Visualizing Fault Induced Traveling Waves in Medium Voltage Systems

Preprint

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National Renewable Energy Laboratory

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VISUALIZING FAULT INDUCED TRAVELING WAVES IN MEDIUM VOLTAGE SYSTEMS

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Abstract – Traveling waves are induced in power systems during most transient events in the grid. These waves travel close to the speed of light in overhead lines and 50% to 60% the speed of light in underground cables. Even though traveling wave-based protection schemes for transmission systems are available commercially, traveling waves in medium voltage distribution networks are still in research space. Compared to transmission system, medium voltage distribution systems contain more reflections and refractions. Thus, visualization is challenging and is critical in locating faults in distribution network. To address this visualization challenge, this paper presents an open-source tool to visualize the traveling waves using Bewley lattice approach. The developed visualization tool will be useful for the protection engineers to detect and triangulate fault locations in the medium voltage systems and isolate the faults.

Index Terms — Traveling wave, Bewley Lattice, distribution system protection, medium voltage distribution system.

I. INTRODUCTION

Increases in distributed energy resources (DER) like photovoltaics, battery energy storage systems in the distribution system cause bi-directional power flows under normal operation. They also contribute very little fault current which is a cause for concern to the traditional protection systems during weak grid and microgrid islanded operation [1]. Existing over-current and directional element-based protection technology may become unreliable with low fault currents when the distribution systems are dominated by DERs. This has created interest to find protection solutions for medium voltage distribution system. In addition to DERs, microgrids are becoming mainstream in distribution systems. Fault current contribution and direction can be influenced by the mode of operation of the microgrids (grid-connected versus islanded). Finally, utilities are closely monitoring high impedance faults in medium voltage distribution systems as these networks cross potential wildfire areas and properly detecting and locating high impedance faults can be critical.

Use of traveling wave signatures for detecting and locating faults is gaining traction for medium voltage distribution systems. This is partly due to improvements in global positioning system (GPS) based time stamping capabilities, availability of high-speed processors, wide band measurement devices, and most importantly, availability of high-speed fiber connectivity to exchange data. Faults in power systems generate traveling waves that propagate in the overhead lines and underground cables in the form of high-frequency waves at finite velocity. These waves are discussed as early as the 1930s in [2]. Yet, products that can use these waves for detection and triangulation of faults in transmission systems was only commercialized recently. The improvements in digital signal processing, high speed fiber end-to-end communication and accurate satellite based global positioning systems have helped in commercializing this technology for transmission system.

This commercialized approach in transmission systems can also be useful in detecting faults in medium voltage distribution systems. But it is not possible to directly leverage the traveling wave approaches to medium voltage distribution systems. The primary reason being the shorter lines in distribution systems requiring wide band voltage and current measurements. Traveling wave-based protection for medium voltage distribution system is in research space and recently much literature work has covered this topic. In [3], a traveling wave based fault-location algorithm for hybrid multiterminal circuits was proposed. In [4], the simulation requirements to model a system accurately for traveling wave studies in IEEE 13 bus system was presented. A review of the use of traveling wave techniques in power systems is presented in [5] and use of the traveling approach in the presence of high penetration of renewables is presented in [6]. Multiple filtering techniques [7], [8] were presented to extract these waveforms from the measured voltage and current values. More literature on this topic can be found in [9].

A commonality in the literature covering the traveling wave topic is the use of traditional plotting tools (X versus Y format) to show the traveling wave signatures. But the traditional X versus Y format is not intuitive to understand the traveling wave origin and understand the reflection and refractions at the impedance mismatch. Understanding the nature of the traveling wave reflection and refraction can be critical to improving the state of the art. Bewley proposed the use of a lattice structure to understand the traveling waves in [2]. Since then, the Bewley lattice is a preferred approach as it is simple and straightforward to visualize waves traveling in the network. Due to the unusual nature of the plotting requirements and niche use of such visualization only in power sector, most of the open-source visualization tools do not have a default approach to visualize the traveling waves in a lattice structure.

The work presented here aims to address this need and provide an open-source tool to visualize traveling wave voltage and current data for protection engineering and researchers. The work presented here discusses the open source tool built based on the Bewley lattice visualization [2] approach for visualizing the time stamped, filtered traveling wave signatures. This tool uses open-source software packages to build the Bewley lattice diagrams. This paper first presents a brief background on traveling wave signatures, followed by the approach used to develop the visualization tool. This is followed by information on the EMTP-RV [10] model used to generate traveling wave data to validate the tool. Finally, the results and summary of the work is presented.

