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COMPARISON OF FAULT LOCATION TECHNIQUES FOR TRANSMISSION SYSTEMS

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Abstract

As a result of market deregulation, many utilities worldwide are finding it increasingly important to locate faults expeditiously. Several techniques can be applied to the problem of fault location on high voltage transmission networks. These predominantly incorporate either impedance or travelling wave methods in order to obtaining an estimate of the fault distance.

This paper demonstrates the additional accuracy obtained when using travelling wave methods. Nevertheless, consideration must be given to the frequency response of substation transducers in order to reduce the uncertainty in the location estimation. This applies particularly in situations where an automated calculation is required.

1 INTRODUCTION

Overhead transmission lines are subject to many kinds of faults due to the exposed nature of the conductors. Accurate and robust fault location techniques are an important requirement for both permanent and intermittent faults.

The use of fault location systems on transmission networks produces several distinct advantages and enables quick restoration or fast repair to other aspects of the power system [1, 2]. These can aid by improving the system availability and performance, as well as reducing operating costs and losses in deregulated electricity markets.

Single ended impedance measuring fault locators are devices that calculate the effective positive sequence impedance to the fault. The estimated distance to the fault is based on this impedance and the known impedance per km of the line. These algorithms are often selected due to their practicality and simplicity. Nevertheless, they are vulnerable to many sources of error. Double ended impedance based fault location algorithms incorporate similar principles, with the exception that they require the voltage and current signals from both ends of a circuit.

The possible use of travelling wave techniques for fault location has been understood for some time, although it is only recently that these systems have begun to appear on transmission networks. These algorithms determine the fault location by recording the time difference between two signal transients. Single ended travelling wave fault locators have been developed for HVDC systems, but have not found a large application on AC networks. Conversely, double ended travelling wave fault location algorithms have proven to be very accurate on transmission circuits. Nevertheless, power systems are frequently switched in such a way that data from only one terminal is available for fault location. Thus, the use of single ended algorithms will remain common despite the introduction of synchronisation mechanisms.

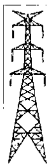
Travelling wave fault locators are potentially very accurate. However they require high bandwidth transducers and the recorded transients are often difficult to interpret [3]. Such fault locators in the past tended to be operated on out-of-service transmission lines to identify broken conductor faults [4]. Recently online techniques have been developed which can incorporate GPS time synchronisation, but these require data from more than one location in the power system, which is not always possible. They also often require the use of existing substation transducers, such as the protection current transformers.

Such fault locators have now been classified into five categories; types A, B, C, D and E [5] that encompass both double ended and single ended techniques.

2 COMPARATIVE ANALYSIS

A Monte Carlo simulation has been conducted to compare the errors expected at various fault positions and line lengths when implementing several algorithms on overhead transmission circuits. This comparison aims to consider several techniques including one travelling wave algorithm, an approach which has proven novel to date. The Monte Carlo approach was selected to compare the expected accuracy of each algorithm in a scenario with multiple significant parameters.

Both results depicted in this paper have been conducted using the Alternate Transients Program (ATP) [6]. A double circuit and single circuit option was created using a distributed parameter line model which was defined at a frequency of 50Hz for the analysis of the impedance techniques. An untransposed frequency dependent travelling wave line model was implemented for the travelling wave algorithm. Both circuit options were based on the same double circuit topology, shown below, whereby the selection of a single circuit analysis was achieved by opening the circuit breakers of line 2.



System Voltage: 330kV
Earth Conductors (EW): SC/AC 7/.162
Phase Conductors (A,B,C): Twin ACSR
(508mm^2 equivalent aluminium area)
Phase Conductor Spacing: 380mm
Soil Resistivity: 100Ωm

	Circuit 1	Circuit 2
Phasing	EW,B,A,C	EW,C,A,B
Height (m)	34.4,27.0,19.9,12.5	34.4,27.0,19.9,12.5
Offset (m)	-5.8,-5.8,-5.8,-6.6	5.8, 5.8, 5.8, 6.6

The circuits are based on the Sydney West to Bayswater double circuit in Eastern Australia, where each phase is comprised of twin ACSR conductors with 508mm2 equivalent aluminum area, spaced by 380mm. A soil resistivity of 100Ωm is also assumed. However, this parameter can vary greatly with the soil conditions.

