Transmission Line Modeling Requirements for Testing New Fault Location Algorithms using Digital Simulators

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Abstract— **Recently, new fault location algorithms for transmission lines, that take advantage of synchronously sampled data were proposed. To thoroughly evaluate the sensitivity of the algorithm to fault parameters and the power system features, it is important to have an accurate model for the power system, especially the transmission line of interest. In this paper, the requirements placed on the transmission line model to make it suitable for algorithm testing, are discussed. Model validation plays an important role too, since the accuracy of the algorithm depends on the accuracy of the model. The paper presents a sample system, and the results of EMTP testing of a certain class of algorithms on the sample system.**

Digital simulator testing of the algorithms is required before actual field trials. Thus, there are some requirements that a simulator set-up should meet, which are also discussed in the paper.

Keywords— **Fault Location, Electromagnetic Transients, Modeling, Synchronized Sampling, Digital Simulators**

I. Introduction

The problem of fault location on transmission lines has been the focus of interest of many researchers in power systems for a number of years. Until a few years ago, fault location algorithms were implemented in conjunction with protective devices, which typically use single-end data only.

Fault location techniques that use data from both or all ends of the transmission line either use post-fault steady state values of the voltages and currents or actual transient data, to compute the fault location.

Algorithms in the first category either filter the transient data, [1]-[5] to extract the fundamental frequency component or use numerical techniques to estimate the post-fault values, [6],[7]. The preprocessing of the transient signal adds to the program execution time, while contributing to the error in the fault location.

Algorithms in the second category [8], use the transient data captured from the time of the fault occurrence. A short data window of around one cycle is used by the algorithms. The only requirement is that the samples of the voltages and currents be synchronized in time. With the easy availability of Global Positioning System (GPS) receivers, it is now possible to acquire accurately time-tagged samples, [9],[10]. No preprocessing of the data is done, nor is there any assumption made regarding the geometry of the transmission line.

In this paper, we will be exploring the dependence of the second category of algorithms on the accuracy of the line model. The line model must be accurate enough to enable a sensitivity study of the fault location algorithm to fault parameters like fault type, location, incidence angle and resistance. The model should be detailed enough to include important components that are present in the system under study. That is, the effects of series compensation, mutual coupling to adjacent lines, line transpositions, line-lengths, shunt reactors, surge arresters and instrument transformers must be modeled accurately.

In the first part of the paper, a brief description of the fault location algorithms using synchronized sampling is given. The assumptions that are made in the algorithm development are discussed. Second, an actual power system is described and some details regarding its modeling are given. The suitability of this model for testing the fault location algorithm will be investigated. Next, the performance of the algorithm on the transient data generated by EMTP simulations of the model system are presented and the causes of the errors in fault location are explained. Finally, the requirements that a digital simulator set-up should meet to allow for algorithm testing are discussed.

II. Fault Location Algorithm

In this section, the fault location algorithms using synchronized sampling are described. Two applications are considered:

- Short Line Algorithm for transmission lines of length less than 50 miles
- Long Line Algorithm for transmission lines of length greater than 150 miles

A. Short Line Algorithm

Consider the lumped parameter representation of a faulted three-phase system shown in Figure 1.

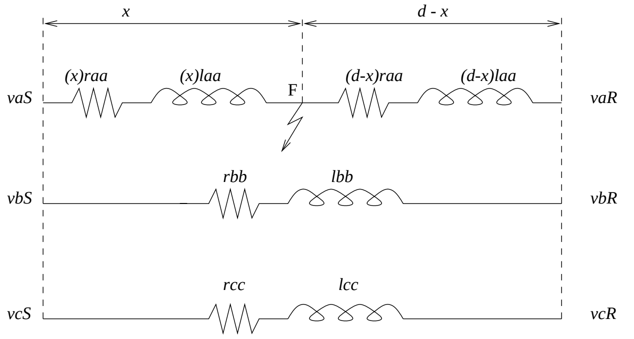

Fig. 1. Short Three Phase Tr. Line with Ph. A to Ground Fault

The fault point is denoted by F at a distance x from the sending end of the line S. End R is the receiving end of the line. Due to the fault, the line is divided into two homogeneous sections. Therefore, the fault point F is the only point on the line where the voltage and current can be expressed as a function of the voltages and currents from both line ends. We also know that the instantaneous values of the voltage and current at point F depend on:

- The instantaneous values of the voltage and current at both ends of the line
- The distance to F from either line end
- The line parameters

Due to the shortness of the line, the shunt capacitance and the shunt conductance of the transmission line are neglected. The series parameters are modeled in the algorithm as a lumped resistance and inductance. The line parameters are therefore defined as:

- Self Resistance r_{aa}, r_{bb} and r_{cc}; $\Omega/unit\ length$
- Mutual Resistance r_{ab}, r_{bc} and r_{ac}; $\Omega/unit\ length$
- Self Inductance l_{aa}, l_{bb} and l_{cc}; $H/unit\ length$
- Mutual Inductance l_{ab}, l_{bc} and l_{ac}; $H/unit\ length$

The expression for the phase voltages at point F due to the sending end voltages and currents is given by:

$$v_{mF}(t) = v_{mS}(t) - x \sum_{p=a,b,c} [r_{mp} i_{pS}(t) + l_{mp} \frac{di_{pS}(t)}{dt}] \quad (1)$$

where $m = a, b, c$.

Similarly, the phase voltages at F due to the receiving end voltages and currents is given by:

$$v_{mF}(t) = v_{mR}(t) - (d - x) \sum_{p=a,b,c} [r_{mp} i_{pR}(t) + l_{mp} \frac{di_{pR}(t)}{dt}] \quad (2)$$

where $m = a, b, c$.

Equations 1 and 2 can be combined to get

$$\begin{aligned} & v_{mR}(t) - v_{mS}(t) \\ & -d \sum_{p=a,b,c} [r_{mp} i_{pR}(t) + l_{mp} \frac{di_{pR}(t)}{dt}] \\ & +x \sum_{p=a,b,c} [r_{mp} i_{pR}(t) + r_{mp} i_{pS}(t) + l_{mp} \frac{di_{pR}(t)}{dt} \\ & \qquad + l_{mp} \frac{di_{pS}(t)}{dt}] = 0 \end{aligned} \quad (3)$$

where $m = a, b, c$.

Writing in discrete form, we get

$$A_m(k) + B_m(k)x = 0 \quad (4)$$

where $A_m(k), B_m(k)$, $m = a, b, c$, $k = 1, 2, ...N$ are defined as

$$\begin{aligned} A_m(k) &= v_{mR}(k) - v_{mS}(k) \\ & -d \sum_{p=a,b,c} [(r_{mp} + \frac{l_{mp}}{\Delta t}) i_{pR}(k) - \frac{l_{mp}}{\Delta t} i_{pR}(k-1)] \end{aligned} \quad (5)$$

$$\begin{aligned} B_m(k) &= \sum_{p=a,b,c} [(r_{mp} + \frac{l_{mp}}{\Delta t})(i_{pR}(k) + i_{pS}(k)) \\ & -\frac{l_{mp}}{\Delta t}(i_{pR}(k-1) + i_{pS}(k-1))] \end{aligned} \quad (6)$$

In equations 5 and 6, $v_{mS}(k)$, $v_{mR}(k)$ are phase ($m = a, b, c$) voltage samples at the instants of time $t = k\Delta t (k = 1, 2, ...N)$ at the line ends S and R respectively. Similarly, $i_{mS}(k)$ and $i_{mR}(k)$ are current samples. N is the total number of samples and Δt is the sampling interval.