II. BACKGROUND ON FAULT INDUCED TRAVELING WAVE

Electrical faults on transmission and distribution lines are detected and isolated by system protective devices. Speedy and precise fault location plays an important role in accelerating system restoration, reducing outage time and significantly improving system reliability. It has been documented that faults on a medium voltage (11 kV) network in the U.S. were responsible for 74% of customer minutes lost, on average 20 minutes per customer, per year [11]. Traveling wave (TW) methods use the naturally occurring surges and waves generated during the fault [12]. At the location of fault, voltage reduces and current increases, launching a high frequency electromagnetic wave in both directions propagating ideally at close to speed of light. Electromagnetic transients move away from fault location in the form of TWs at a finite velocity which is captured by current transformers (CT) and filtered for high frequency content to measure the polarity and time delay. With the advancements in digital signal processing, TW methods have been successfully used in transmission for fault detection and location [12], [13].

Most of the literature covering traveling waves has used traditional X-Y axis line plots to analyze the traveling wave data filtered from current and voltage measurements. There are few papers in the literature that cover alternative approaches to visualize traveling waves. A lattice diagram-based approach was first presented by Bewley in his journal publication [2] and in his book [14]. In [15], a JAVA based tool was developed for analysis of TWs. In [16], and [17], a MATLAB [18] based tool was created to analyze the TWs in 2D and in 3D. In [19], red-green-blue coloring method was used to visualize the traveling waves. Other than these tools, there are no readily available software packages to create Bewley lattice diagrams.

These tools were either written in outdated version of software (an earlier version of JAVA from 2000) or commercial software (MATLAB). There is a lack of open-source tools to analyze the simulated traveling wave data and field-obtained traveling wave data. To address this, we utilized the information provided in the literature and created an updated version of the visualization tool in Python (an open-source programming language that is widely used by researchers). We developed this open-source tool for students, researchers, and engineers to use for their visualization needs when working with traveling wave research and development of medium voltage systems faults. This tool can be used with data from most type of fault data.

III. SOFTWARE DEVELOPMENT

To visualize a Bewley lattice of a fault, we need to know a few specific characteristics of the power system under study. First, we need to have a single dimensional representation of the path that we wish to visualize. Given that the interconnected nature of a power system is inherently two dimensional, we need to simplify the representation of these two-dimensional representations to a single path through the system that traverses specific power lines. Second, we need to understand the speed of traveling waves in the line segments in our network under study. In overhead lines, traveling waves travel close to 90 percent of the speed of light and in underground cables it is approximately 50% to 60% the speed of light. We need a way to express this characteristic information in the visualization tool. With these two critical pieces of data, we can construct a Bewley lattice of the system under study.

In our software, we represent the inputs as simple lists. For example, assume we have a single line under study with 100% the speed of light (not realistic but assumed to show upper bound) and the traveling wave is initiated in the middle of the line, which has a length of 3000m. We could represent this in Python as two lists, where the index of the list corresponds to a specific line segment. Here, efficiency indicates the characteristic speed of the line segments. Efficiency of 1 indicate the speed of light.

```
line_lengths = [1500, 1500]
efficiency = [ 1, 1]
```

We can then use the Bewley lattice package to visualize this system by simply instantiating the `bewley.Segments` object and passing this information to it. By default, the `Segments` object assumes the traveling wave will be initiated in the middle of the line, which in this case is index = 1, however this can be modified for different cases. The resulting graph of the above system is shown in Fig. 1.

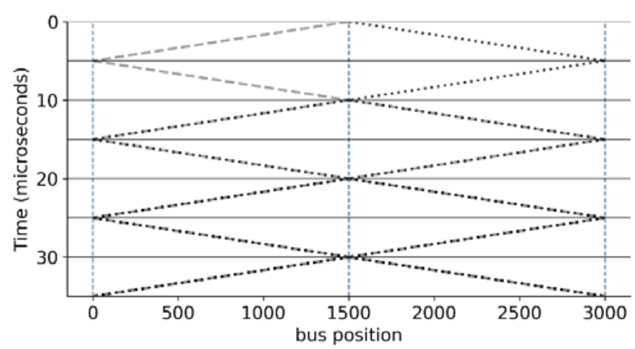


Fig. 1 3000 m line section with a traveling wave initiated at the middle of the line

```
fault_index = 1
lattice = bewley.Segments(line_lengths,
efficiency, fault_index )
lattice.create(lines=30,left_color="#1b9e77",
right_color="#d95f02")
```