An application was developed to independently create the ATP source files, run the transients program and analyse the results. This provided the option of inserting B-E (earth), A-B (phase), and A-C (inter-circuit) faults. Each calculation was performed 50 times at each fault position, ranging from a fault at 5% of the line length to 95%, in 5% increments. These considered the statistical variations in source impedance, pre-fault current and the fault resistance. Thus there are 18,050 simulations incorporated in each of the following algorithm error distributions.

2.1 Algorithms Considered

The algorithms considered in this analysis are detailed below, whereby the main objective was to select commonly used, whilst differing, techniques.

2.1.1 Distance Algorithm based on Impedance

The simple distance algorithms are an old fault location technique, which are now only used for line protection. To measure the distance to all faults that involve more than one phase, the distance relay compares the voltage between the two faulted phases with the difference between the phase currents. However, earth fault relays use faulted phase current and residue current measurements. Consequently, some calculations are needed to equate the observed phase impedance to that of the positive sequence line impedance. This is achieved with the Residual Compensation Factor [7].

Once the apparent positive sequence impedance has been calculated using the simple "impedance" technique, the fault location is obtained by dividing the apparent impedance by the line impedance and multiplying by the known line length.

2.1.2 Distance Algorithm based on Reactance

The apparent "reactance' values can be used in the distance calculation to help eliminate the effects of fault resistance when there is light loading. These techniques work reasonably well for homogeneous systems where the fault current doesn't include significant resistance or large pre-fault loads [8].

2.1.3 Takagi Algorithm

The Takagi [8] technique improved the simple reactance method by essentially correcting for load flow and fault resistance:

$$m = \mathrm{Im}(V_S I_{fS}{}^*) / \mathrm{Im}(Z_L I_S I_{fS}{}^*) \qquad (1)$$

$$I_{fS} = I_{S_0(FAULT)} - I_{S_0(PRE\text{-}FAULT)} \qquad (2)$$

where m is the fault distance, V_S the phase voltage, I_S the phase current, I_{S_0} the zero sequence phase current, and Z_L the line impedance.

Some relays [9] use phasor quantities developed by discrete Fourier transformations, and implement this or another expanded equation, shown below:

$$m = \frac{\mathrm{Im}(V_S)\,\mathrm{Re}(I_{fS}) - \mathrm{Re}(V_S)\,\mathrm{Im}(I_{fS})}{\mathrm{Im}(I_S.Z_L)\,\mathrm{Re}(I_{fS}) - \mathrm{Re}(I_S.Z_L)\,\mathrm{Im}(I_{fS})} \qquad (3)$$

Both of these fault location algorithms also require another embedded procedure to determine the fault type before the calculation is processed, since the location algorithm is based on the respective fault loop impedance [9].

Further improvements have been made over these algorithms, which account for source impedances and mutual coupling [8]. However, these are not as commonly employed.

2.1.4 Synchronised Phasors

For circuits where the voltage and current vectors are synchronised, the simple double ended approach can be adopted. This technique does not require the zero sequence parameters for the line, which is a significant advantage [1].

On the assumption that there is only one fault on the line, two equations are generated from each line terminal. These can be equated and solved using any of the sequence parameters, although the positive sequence values are commonly used:

$$m = Magnitude[(V_{S1} - V_{R1} + Z_1 I_{R1})/(Z_1(I_{S1} + I_{R1}))] \qquad (5)$$

where V_{S1} is the positive sequence voltage at the relay terminal, V_{R1} the positive sequence voltage at the remote terminal, I_{S1} the positive sequence current at the relay terminal, and I_{R1} the positive sequence current at the remote terminal.

2.1.5 Unsynchronised Phasors

The unsynchronised phasor technique proposed in [10] may be solved using the positive, negative or zero sequence parameters from the faulted circuit. However, the positive sequences are again used, as this provides a location for all faults despite some increased errors for high impedance faults.

2.1.6 Compensated Unsynchronised Phasors

Sachdev et al. [11] provides a simple method to compensate for the shunt capacitance of long lines. This technique based on the equivalent Pi model is also described in [10], and assumes that the fault voltage is small compared with the voltage at the line terminals, as well as the impedance of the capacitive branch at the fault being larger than the fault resistance.