Equation 4 is over-specified since it has more equations than unknowns, the distance to fault x. x is determined using a *Least Square Estimate* given by

$$x = -\sum_{m=a,b,c} \sum_{k=1}^{N} A_m(k) B_m(k) / \sum_{m=a,b,c} \sum_{k=1}^{N} B_m^2(k) \quad (7)$$

Equation 7 is the explicit fault location expression for the short three-phase transmission line.

B. Long Line Algorithm

In the case of transmission lines longer than 150 miles, the shunt capacitance of the line cannot be neglected. The line however, is assumed to be lossless, since the contribution of the resistance r to the series impedance and the contribution of the conductance g to the shunt admittance can be considered negligible. Consider the unfaulted transmission line shown in Figure 2. The length of the line is d.

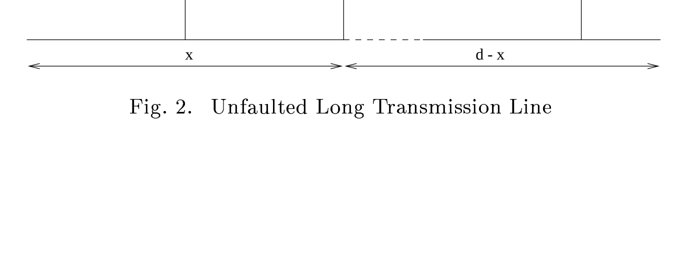

Fig. 2. Unfaulted Long Transmission Line

The l and c are the series inductance and shunt capacitance per unit length. The voltage and current at the point F, at a distance x from S is given by

$$v_F(t) = \frac{z}{2}[i_S(t-\tau_x) - i_S(t+\tau_x)] + \frac{1}{2}[v_S(t-\tau_x) + v_S(t+\tau_x)] \quad (8)$$

$$i_F(t) = -\frac{1}{2}[i_S(t-\tau_x) + i_S(t+\tau_x)] - \frac{1}{2z}[v_S(t-\tau_x) - v_S(t+\tau_x)] \quad (9)$$

These equations follow directly from Bergeron's traveling wave equations. Here, z is the characteristic impedance of the line and τ_x is the travel time to point F from end S. They are defined as

$$z = \sqrt{\frac{l}{c}} \quad (10)$$

$$\tau_x = x\sqrt{lc} \quad (11)$$

The voltage and current can also be written in terms of the end R voltages and currents by replacing the subscript S with R and changing the travel time τ_x to τ_{d-x} which is the time to travel from end R to F.

Now, if a fault occurs at F, then the voltage at point F due to the end S voltages and currents will be the same as the voltage at F due to the end R voltages and currents. Thus the fault location equation becomes

$$\begin{aligned} &\frac{z}{2}[i_S(t-\tau_x) - i_S(t+\tau_x) \\ &\qquad - i_R(t-\tau_{d-x}) + i_R(t+\tau_{d-x})] \\ &+ \frac{1}{2}[v_S(t-\tau_x) + v_S(t+\tau_x) \\ &\qquad - v_R(t-\tau_{d-x}) - v_R(t+\tau_{d-x})] = 0 \end{aligned} \quad (12)$$

Thus, the distance to the fault does not appear explicitly in the equation. When this equation is discretized based on the sampling interval, the travel times to the point F from either end will not be exact any more. The right hand side of equation 12 will therefore have a finite non-zero value. Now, based on the sampling time step, the line can be divided into a number of discrete points, and equation 12 can be used to compute the error voltage at each of those discrete points. The point which yields the least error is the fault point.

This method is obviously very strongly dependent on the sampling frequency. For accurate fault location, very high sampling frequencies ($> 50KHz$) are required, using this method only. To reduce the sampling frequency, the approximate point is used as a guideline. Once the least-error point is obtained, the voltages and currents at the points adjacent to this point can be computed using the discretized versions of equations 8 and 9, the single end equations.

The line section between the adjacent points is now modeled as a short transmission line and the fault location is calculated more accurately. This method thus uses more calculations when compared to the short line algorithm.