Notice in Fig. 1 we have styled the left and right side of the traveling wave injection point. The left side is as a grey dashed line and the right side is a dotted black line. The color, style, and size of each line can be assigned to allow for a customization. Fig. 1 also shows that when the lines have the same length, same tower structure and thus same speed, the rebound will occur at the same time at the ends the line. If we modify any of these assumptions, the lattice will change to reflect these modifications. For example, making the traveling wave initiation at 25% of the line from the left means that the wave traveling to the right will need to travel three times further to reach its end. In Fig. 1 and Fig. 2, the left and right most ends indicate a major impedance mismatch which will cause the traveling waves to reflect and refract. Depending on the line losses, these waves will attenuate accordingly.

```
line_lengths = [750, 2250]
efficiency = [ 1, 1]
```

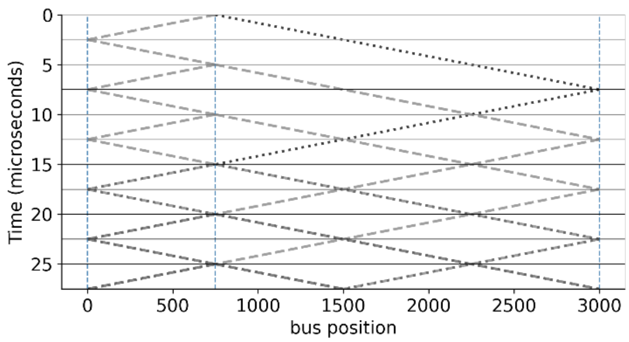


Fig. 2 3000 m line section with a traveling wave initiated at 750 m from the left bus

In addition to the above-mentioned factors, the difference in traveling wave speed in the lines will also have an impact on the lattice. If we assume the fault occurs at this transition where the line goes from an overhead line to underground cable, we might have the following scenario, where the travel time is doubled for the right side because the traveling waves will travel close to 50 percent the speed of light in the right-hand side segment. This can be programmed as shown below and the lattice structure will resemble Fig. 3.

```
line_lengths = [1500, 1500]
efficiency = [ 1, 0.5]
```

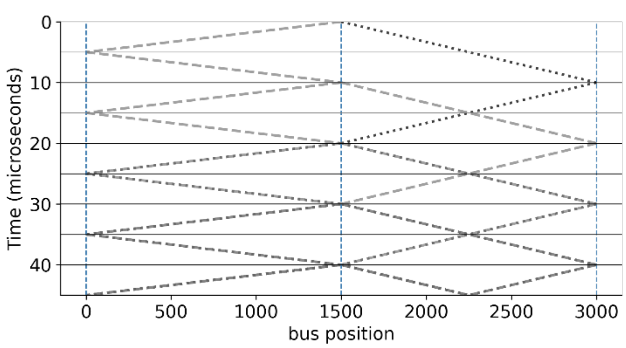


Fig. 3 3000 m line section with a traveling wave initiated at the intersection of overhead line and underground cable

Multiple lines can also be joined together with various traveling wave speed to produce a lattice of even greater complexity. One such complex lattice structure is shown in Fig. 4.

```
line_lengths = [1000, 1000, 500, 500, 1000, 1000]
efficiency = [0.99, 0.95, 0.9, 0.9, 0.8, 0.7]
fault_index = 3
```

The software can be downloaded from https://github.com/NREL/bewley and installed into an environment using Python standards. The Segments object mentioned earlier is a class that creates and builds a list of Segment objects that represent the lines in the fault lines in the graphs above. The Segments are built by iterating over a set of objects from each side of the fault, keeping track of which Segment currently has the lowest value, and therefore, needs to make progress on the next step. The amount of time the system is simulated is a function of the number of line segments we wish to create, which is specified by the lines parameter in the create method. Fig. 5 shows the steps involved in creating the lattice structure.

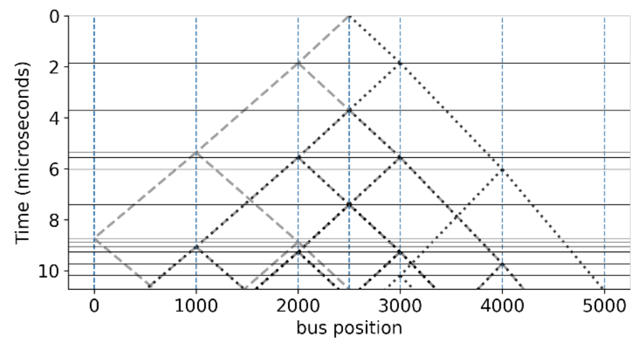


Fig. 4 Multiple lines modeled with different lengths and different wave propagation speed

Each lattice starts with a fault location and a right and left trajectory as shown in the left-most graph. Then, during each step, we look at the leaf nodes of the graph for the leaf with the lowest value. This leaf then takes a left and right step within the bounds of the system. The middle graph shows the green line taking a single step inward because the left step in this instance would be out-of-bounds. Again, the green line is the lowest leaf node, so it again takes a left and right step as shown in the right-most graph. This process continues for a specified number of steps to produce the lattice.

