Review of the Application and Development of the Travelling Wave Principle Applied to Fault Location on Overhead Line Feeders

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Abstract – This paper reviews the development of overhead line fault locators based on travelling wave techniques and provides examples of use in transmission systems.

Keywords**:** Overhead lines, Fault Location, Travelling Waves

1. INTRODUCTION

It is generally accepted that accurate fault location on transmission lines is a necessity to reduce downtime, allow the implementation of preventive maintenance to known trouble spots and to reduce cost and manpower requirements on line patrols. The traditional method of fault location has been based on impedance techniques that are now conveniently incorporated in digital protection relays. The consistency of distance to fault results, however, is often variable. This paper introduces an alternative, more accurate, method of fault location based on travelling wave technology that significantly enhances a Power Company's ability to respond to line trips faster and with more precision.

2. CATEGORIES OF FAULTS

Faults on overhead transmission lines can be divided into three categories, permanent faults, intermittent or recurring faults and transient faults. Permanent faults are normally rare but when they do occur it is essential to locate them fast to instigate repairs. Most faults on overhead networks are either intermittent or transient and can be successfully re-closed. Intermittent faults are caused by damaged insulation, vegetation, conductor clashing or the occasional over voltage caused by switching surges. These faults can reoccur. Transient faults are one off instances caused by birds, lightening and bush fires. Traditionally intermittent or transient faults were not taken too seriously but there is an increasing awareness and concern over power quality and system stability issues that are driving a need to reduce the number of line trips by targeting preventive maintenance at known trouble spots. This can only be achieved if accurate consistent fault location is available.

3. TRADITIONAL IMPEDANCE METHODS

For the past 35 years the method for fault location on overhead lines has been based on impedance techniques. The reactance of the line is calculated for the period when the fault current is flowing and the ohmic result converted to distance based on the line parameters. Impedance fault location is now conveniently implemented in most digital protection relays A distance to fault (DTF) result is calculated at each end of the line and made available locally in the substation or transmitted to a remote location. Impedance algorithms have been refined over the years but it is widely recognised that the method is subject to errors when the fault arc is unstable, when the fault resistance is high and fed from both ends and when circuits run parallel for only part of the route length. Accuracy is also dependent on CT and PT phase and magnitude response, the assumption that the line is symmetrical (identical line impedance on all three phases) and the assumption that a simplified lumped line model as opposed to a distributed parameter model will suffice. Accuracy is also limited by faster fault clearance times on many networks (5 to 6 cycles) resulting in a limited data window for filtering DC offsets and transient harmonic content. The absolute error increases with line length hence the accuracy of impedance fault location is referred to as a percentage of line length. Errors can typically be from 1 to 15% of line length depending on the type of fault. Phase to phase faults are more defined and give the best accuracy but phase to earth faults with high fault impedance can result in a large error. On a 100Km circuit the error could range from 1Km to 15Km or more depending on conditions. Furthermore the impedance method is not suitable for series compensated lines and teed circuits. There is a need for an alternative method of fault location that provides accurate, consistent fault location results on all types of fault.

4. INTRODUCTION OF TRAVELLING WAVE TECHNIQUES

The use of travelling waves for fault location on overhead lines was reported as early as 1931 [1] but it was not until the 1950s that the techniques were refined and practical systems developed for field use [2 and 3]. Overhead line fault locators were classified into Types A, B, C and D according to their mode of operation. Type B and C systems include pulse or signal generating circuitry. Type B is double ended and C single ended. In comparison Type A and D modes are inherently much simpler as they rely on the fault to produce one or more travelling wave transients from which the fault location can be determined. Type D is double ended and Type A single ended. Equipment developed during the 1950s, although effective, was expensive to install, cumbersome and required significant maintenance and therefore application was limited. Nevertheless in the early 1960s several 275 and 400KV lines in the UK were equipped with Type C fault locators [4].