Bergeron's equations are valid for single phase transmission lines only. Therefore appropriate modal transformations will be required to locate the approximate fault point. The reconstruction at the adjacent points is also performed in the modal domain. The modal values are then transformed to the phase domain, before applying the short line algorithm.

C. Model Requirements Imposed by the Algorithms

The nature of the short and long line algorithms imposes a number of requirements on the power system model:

- The short line algorithm requires the transmission line to be modeled as a lumped parameter series R-L component. Shunt conductances and capacitances are neglected in the short line algorithm.
- The long line algorithm requires the transmission line to be modeled as a distributed parameter component. Shunt conductance and series resistance are neglected in the algorithm, while the shunt capacitance and series inductance are included.
- Both the algorithms depend upon the accuracy of the line parameters. Therefore, the verification of the power system model is very important.

III. Modeling of a Sample Power System

In the previous section, some of the requirements imposed upon the model of the power system by the fault location algorithms, were discussed. In this section, the model of a sample power system, containing a long transmission line (242.4 miles), is presented. It is shown that the modeling of the system makes it suitable for testing the long line algorithm.

A. System Description

The sample power system that was picked to evaluate the fault location algorithm is shown in Figure 3 in the Appendix. The transmission line of interest is the 242.4 mile long 525 KV transmission line between the Mead and Westwing substations. Along the first 204.9 miles from Mead, the line is strongly coupled to the 345 KV line between Mead and Liberty substations. There is also a section on the line that is coupled to two 525 KV lines between the Palo Verde and Westwing substations.

Other transmission lines that are not shown in the figure, but are part of the system are:

- 525 KV transmission line between Mead and Marketplace substations.
- 525 KV transmission line between Westwing and Navajo substations.
- 525 KV transmission line between Westwing and Moenkopi substations.

Power equipment that are part of the system are:

- Series compensation capacitances on the Mead - Westwing line.
- 525/230/34 KV Autotransformer at Mead and Westwing substations.

- 345/230/24 KV Autotransformer at Mead and Liberty substations.
- Line entry surge arresters at Mead, Westwing and Marketplace.
- Line shunt reactors at Mead and Westwing.
- Circuit breakers.

It is clear that the system of interest is a complex system. The transmission line itself cannot be taken in isolation to test the fault location algorithm. Therefore, an accurate model of the power system is required.

B. Modeling of the Power System

The system described above is modeled using the Electromagnetic Transients Program (EMTP) [11]. The fault location algorithm requires that the long transmission line be modeled as a distributed parameter component. Keeping in mind that the line parameters are frequency dependent, the FD line model was chosen to represent the transmission line. The other transmission lines were also modeled using the FD line model. Transmission tower geometries were available in all the cases, and therefore the line models could be generated using the AUX routine of the EMTP.

Series compensation capacitors are located at both ends of the Mead - Westwing line. The capacitors are protected with MOVs and spark gaps. The TACS subsystem of the EMTP was used to model these components.

Detailed models for the shunt reactors, surge arresters and autotransformers were also developed.

Several staged fault tests were performed at Mead to verify the model of the system. The model has not been compared to actual data from faults along the line.

The detailed modeling of the system makes it suitable for testing the fault location algorithm.

IV. Performance of the Fault Location Algorithm

In Section II, the generic fault location algorithm for long transmission lines was described, while in Section III, a detailed model of a sample power system was discussed. It was also shown that the model is detailed enough for testing the algorithm. In this section, the results of testing the algorithm on data generated from simulating the model are presented. Due to certain approximations made in the model, regarding the transmission line parameters, there will be errors in the fault location. Some of these approximations are generic in the sense that they would apply to any transmission line. Some are specific to the system at hand. The approximations made are described below:

- Discretization of the line:The transmission line is discretized based on the sampling frequency. This is a physical limitation of the sampling mechanism being used. However, Data Acquisition systems with sampling frequencies as high as 20 kHz are available, and they can help mitigate the problem.
- Lossless line assumption: For ease of computation, the algorithm assumes that the transmission line is lossless. This will cause an error in the location, because lines in practice do have a finite series resistance especially in the ground mode (Mode 0). This means that single line to ground faults will be more prone to error than the other fault types.
- Frequency Dependence of Line Parameters: The algorithm does not consider the dependence on frequency of the line parameters l and c. But it should be noted that these parameters are determined at a high frequency. For example, for the sample test system, a frequency of 2 kHz is used. Since the algorithm requires only transient data from the instant of fault occurrence, using constant parameters, at this high frequency, should not cause significant errors.