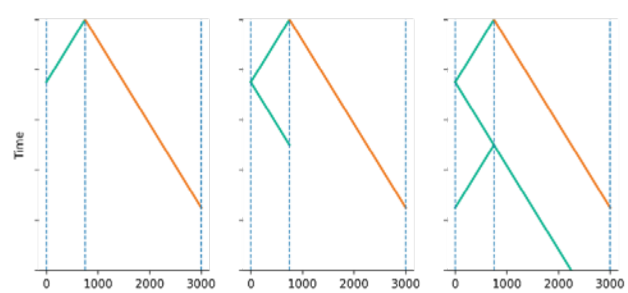


Fig. 5 A visual example of how the lattice segments are constructed iteratively. Initially there are two, the right and left sides. The next step adds two more segments to the segment that has the lowest value. This process repeats until the desired number of segments is reached.

The software tool takes information like the line length, anticipated wave speed, impedance mismatch location to create a theoretical Bewley lattice structure in the center. Once the lattice structure is built, the filtered waveforms will be added to create a whole picture of the waves along with the anticipated lattice-based reflection and refractions. Since the lattice structure uses the Matplotlib [20] library, it is straight-forward to create subgraphs and use the critical lines from the `lattice` object to connect the multiple plots together. The lattice itself can be plotted on any axis of the subgraph. Examples of this is shown in section V where all three subgraphs plot the horizontal critical points from the `lattice` object, the two end graphs have additional timeseries, and the middle graph axis is passed to the `lattice` object for plotting. There is example code for this in the repository. The next section presents the cases simulated in EMTP-RV to generate data and verify the developed visualization tool.

IV. SIMULATION TEST CASES TO VALIDATE VISUALIZATION TOOL

Multiple cases were simulated in EMTP-RV by modeling two different network structures. Traveling wave studies need line models to be valid in the frequencies under study. This necessitate the need for using models that are valid for a wider range of frequency. And such wide band models use tower information, conductor information and in case of underground cables, cable information to generate the wide-band models. This section describes the network structure of the models, tower structure used in the models, and current injection information.

A. Current injection information:

Typically, traveling waves originating from faults or lightning strike propagate in the form of high frequency impulse waves in the lines. These waves are unidirectional which are characterized by fast rise time followed by a slow fall time. Impulse waves can be represented as double exponential equation as shown in (1). From eq. 1, I_m is the peak value, α and β are wave shaping constants defined by rise and fall time. The constants are calculated based on rise and fall time of the wave which is described in [21]. Impulse current wave (0.5/50 μs) used in the simulation case is shown in Fig. 6.

$$I = I_m\left[e^{-\alpha t} - e^{-\beta t}\right] \quad (1)$$

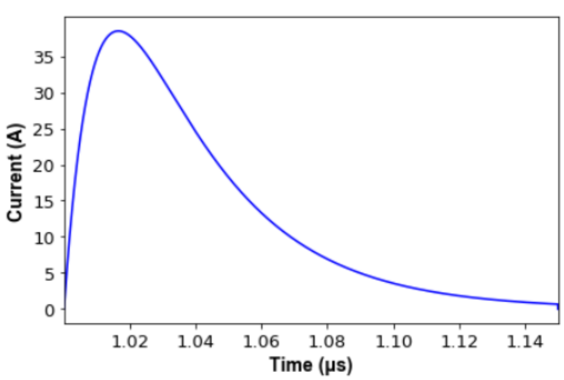


Fig .6. Impulse Current Wave

This paper also presents one case with square wave injected instead of impulse waveform. A square wave of pulse width 20ns and a magnitude of 100 A is injected at the same location instead of impulse waveform. Square waveform and lossless lines are not realistic in the field. But, square waveform in a lossless medium can clearly show the additive effects of reflections in the lines. This can be a useful debugging use case for protection engineers.

B. Network used in the simulation:

Fig. 7 shows the network structure modeled in EMTP-RV with a current injection block in the middle. The current injection block is then used to inject a short pulse that replicates a traveling wave in one of the phases. Since there are no options to add a current injection in the middle of the line, we split the single line into two lines and applied the short current pulse.