The commercial development of overhead line fault locators was kick started in the 1990s by advances in digital electronics, microprocessors and communications and through the courtesy of the US military in opening up the GPS satellite system for public use. A reliable and accurate fault locator, called a TWS, was produced that could function simultaneously as a Type A and a Type D device. A new mode defined as Type E was also proposed. Furthermore the prohibitively high costs of previous implementations have been reduced for both the hardware and, especially, for the installation and maintenance requirements.

4.1 TYPE D MODE

The Type D mode is the only reliable method of fault location using travelling waves that does not involve expertise in the analysis. It is therefore used for commercial use especially given that the tendency in most Utilities is to reduce manpower with the resultant loss of experienced personnel.
The principle of Type D is shown in the lattice diagram in Fig 1. The fault generates travelling waves that propagate to each end of the line at a velocity set by the dielectric. For air the velocity equals the speed of light, 300m/µs. Note that the polarities and magnitudes of the transients appearing at the line ends will differ depending on whether current or voltage sensors are used as well as the nature of the line terminations. The diagram is intended to show how the energy contained in the system varies in space and time.
Distance to fault can be calculated from the following equations:

$$L1 = [(L1+L2) + (TA-TB).v] / 2 \qquad (1)$$

$$L2 = [(L1+L2) + (TB-TA).v] / 2 \qquad (2)$$

v = propagation velocity.
TA and TB are the arrival times of the waves at ends A and B respectively.

For success it is essential to have synchronized clocks in the TWS devices. This is achieved by use of the GPS system. It is also necessary to have communication channels to each substation such that data can be transferred to a central location for the distance to fault calculations to be automatically performed. These channels can be via a modem (telephone line or a GPRS network), Ethernet connection or through the SCADA system.

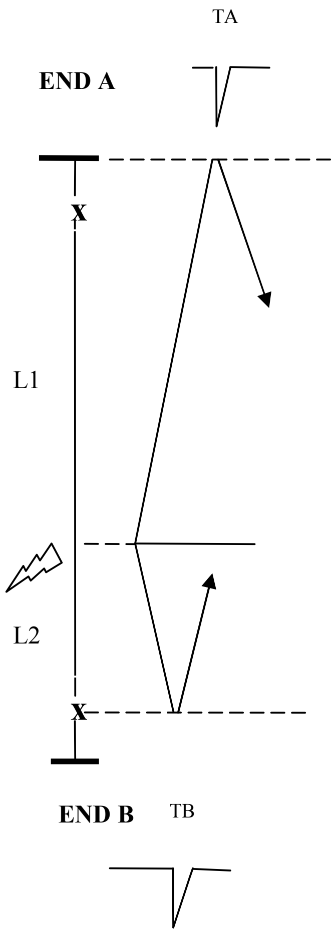

Fig 1. Lattice Diagram for Type D operation

4.2 TYPE A

Type A is a single ended method which uses transient capture at one end of the line to determine the fault position. An experienced operator is needed to analyse the resultant waveforms and even then a successful outcome is not guaranteed. The lattice diagram shown in Fig 2 illustrates what happens when the fault generates a stable low resistance arc. The technique relies on the busbar and other connected lines to present a sufficiently large impedance mismatch to cause a significant amount of the arriving energy to be reflected back to the fault. The fault site is a very low resistance arc that reflects the entire signal back towards the line ends.