Using these assumptions, new phase currents can be determined and the fault location can be re-estimated. This is often an adequate technique as the accuracy of distributed line algorithms appear to be constrained by the transducer and parameter errors rather than due to the omittance of the line capacitance [10].

In the following analysis, this technique has been applied to the unsynchronised phasor algorithm described previously.

2.1.7 Double Ended Travelling Wave

The double ended travelling wave technique also requires a synchronising signal at either terminal. This commonly employs the use of the GPS. When a fault occurs, both locators record the arrival time of the initial transient pulse, where the difference between the two recorded times can be used to determine the fault position.

The resulting location can then be obtained from a relatively simple relationship:

$$m = \frac{l}{2} + \Delta T\left(\frac{v}{2}\right) \qquad (6)$$

where ΔT is the difference in observed signal times, v the modal velocity of the circuit, and l the line length.

2.2 Monte Carlo Investigation

The fault resistance, pre-fault load flow and source impedance variations are considered in the following Monte Carlo analysis. Other parameters have not been included due to the lack of data concerning the variation in soil resistivity and tower footing resistances, as well as the variations in conductor height, etc. Furthermore, these parameters are commonly static and can be determined accurately from measurement.

Three-dimensional surfaces for each algorithm are obtained by averaging the results of the analysis for each configuration including single and double circuit operation, where the error has been calculated as shown below. The absolute errors have been shown as they hold the most significance to the field engineer whose task is to locate the fault.

$$error = |calculated\ location - actual\ location| \qquad (7)$$

The following figures have all been developed with the application of the algorithms at one line terminal only. This has been performed to compare both the single ended and double ended algorithms from the same measurement location.

2.2.1 Fault Statistics

Several useful fault statistics are provided in references [12, 13, 14, 15]. However, Transgrid's outage statistics from 1992 to 1996 indicate that out of the 0.82 trips per 100km per annum, 75% were phase to earth faults. The remaining trips constituted double phase to earth (18%), three phase (4%), and phase to phase (3%).

The phase to earth fault impedance distribution was based on 100 fault incidents, as described in reference [15]. Conversely, the phase fault impedance distribution assumes a simple linear resistive model between the two phases, as per the geometry described previously. The resulting impedance calculation was then given a further variance of 0.04Ω associated with a Gaussian distribution.

2.2.2 Line Loading Conditions

A cumulative probability distribution for loading conditions was also developed from the operational records of a major 330kV double circuit supplying Sydney. This data was obtained for the period between the 1st January 2002 and the 1st January 2003.

2.2.3 Source Impedances

The Monte Carlo process also randomly selected source impedances from more than thirty 330kV lines within Transgrid's network. Each of the impedances was then randomly applied to the circuits in question.

2.2.4 Distance Algorithm based on Impedance

Fig. 1 shows that the simple impedance based distance algorithm is considerably inaccurate for all line configurations and lengths. However, the errors generally decrease slightly as the line length increases since the larger line impedance overcomes the impact of fault resistances.

The large errors associated with this algorithm can be attributed to the fault resistance probability distribution, and that 75% of the simulated faults were phase to earth. For this reason, directional earth fault comparison schemes are often incorporated with distance protection schemes on such circuits.

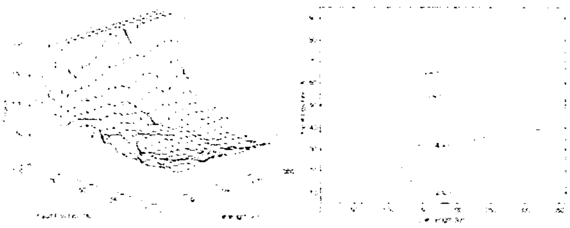


Figure 1 - Impedance distance algorithm

2.2.5 Distance Algorithm based on Reactance

Using the reactive components of the fault and line impedance, greatly improves the accuracy of the distance technique. However, as shown in Fig. 2 the absolute error is again still considerably large.

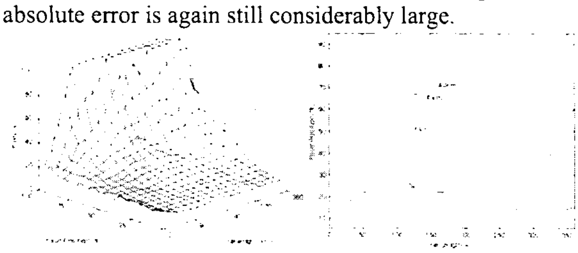


Figure 2 - Reactance distance algorithm

2.2.6 Takagi Algorithm

Applying the Takagi algorithm reduces the average error further due to the inherent fault resistance and pre-fault load compensation. It can also be noted from Fig. 3 that the effects of line capacitance appear negligible for circuits less than 100km in length.