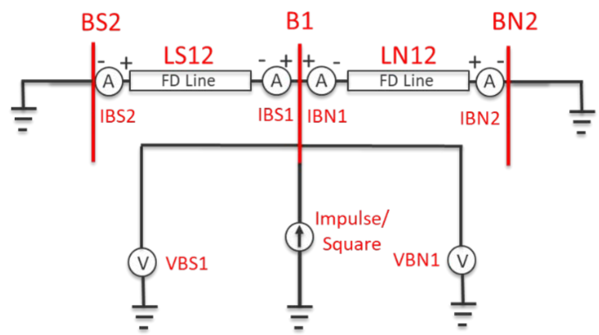


Fig. 7 EMTP-RV model with current injection in the middle of the line

Fig. 8 shows the additional lines added to Fig. 6 to replicate a complex medium voltage distribution system and introduce more reflection and refraction points. From the one-line circuit seen in Fig. 7, three lines with different surge impedance added on both sides to create more reflection points. LN34, LN56, and LN57 have the line lengths of 0.5, 0.7 and 0.7 km respectively. In addition, once the signal in injected, a 50 Ohm resistor was connected to emulate the fault impedance which is usually seen by the reflected traveling waves and mimic the reflection and refraction introduced by the fault impedance in the field.

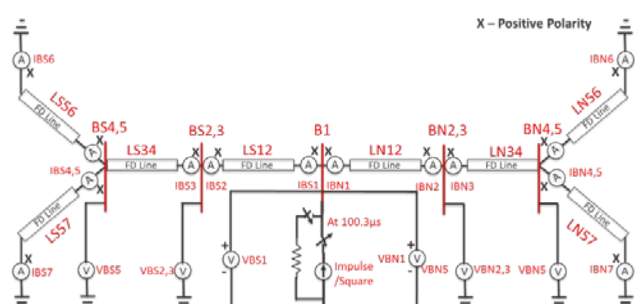


Fig. 8 Additional lines added to the single line model to replicate reflection and refractions in distribution system

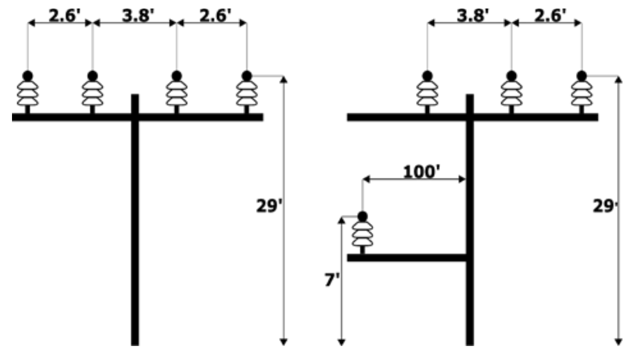
EMTP-RV allows the user to select the lines to be lossless or lossy. We ran multiple simulations with the two-network structure in lossless mode and lossy mode. In lossless line case, the injected wave keeps going back and forth at the speed of light creating multiple reflections without losing any energy. In lossy lines, conductor skin effect offers high resistance to high frequency transients thereby attenuating the signal quickly.

Distribution lines being very short creates difficulty in understanding the short travel times and quick reflections. At any location on the line, TW is the sum of forward (FW) and backward waves (BW). We used two types of input to the current injection block: an impulse source and a square wave. With the impulse source, waves stacking on top of each other makes it difficult to estimate arrival times and magnitude. But square waves would create a step ladder and makes it visually easier to distinguish between FW and BW.

Wave energy is usually absorbed by the line resistance as it travels back and forth along the line. Fault impedance at the source injection point also attenuates the signal. The impedance mismatch between the lines in Fig. 8 is created by varying the line geometrical parameters like spacing and height. We added grounding at both ends of the line to maximize (twice) the reflection of current. Current measurement block in EMTP-RV is used to understand the behavior of traveling waves in these lines. Due to limited space, only selective cases are presented in this paper. A key point to note is that to make the visualization easier, these models were not energized by a voltage source. The only source in the model is the current injection. This allows us to extract clean traveling waves and present a clear view of the impact of reflection and refraction. Since this network is not energized in the simulation and only a current injection was used, there is no need to filter out the high frequency waves.

C. Tower structure information:

Fig. 9 (a) & (b) shows the geometric configuration of tower structure and line spacing for FD lines in Fig. 7 & 8. Lines LN12, LS12, LN56, LS56, LN57, LS57 are modeled in EMTP-RV using Fig. 9 (a) and LN34, LS34 are modeled using Fig. 9 (b). Two tower configurations are chosen to create the different surge impedance between the lines.