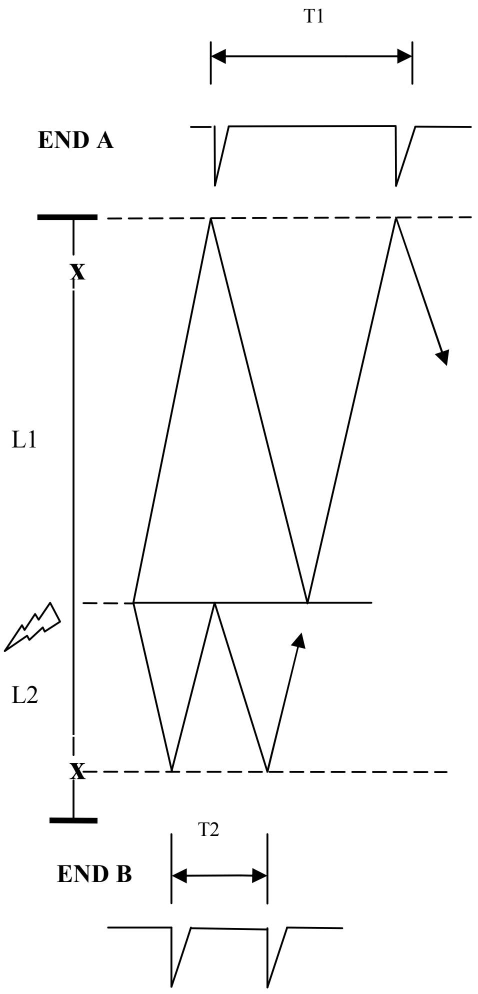

Fig 2. Lattice Diagram for Type A operation with a stable low resistance arc

By capturing and measuring the time difference between the first two pulses it is possible to calculate the distance to fault as follows:

$$L2 = [T2 \times v]/2 \qquad (3)$$

$$L1 = [T1 \times v]/2 \qquad (4)$$

In practice the arc resistance may not be so low as to reflect all of the pulse energy arriving at the fault. Some will be transmitted causing more complex waveforms at the line ends.

Other types of fault characteristics produce a different pattern of recorded pulses. Fig 3 shows the situation when the fault is characterised by a transient arc that self extinguishes. In this instance the initial wave reflected from the line end passes through the fault site and onto the opposite line end. This time the distance to fault calculated from the time difference between the first two pulses is the length from the opposite end of the line. The distance to fault in this instance is calculated from:

$$L1 = [T2 \times v]/2 \qquad (5)$$

$$L2 = [T1 \times v]/2 \qquad (6)$$

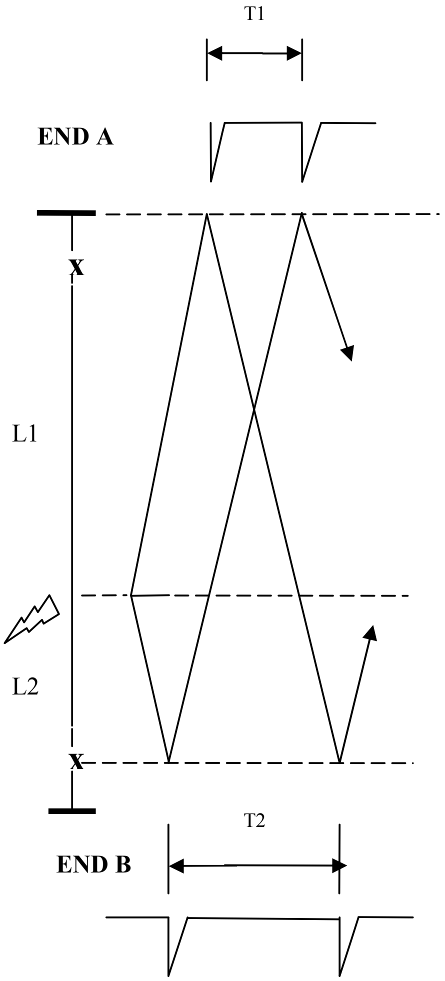

Fig 3. Lattice Diagram for Type A operation with a transient arc

A further more complicated scenario is where the arc extinguishes after the reflection has arrived from end B but before the reflection from A. This scenario leads to yet another set of options for determining distance to fault.

This brief analysis of the Type A method of fault location demonstrates that it is not an easy process to interpret waveforms. The difficulty increases further in practical situations where extra reflections return from impedance discontinuities beyond the line ends. The

Type A method is useful in confirming a result in certain cases but it is not practical where operators expect to receive distance to fault values quickly after a line trip without having to rely on expert knowledge.

4.3 TYPE E

It can be seen from the description of the Type D mode of operation that knowing the line length (L1+L2) is necessary to calculate the distance to fault. Line length is normally obtained from records but it is possible to measure the length by use of the propagation velocity and a type E test shown in Fig 4.

