voltage profile color pattern for a 1-phase-to-ground fault using ground mode voltage

- Circular representation using aerial and ground mode voltages

Following sections will provide the implementation along with the illustrative examples.

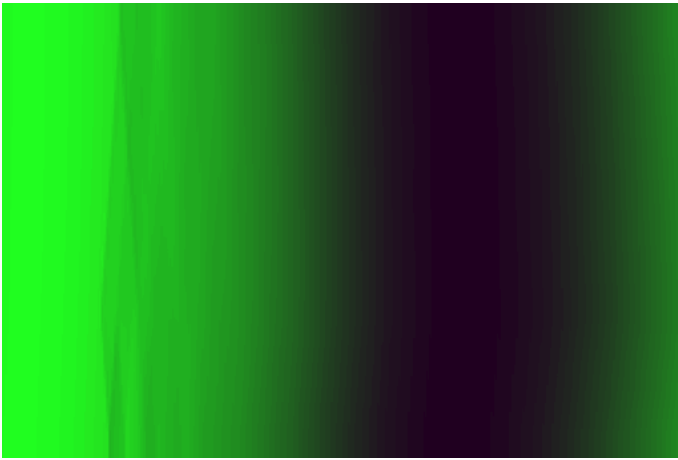


Fig. 11. Voltage profile color pattern for a 1-phase-to-ground fault using aerial mode voltage

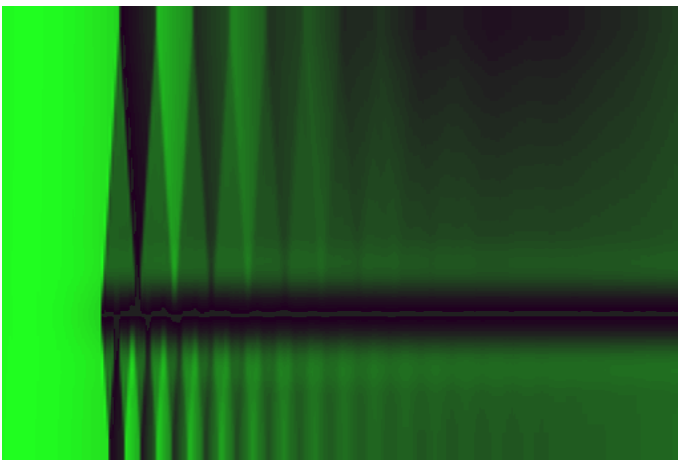


Fig. 12. Voltage profile color pattern for a 3-phase-to-ground fault using aerial mode voltage

1) *Triangular Pipes*: The 3-phase instantaneous voltage values are directly used to obtain the triangular representation. For each line section at each time step the voltage value of each phase is first normalized and then it is treated as a vector with a magnitude of the instantaneous value of the corresponding phase and with 0, 120 and -120 degrees angle for phase A, B and C respectively. Once the three vectors representing the 3-phase instantaneous voltages are drawn, the triangular shape is created by connecting the head of the three vectors as shown in Figure 2. These operations define the transformation function in Equation (2)

The triangles representing the 3-phase instantaneous voltage values of the line sections are placed one after another in the 3D space and the triangular representation of the voltage profile is obtained.

The transient animation is created by using MATLAB Visualization Toolbox and two screen shots of the animation are shown in Figure 13 and in Figure 14 from perspective view and another two screen shots are shown in Figure 15 and in Figure 16 from front view.

2) *Circular Pipes*: After the simulated 3-phase voltages are obtained, the Clarke transformation is applied and aerial and