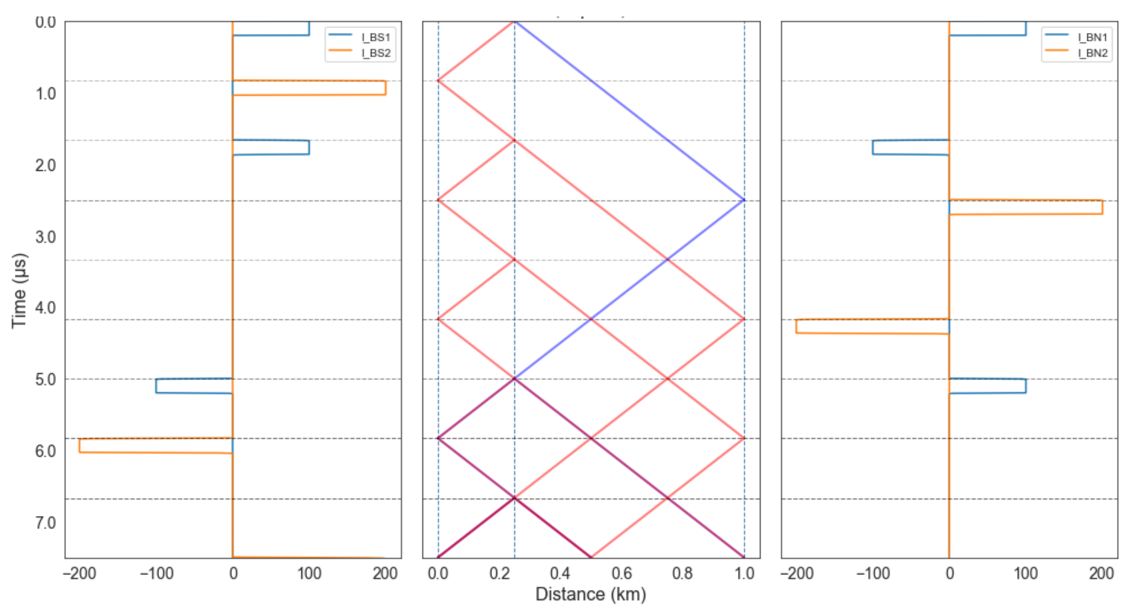


(a) (b)

Fig. 9 Overhead line tower geometry

V. VISUALIZATION RESULTS

We ran multiple simulations with the lossless and lossy line models. Lossless line models clarify the impact of the sum of the FWs and BWs. Fig. 10, Fig. 11, and Fig. 12 presents the plots from the visualization tool with the data generated from different use cases. Lossy line models are more realistic and can be challenging to understand in systems with many reflections and refractions. In this section, we present the lossless line model with a short square wave. This is not realistic in the field as most waves are closer to impulse than square pulse. But, as mentioned earlier, this can be very useful in visualizing and understanding the sum of FWs and BWs and its impact in lattice structure. The results from lossy line models are more realistic and closely resemble fault induced traveling wave. This section also present results from lossless line model results of network structure shown in Fig. 6 and results from lossy line model results of network structure shown in Fig. 7. In case 1 and case 2 presented here, the fault impedance was not included.



(a) (b) (c)

Fig. 10 (a) Measured current at terminal BS2 (in A), (b) Mathematically computed Bewley-Lattice diagram for the simulated circuit, and (c) Measured current at terminal BN2 (in A).

Fig. 7 shows the current is injected at terminal B1 which is located at 25% of the distance from terminal BS2. LN12 and LS12 are split from a single line of length 1km to create a different wave arrival time at BS2 and BN2. There is no impedance mismatch at B1 because LN12, LS12 has the same line structure. Characteristic impedance (ZC) does not depend on the line length. Both lines have the same wave velocity which is speed of light. For the current measurement blocks, TW into the polarity is positive and out of polarity is negative. So, the FW and BW may have different polarities when they are added the sum of FW and BW can sometimes be more positive or more negative depending on the magnitude of both waves.