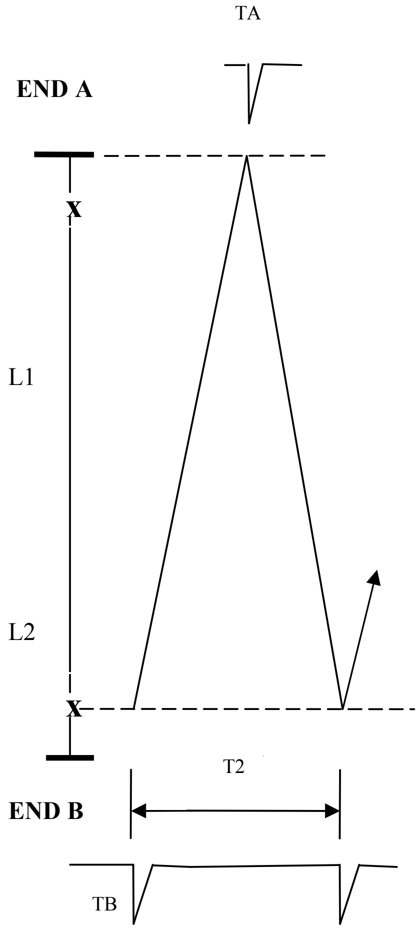

Fig 4. Lattice Diagram for Type E operation energising a dead line

The line is energised by closing the circuit breaker at end B with end A being open. Note that the waveform at end A will drastically change in magnitude depending on whether the voltage or current component of the wave is captured. The line length can either be calculated using equation (1) or (2). Note that in this case L2 = 0 and L1 equals the line length. Alternatively the following equation can be used:

$$\text{Line Length} = [T2 \times v]/2 \qquad (7)$$

5. Voltage or Current Transients

The analysis thus far is showing that the use of travelling waves for fault location is viable, particularly in the Type D mode. Practical implementation, however, is still vital for success. The decision on whether to capture the voltage or current part of the travelling wave is important. The relationship between the two components is as follows:

$$\text{Iwave} = \text{Vwave} / Zo$$

where Zo is the characteristic impedance of the line. The reflection due to the impedance discontinuity at a line end is different for the two components as follows:

$$\mathbf{V}\text{reflection factor} = \frac{Zs-Zo}{Zs+Zo}$$

$$\mathbf{I}\text{reflection factor} = \frac{Zo-Zs}{Zs+Zo}$$

Zs is the impedance of the terminating busbar which, if it has a total of n similar lines connected to it, will be:

$$Zs = Zo/(n-1)$$

The reflection factors now become:

$$\mathbf{V}\text{reflection factor} = (2-n)/n$$
$$\mathbf{I}\text{reflection factor} = (n-2)/n$$

The voltage and current transients measured at the substation busbar are the sum of incident and reflected waves which in per unit terms based on the number of lines n is:

$$\text{Voltage} = 2/n \qquad \text{Current} = (2n-2)/n$$

From this it can be seen that as the number of lines increases the voltage transient tends to zero while the current transient tends to double. At transmission substations there are normally multiple lines connected and given that the protection CT is capable of passing the high frequency signals it is clear that, except for special circumstances, the current transient is best for fault location applications. High frequency couplers can be fitted to the CT secondary wiring without the need for line outages.

6. Benefits of Travelling Waves

The travelling wave technique for fault location does not rely on any of the factors that are the cause of errors in traditional impedance methods. Equipment working in the Type D mode based on current transients is easy to install and the accuracy is set by two parameters, the ability to measure the arrival time of the pulse and the line length. Results are accurate and consistent for all types of faults, permanent, intermittent and transient. Faults can be located without the need for helicopters or multiple line patrol teams. Faster more accurate location means reduced downtime and the confidence to plan preventive maintenance at sites of intermittent faults thereby reducing nuisance tripping.

7. TWS Parameters and Accuracy

The main parameters of the TWS device are a GPS time tag accuracy of 1μs and a digital sampling rate of 1.25MHz to capture the current transients. This results in a best theoretical accuracy of +/-150m or approximately one span. This accuracy is independent of line length except on lines longer than 1000Km where dispersion makes it more difficult to measure the exact arrival time of the wave.