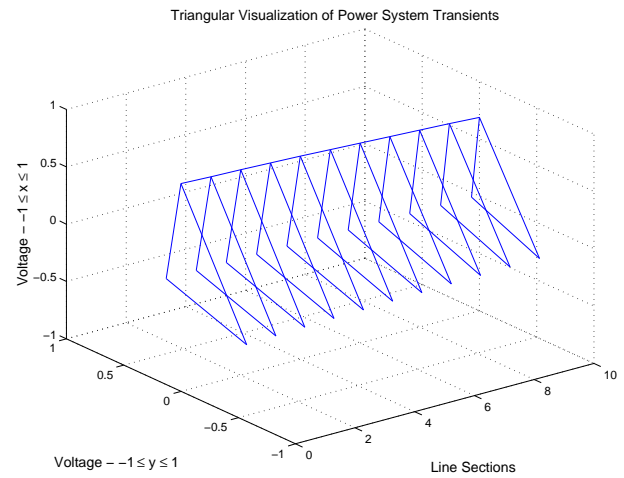


Fig. 13. Perspective view screen shot-1 of triangular animation of voltage profile before a 3-phase-to-ground fault

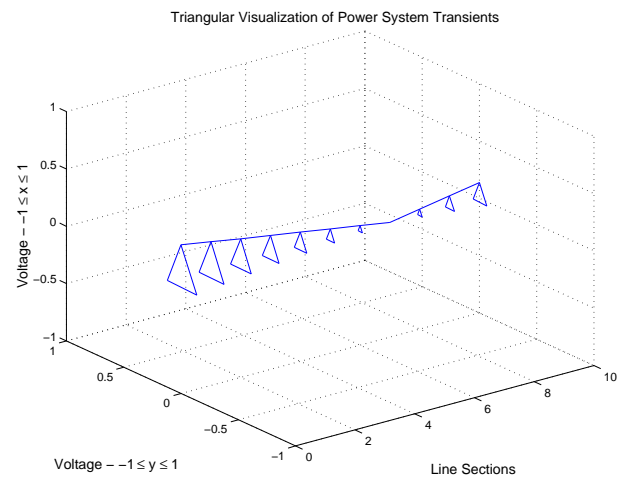


Fig. 14. Perspective view screen shot-2 of triangular animation of voltage profile during a 3-phase-to-ground fault

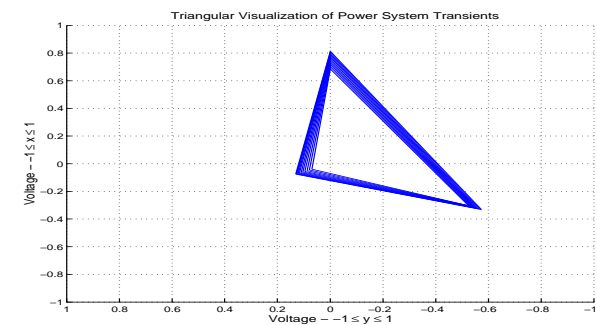


Fig. 15. Front view screen shot-1 of triangular animation of voltage profile before a 3-phase-to-ground fault

ground mode voltages are calculated for every line section at each time step. The instantaneous voltage values of the two modal components are used to create an ellipse as illustrated in Figure 3 which consists of two components. The operation

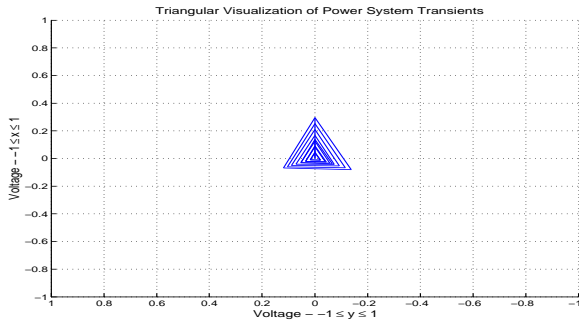


Fig. 16. Front view screen shot-2 of triangular animation of voltage profile during a 3-phase-to-ground fault

of transforming the 3-phase information into 2-component information basically constitutes the transformation function in Equation (2).

The ellipse of each line section is placed one after another in 3D space and the circular representation of the voltage profile is obtained.

As shown in Figure 17, since the ground mode is 0 before the fault occurs, there is a single line instead of an ellipse representing the sinusoidal change in aerial mode. Once the fault occurs, the modal voltages together create the elliptical shapes at each line section as shown in Figure 18. Two screen shots of front view of the animation is given in Figure 19 and Figure 20.