The above approximations are generic in nature. The main sources of error are due to sampling frequency variations, and due to neglecting the Mode 0 resistance.

The approximations made due to the nature of the test system are:

- Mutual Coupling to Adjacent Lines: The 525 KV Mead - Westwing line is mutually coupled to the Mead-Liberty 345 KV line for the first 204.9 miles from the Mead substation. The line is also coupled to the two 525 KV lines between the Palo Verde and Westwing substations for a 16.7 mile section. The data acquisition system being used provides synchronized samples of voltage and current only from the ends of the Mead-Westwing line. Thus, the algorithm neglects the effect of mutual coupling with the Mead - Liberty and the Westwing - Palo Verde lines. This is expected to be a significant error source. This error could be eliminated if data from all ends of the mutually coupled lines is available [12].
- Line Parameters of the 525 KV Line: The tower geometry of the transmission line is known. The line parameters are then determined by running the EMTP AUX program on this tower configuration. The fault locator uses the modal parameters and the modal transformation matrices at the frequency determined by the AUX program. The actual line parameters may be different, which would cause an error. A method to automatically measure the line parameters can be implemented to reduce this source of error [13].

Using the detailed system model, a number of simulations were performed using EMTP, with variations in the fault parameters:

- Fault Locations: 79.8 miles from Mead (33%) and 223.5 miles from Mead (92.2%).
- Fault Types: Phase A to Ground and Phase B to C.
- Incidence Angles: 0^o and 90^o.
- Fault Impedance: 3Ω and 50Ω.

The transient data produced by EMTP for the above cases were then tested on three kinds of fault location algorithms:

- Approximate Fault Location: As described previously, the algorithm transforms the phase voltages and currents into the modal domain using the T_v and T_i obtained from

EMTP. Using the Mode 0 (Ground Mode) l and c, and equation 12, the least error point is obtained, which is the approximate fault location.

• Hybrid Fault Location: This is an extension of the previous step. Using the single end traveling wave equations, the voltages and currents at the points adjacent to the approximate fault point are computed. The approximate point is determined using Mode 0 values. Therefore the adjacent points will be located at integral multiples of Δt only in Mode 0, while in Modes 1 and 2, the same adjacent points will be non-integral multiples of Δt. The reconstruction at the adjacent points can therefore be done in two ways:

– Reconstruction using the Mode 0 point for Modes 1 and 2 also.

– Reconstruction using interpolation for the Modes 1 and 2, (The Mode 0 location is an integer).

The results of testing these three kinds of algorithms on the EMTP simulation data are presented in the tables below. The fault location error is calculated using

$$Error\ (\%) = \frac{|Actual\ loc. - Computed\ loc.|}{Line\ Length} \times 100\% \quad (13)$$

The sampling frequency is $20KHz$.

Fault Res.	Inc. Angle	Longline Approx.	Longline No Interp.	Longline Interp.
Fault Location - 79.8 Miles (33%)				
3Ω	0^o	1.079	0.525	0.264
	90^o	1.079	0.342	0.040
50Ω	0^o	1.079	1.022	0.217
	90^o	1.079	0.066	0.472
Fault Location - 223.5 Miles (92.2%)				
3Ω	0^o	3.322	1.647	2.011
	90^o	3.322	1.524	1.743
50Ω	0^o	0.427	0.259	0.124
	90^o	0.427	0.924	0.297

TABLE I
FAULT LOCATION ERROR (%) - A-G FAULT

The first thing that has to be realized is that the line is mutually coupled with the Mead - Liberty line for 204.9 miles, which is around 84% of the line length. The short line refinement to the fault location is applied after the approximate point is located. Therefore, the final location will be as good as the approximate point location.