A. Case#1: Lossless Line with Square Wave injected

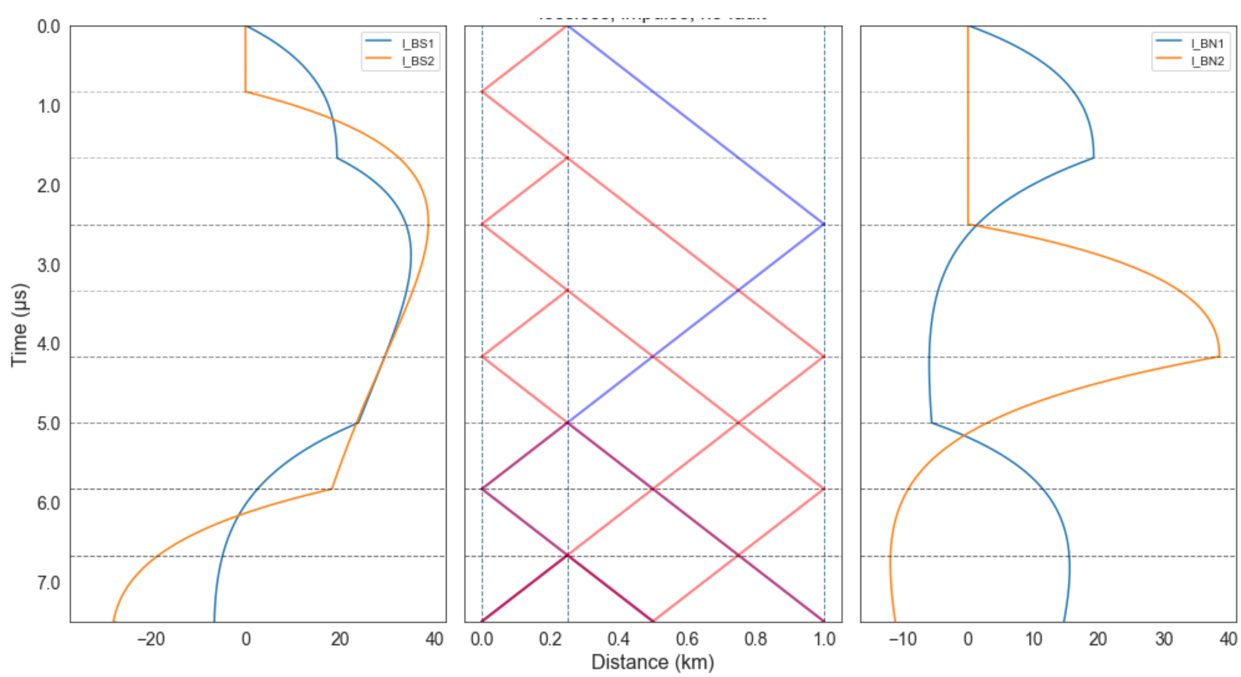
Fig. 9 presents the mathematically computed Bewley-Lattice diagram, the measured current at terminals BS1, BS2, BN1 and BN2. A square wave of pulse width 20ns is injected at the source location in Fig. 7. The shorter pulse width is chosen to observe the FW and BW caused by reflections. Current wave magnitude doubles due to the grounding at bus BS2. This behavior can be seen in Fig. 9 (a) at 1μs in the measurement I_BS2. Since the period is short, there is enough time to travel in both lines. The side-by-side lattice diagram confirms the anticipated reflections at bus BS2 (at 1 microsecond), measurement at BN1 (this is not realistic in the field most of the time as there is no measurement near faults) and bus BN2 (approximately 2.5 microsecond). As we move further down the lattice, the square pulses match the lattice structure. The measurements at location BS2 and BN2 indicate that the current values doubled due to the grounding at the end. Since the lines modeled are lossless, there is no deterioration in the waves injected.

B. Case#2: Lossless Line with Impulse Source

Fig. 10 presents the mathematically computed Bewley-Lattice diagram, the measured current at terminals BS1, BS2, BN1 and BN2. The horizontal lines in Fig. 10 (b) correspond to the time instances at which a reflection happens either at end BS2 or BN2. It can be observed from Fig. 10 (a) and (c) that at all the instances where a reflection should happen, either one of the currents shows a change in behavior. From Fig. 10 (a), the reflected wave from BS2 adds to the injected wave because the line LS12 is very short and travel time is short whereas in Fig. 10 (c), they do not add because LN12 is three times longer compared to BS12. With the known network parameters and using our visualization tool, TW arrival time can be estimated for protection.

C. Case#3: Lossy Line with Impulse Wave and Fault Impedance

Fig. 11 shows the result from using the network from Fig. 7 with a lossy line, and a fault impedance added at the traveling wave injection point. This fault impedance simulates the high impedance fault of 50 ohms, which will absorb more wave energy. There will be minor reflections of smaller waves from fault impedance. Fig. 11 shows the novelty of the proposed tool. The tool can take in multiple line segments and able to plot the traveling waves on the left and right side for the users to analyze the results. This case presents the capability of the tool to consider complex network segments, calculate the Bewley lattice structure, and plot the measurements to the left and right of the lattice.