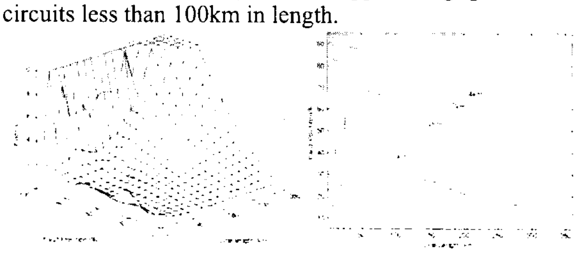


Figure 3 - Takagi algorithm

2.2.7 Synchronised Phasors

The use of synchronised phasors for fault location can give very accurate results for short lines, and when assuming that there is no transducer error. However, the effects of line capacitance can be seen on the circuits longer than 200km from Fig. 4

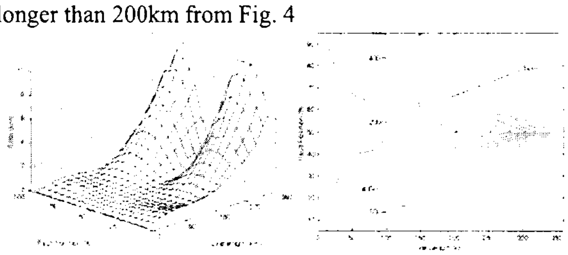


Figure 4 – Synchronised phasor algorithm

2.2.8 Unsynchronised Phasors

Fig. 5 illustrates the application of a Newton Raphson solution to synchronise the recorded voltage and current phasors. The fault location algorithm was applied when the difference in observed phase angles between iterations was less than $1x10^{-4}$ radians.

This technique appears to degrade the accuracy for faults occurring near either end of long circuits, when compared to the synchronised case as shown in Fig. 4.

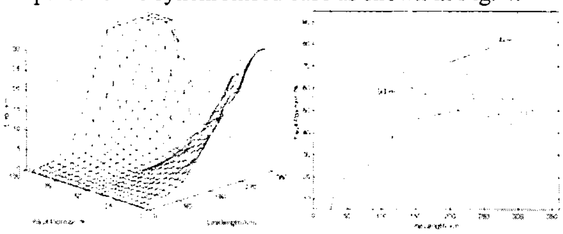


Figure 5 – Unsynchronised phasor algorithm

2.2.9 Compensated Unsynchronised Phasors

Some of the inaccuracies shown in the previous plots can be overcome by employing simple compensation for the susceptance of long lines, described previously. More ideal compensation may be incorporated through the use of a distributed parameter line model in the algorithm.

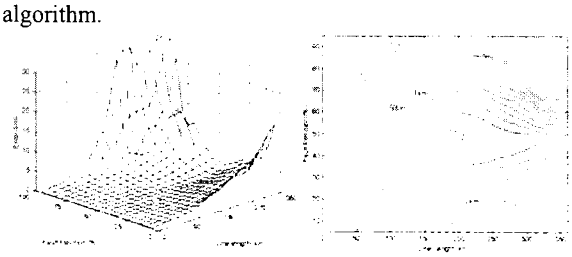


Figure 6 – Unsynchronised phasor algorithm with compensation for line capacitance

2.2.10 Double Ended Travelling Wave

Applying the travelling wave algorithm to the simulation, and recording the arrival times of the transients creates an error distribution that is reasonably consistent for all line lengths. Assuming there is no transducer attenuation or distortion, the overall error is limited by the sampling rate of 1.25MHz to around 200m.