Considering the Phase A to Ground fault, for a fault location of 79.8 miles, which is well within the mutually coupled section, the approximate point is 1.079% in error. The Mode 0 distance (in one Δt) is 7.0167 miles. Therefore, the approximate point is located at 77.1837 miles, which is $11\Delta t$ from the Mead substation. The point at $12\Delta t$ distance will not be the closest point to the fault. Using the location of the approximate point, the short line refinement is applied at the adjacent points, with and without interpolation. As can be seen from Table I, the error percentages reduce. The interpolation method behaves more consistently than the one without interpolation.

Fault Res.	Inc. Angle	Longline Approx.	Longline No Interp.	Longline Interp.
Fault Location - 79.8 Miles (33%)				
3Ω	0^o	1.079	0.586	0.490
	90^o	1.079	0.318	0.226
50Ω	0^o	1.079	0.485	0.549
	90^o	1.079	0.428	0.014
Fault Location - 223.5 Miles (92.2%)				
3Ω	0^o	2.467	0.775	0.041
	90^o	2.467	0.094	0.054
50Ω	0^o	2.467	1.730	0.427
	90^o	2.467	1.407	0.656

TABLE II
FAULT LOCATION ERROR (%) - B-C FAULT

When the single line fault is moved out to 223.5 miles, the approximate point is 3.322% in error for the 3Ω fault. This means that the point located is at a distance of around 231 miles from Mead. Consequently, the refinement using the short line algorithm also suffers. With interpolation, an increase is seen in the error percentages.

But for the 50Ω fault, the approximate point is 0.427% in error, that is, it is at a distance of 224.5 miles from Mead. In this case, the short line refinements yield much better results. The interpolation method shows better results.

Table II shows the results for Phase B - C faults. For faults at 79.8 miles, the approximate point is the same as in the case of the single line to ground faults. Both the short line methods show improvements. When the fault is at 223.5 miles, the approximate location is 2.467% in error, that is, the distance is around 217.5 miles, for both fault resistances. However, unlike the single line fault, the short line algorithm yields good results, with the interpolation method being better than the non-interpolation method.

The following observations can be made:

• The approximate point location is influenced strongly by the mutual coupling and the effect of the Mode 0 resistance.

• Inside the 204.9 mile section, approximate point location is consistent for different fault types, incidence angles and resistances.

• Outside the 204.9 mile section, for the single phase fault, the location is not consistent. Mutual coupling and the effect of the Mode 0 resistance combine to create large errors. If the approximate location is close to the actual location (for the 50Ω fault), the final location improves.

• For the Phase B - C fault, location outside the 204.9 mile section is consistent. The final location improves upon the approximate point location.

• The interpolation method behaves more consistently than the non-interpolation method.

V. Digital Simulator Requirements

Before actual field testing, it is necessary that the algorithm be tested using a digital simulator, to get a feel for how the algorithm will behave in the field. For ease of testing, such a simulator should be equipped with a user-friendly Graphical User Interface (GUI). It should be possible to draw one-line diagrams of the test-system in the GUI, using icons and a *click-and-draw* method. For testing of the fault location algorithm, the following features are required:

- Varying the fault location along the transmission line: At the beginning of the testing, the user should be able to specify the locations on the transmission line, where the faults should be introduced. This can be done either using pre-assigned node names, or as percentages of the line-length.
- Varying the types of fault: It should be possible to vary the fault types from the GUI. For the transmission line of interest, the user should be able to specify the fault types that are of interest. Alternatively, all the eleven fault types should be tested for.
- Varying the incidence angles: Through the GUI, the user should be able to select different incidence angles, or specify a range of angles, with a certain increment.
- Varying the fault impedance: From the GUI, the user should be able to specify different fault impedances, or a range of impedances. For multiphase faults to ground, it should be possible to specify impedances between phases and to ground, separately.