8. Field Results

Two separate sets of results have been obtained from two different Utilities to confirm the obtainable accuracy.
Table 1 gives results from a relatively short (35.1Km) 400KV circuit between Strathaven and Kilmarnock South over a two year period.

Strathavan – Kilmarnock South 400KV Length 35.1Km		
TWS DTF (Km)	Actual DTF (Km)	Error (Km)
27.2	27.0	0.2
20.4	20.4	0
22.0	22.0	0
20.8	21.2	0.6
24.0	24.0	0
25.3	26.0	0.7
20.9	20.4	0.5

Table 1 Results from Scottish Power

Table 2 gives results from a 140Km circuit in ESKOM, South Africa over a 6 month period. This also includes comparative results from impedance relays. Line patrols confirmed that the TWS was correct every time. The errors observed in the relays ranged from 1.7% to 23%.

140Km ESKOM circuit			
TWS Scheme		Impedance Scheme	
Venus (Km)	G'dale (Km)	Venus (Km)	G'dale (Km)
121.8	19.5	92.8	17.19
110.7	30.6	108.8	28.5
97.6	43.7	91.5	40.5
22.9	118.1	18	94
121	20	104	18

Table 2 Results from ESKOM

TWS units have been used in the US to track lightening strikes both direct and indirect. A study was conducted in 1996 comparing TWS travelling wave results with the FALLS system of lightening detection. [5]. The correlation between the two was good.

9. TWS Implementation and Development

About 1000 TWS units are in use in approximately 70 Utilities in 30 countries. When the units were initially installed they tended to be operated by protection engineers who had time to download and process data after faults occurred and pass on fault location results to the Operations departments. More recently there has been a shift in emphasis. Distance to fault results are required to be available in the dispatch centre automatically within minutes of a line trip and used to influence re-close decisions and guide maintenance crews. Such a shift in emphasis has led to the development of new software that polls TWS devices on a continuous basis and displays results on a simple screen where filters can be set based on time, circuit or keywords to further simplify the presentation. The more strategic positioning of the TWS means it is also important to monitor availability on a routine basis. Health check functionality has been built into the polling software to monitor the integrity of the communications channels and the quality of the GPS lock. The polling rate and the number of TWS devices on the network determine how quickly results can be gathered and displayed. One Utility in the US with 25 devices and with Ethernet connections to the substations can display results within 5 minutes of a line trip. One or two Utilities are choosing to collect TWS trigger directories via the SCADA communication channels. The downside to this is that special software has to be provided on the SCADA host to link data from different circuit ends to calculate distance to fault results.
It is possible to improve the accuracy of the calculated distance to fault by sampling waveforms at a faster rate and time tagging triggers to better than 1μs. Technology is readily available to do this but it must be implemented in conjunction with better transducers that provide transients with higher bandwidth such that

the arrival time of the pulse can be better defined. This is being investigated even though it could lead to higher costs and more expensive installation procedures. For now the accuracy of the existing device, one span, is still regarded as adequate throughout most of the industry.

10. Conclusions

It has been proven by practical implementation that overhead line fault location using travelling waves is both viable and more effective than impedance methods. Developments are underway to meet new levels of expectation within the Power Industry and to improve accuracy and response times further.

References

[1] Rohrig J., 1931, ‘Location of faulty places by measuring with cathode ray oscillographs’, Elekt. Zeits., 19th February, 241-242
[2] Lewis L.J., 1951, ‘Travelling wave relations applicable to power-system fault locators’, AIEE Trns., Vol 50, 1671-1680
[3] Stringfield T.W et al, 1957, ‘Fault location for overhead lines’, AIEE Trans., August, 518-526
[4] Jamieson E., 1969, ‘Automatic fault location on overhead transmission lines’, Electrical Review, 5th December, 833-835
[5] Gale,P.F.,Burnett,R.O. and Cummins,K., ‘A study of power line response to lightning using GPS based Travelling Wave Fault Locators and US National Lightning Detection Network’, Fault and Disturbance Conference, Arlington, Nov 1996

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