(a) (b) (c)

Fig. 11. (a) Measured current at terminal BS2 (in A), (b) Mathematically computed Bewley-Lattice diagram for the simulated circuit, and (c) Measured current at terminal BN2 (in A).

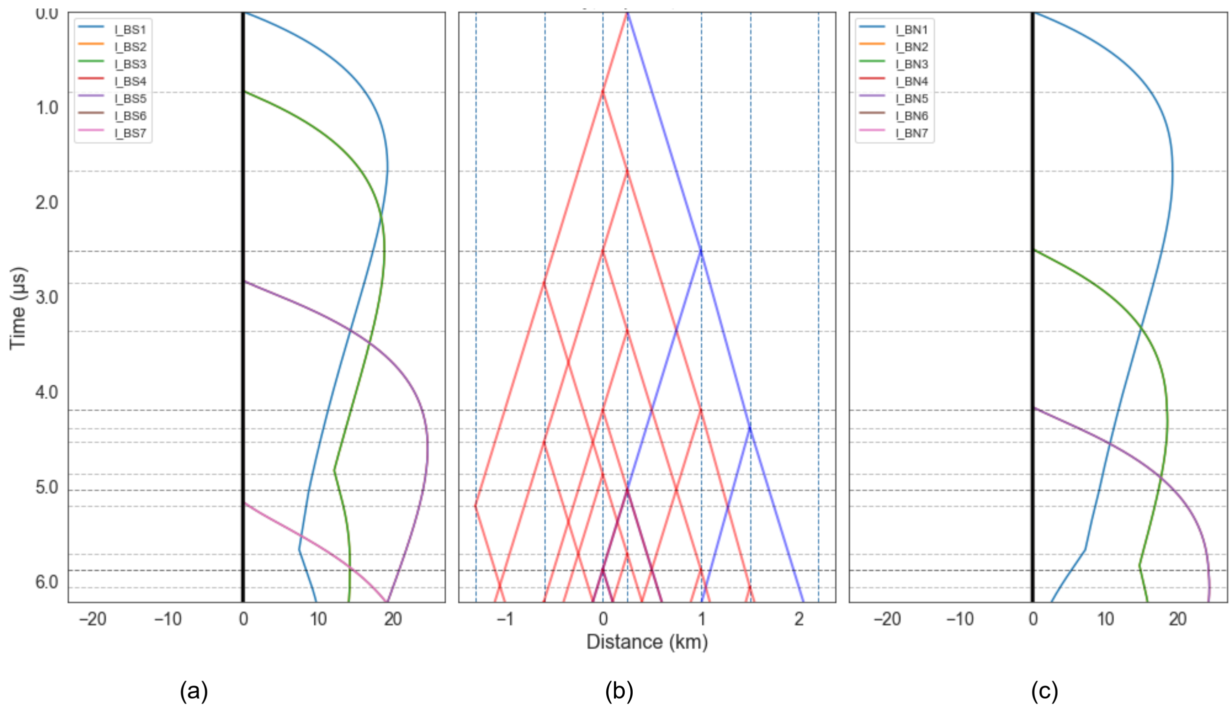


Fig. 12 (a) Measured current on south side(in A), (b) Mathematically computed Bewley-Lattice diagram for the simulated circuit, and (c) Measured current on north side (in A).

VI. CONCLUSIONS

Traveling wave signatures can be useful in medium voltage distribution systems in detecting and locating faults. Once these signals are filtered from raw voltage and current measurements in the field, simple calculations can be used to track the origin of the transient event. Multiple papers have covered the topic of fault detection and triangulation using traveling waves. The work presented here focused on providing an open-source tool

that can supplement or complement the fault detection and triangulation by providing a visualization tool. The open-source tool presented here uses Bewley lattice structure to visualize traveling waves. This paper provides background on the approach used to build the tool and the steps needed to model the lines, perceived fault location, and potential impedance mismatches. This tool can be used with data generated by EMT simulation tools and data from the field to visualize and analyze fault induced traveling waves. The software uses the network information from the user to create the lattice structure. Based on the measurement location of the data, users can plot the traveling waves alongside the theoretical lattice structure for traveling wave studies. We used a simple EMTP-RV deenergized line model and injected impulses and square waves to create example data to validate the developed visualization code. The current data measured from the simulation matches the theoretical lattice structure calculation used in the visualization tool. The work presented here is an early attempt on building a visualization tool. This tool is available in open source for users to download, make necessary updates and improved based on user requirements.

VII. ACKNOWLEDGEMENTS

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