It is obvious from the above requirements that there can be a large number of cases that need to be run for complete testing of the algorithm. Therefore, a batch testing facility, where no user intervention is required once the test parameters have been specified, is also required.

The portion of the simulator that actually simulates the system must be capable of accurately modeling the system under test. The simulation software must be validated on as large a number of cases as possible. If the results of the simulation cannot be trusted, then the accuracy of the fault location algorithm cannot be judged.

Instrument transformers must be accurately modeled. This is important because the data for the fault location algorithm comes from the secondary of these devices.

Other desirable features that a digital simulator should have are:

- Introduction of data synchronization errors: It is necessary to test the algorithm under a synchronization error condition, since such errors will occur in the field. The simulator should be able to produce such data.
- Automatic change in the power system configuration: This could imply disconnecting a mutually coupled line, or changing the location of the data sampling points.
- Automatic compilation of results: The errors in the fault location for the various cases must be compiled and presented in an easy-to-read form.

VI. Conclusions

Fault location algorithms using synchronized samples of data from both ends of a transmission line were developed at TAMU. These algorithms can be used for locating faults on short as well as long transmission lines. The simulation models of the transmission lines must satisfy certain requirements, that were presented in this paper.The short transmission line must be modeled as a lumped parameter series R-L component, while the long transmission line must be modeled as a distributed parameter component. The synchronized sampling algorithm for fault location was also described. A sample power system, with a long line, mutually coupled to another adjacent line, was described. The model was developed by Western Area Power Administration (WAPA). It was also shown that the model of this line was detailed enough to test the fault location algorithm. The results of EMTP testing of the fault location algorithm were presented.

The fault location errors were inconsistent for single line to ground faults when the fault is outside of the mutually coupled portion of the line. The error arises due to the fact that the location algorithm neglects the effect of the mutual coupling and the Mode 0 resistance.

The errors were consistent for two phase faults, regardless of the actual fault location. This can be attributed to the fact that Mode 0 effects are not that pronounced for two phase faults.

Further testing of the algorithm will use instrument transformers. Also, signal pre-processing like filtering of the transients will be considered to see if the pre-processing can mitigate the errors due to the assumptions made in the algorithm.

A future area of research is to accurately estimate the parameters of the line from the captured data, rather than depend on parameters from a model, which may not be very accurate in the first place. Thus, with parameter estimation, any kind of transmission line configuration can be handled.

The requirements for digital simulator testing of the algorithms were also presented.

VII. Acknowledgment

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Appendix

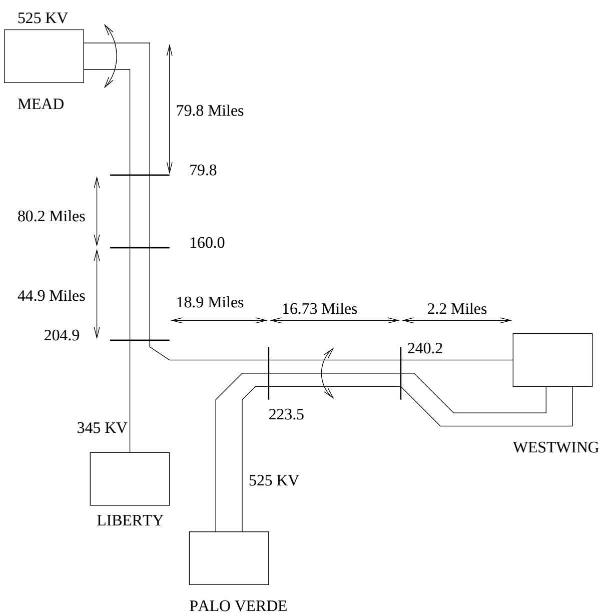

Fig. 3. One Line Diagram of the Sample Power System

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