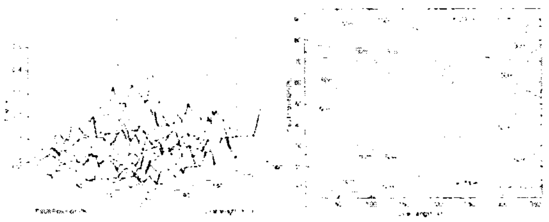


Figure 7 – Calibrated traveling wave algorithm with ideal transducers

However, Fig. 8 shows a typical scenario that is based on the observed signals from different travelling wave recorder sites within a 330kV network. The transfer function relation ship *(H)* between the 330kV line current and recorded signals is assumed to be of the form shown below:

$$H(s) = \frac{Ks}{(s+p_1)(s+p_2)(s+p_3)(s+p_4)} \quad (8)$$

The relationship is dominated by a lightly damped complex pole pair (P_1 and P_2). Table 1 describes the positions of these poles for a 186km long feeder in this network.

	Natural Frequency	Damping
Local Line Terminal	3.52×10^5 rad.s^{-1}	0.219
Remote Line Terminal	1.10×10^5 rad.s^{-1}	0.112

Table 1 – Dominant Pole Locations for a 330kV circuit

Applying the filtering characteristics from this circuit to the Monte Carlo simulation results in consistent errors that increase at locations close to the remote line terminal while the feeder is short. However, the errors increase more towards the local busbar as the line length increases.

Note that the simulations determined the arrival times of the transients using threshold levels in the time domain, set to half the overall signal magnitude. These errors can increase further with a greater loss of the higher frequency signal component, or with an increase in the threshold level, and in situations where the filtering characteristics of the coupling devices at either end of the line differ greatly.

Figure 8 – Filtering coefficients applied from a 330kV circuit

Calibration errors can also occur when specifying the electrical line length and the modal velocity in (6). In this case, the error in distance increases as the fault occurs further from the centre of the circuit, as well as with an increase in line length. Appropriate calibration can assist in reducing the errors experienced in Fig. 9.

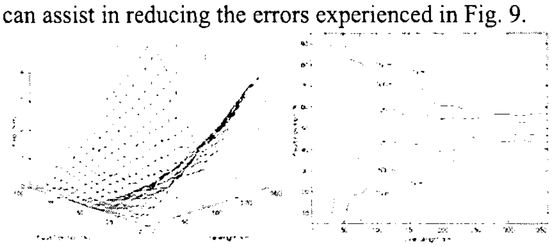


Figure 9 – Calibration error of 2.5% in line length or velocity

3 DISCUSSION

Each algorithm, described above, is susceptible to different forms of uncertainty, whereby fault resistance and pre-fault load are generally the most critical to impedance based methods. However, accuracy in timing and the frequency response of the monitoring equipment are the most significant parameters when considering travelling wave techniques.

This paper demonstrates that the travelling wave technique is often the best performer for long circuits, followed closely by the synchronised phasor algorithm. However, it appears that the unsynchronised phasor techniques are also quite good for application on most circuits.

Some sources of uncertainty can be considered static and thus can be compensated, while others such as transducer error produce uncertainties to all algorithms that rely on the transducer output. Hence, the above analysis provides a clear comparison between the impedance based algorithms. However, when comparing the travelling wave and impedance based algorithms, the relative transducer frequency responses must be considered.

The variance in the observed error is also greater for the impedance algorithms, while the double ended travelling wave technique is less susceptible to dynamic variations in the significant sources of uncertainty.

The accuracy of both the impedance and travelling wave techniques are often unintentionally constrained, where the accuracy of the impedance methods is inhibited by several unknown parameters including the fault resistance, mutual coupling and the transducer errors. However, the travelling wave techniques are generally affected by the frequency response of the coupling transducers and the secondary cabling to the recording device.

Despite the many advantages, the application of travelling wave methods appears to be restricted to lines in excess of 10km, or more, in length. This is generally due to the low pass filtering effects that exist in real systems and the additional cost of implementing this technique on transmission circuits. In real terms, accurate fault location is not as important on shorter lines as these are generally easier to patrol by ground crews, or helicopter, than those which are very long or are situated through inaccessible terrain.

4 CONCLUSION

Accurate and robust fault location techniques are an important requirement for transmission systems. Several varied algorithms have been described in this paper, many of which are commonly used in fault location systems.

A Monte Carle simulation approach has been taken to compare the impedance based and travelling wave algorithms under the same system conditions. This has demonstrated the strengths of the double ended techniques, in particular the travelling wave algorithm, in terms of the accuracy and variance of the location estimation.

However, the reliability and additional cost of double ended systems must be considered before the technique is applied to a particular circuit.

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