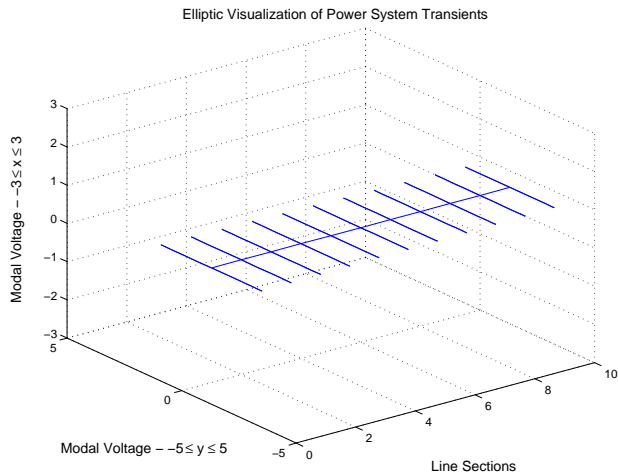


Fig. 17. Perspective view screen shot-1 of circular animation of voltage profile before a 1-phase-to-ground fault

IV. CONCLUSIONS AND FUTURE WORK

Two methods to visualize the power system transients are presented in this paper. Illustrative examples show that painted transients and pipe animations help understanding the transient behavior of the power systems. It is also noted that the work is currently on-going and previously described simulation and animation program in [11] is still being improved using the presented visualization and animation techniques.

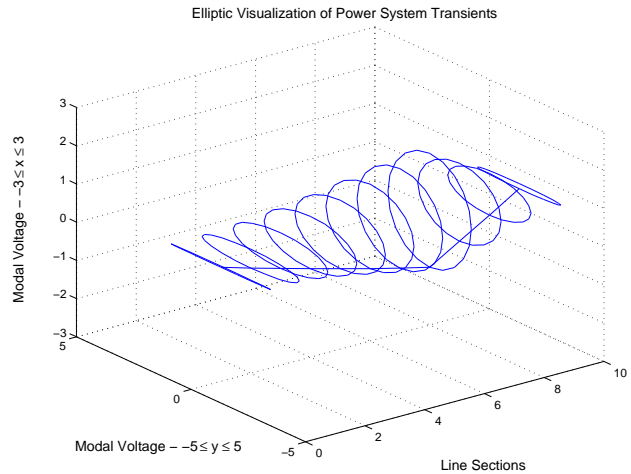


Fig. 18. Perspective view screen shot-2 of circular animation of voltage profile during a 1-phase-to-ground fault

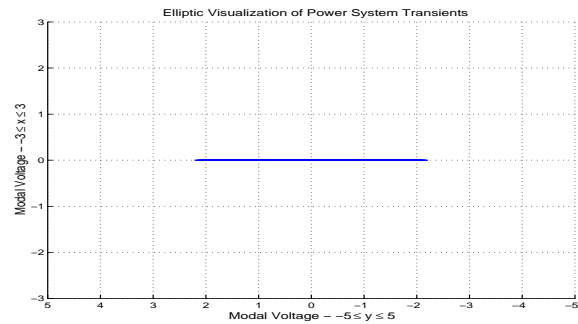


Fig. 19. Front view screen shot-1 of circular animation of voltage profile before a 1-phase-to-ground fault

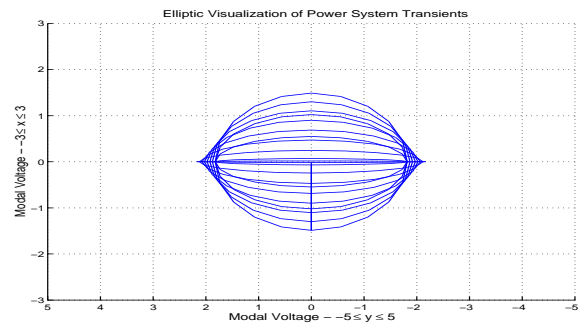


Fig. 20. Front view screen shot-2 of circular animation of voltage profile during a 1-phase-to-ground fault

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