Challenges and Solutions for Fast and Accurate Fault Location and System Restoration

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The Need for Fault Location

Highly accurate distance to fault results has obvious advantages and cost benefits when applied to overhead transmission lines (greater than 100KV). Being able to dispatch repair teams to the fault site without the need for time consuming and potentially dangerous line patrols and expensive helicopter air time results in faster restoration time and improved system security. Emergency measures invoked to guard against the possible effects of a second or third fault in the same vicinity can be expensive. There is a prime economic driver to quickly isolate the faulted section, undertake repairs and return a network to normal operational status in the shortest possible time.

There is probably a greater need for fast and accurate fault location on sub transmission networks (less then 100KV). These networks are more extensive, are less robust and therefore more prone to faults and often have less redundancy so the impact of faults is more likely to contribute to the 'customer minutes lost' parameter most Regulators use to assess Utility performance.

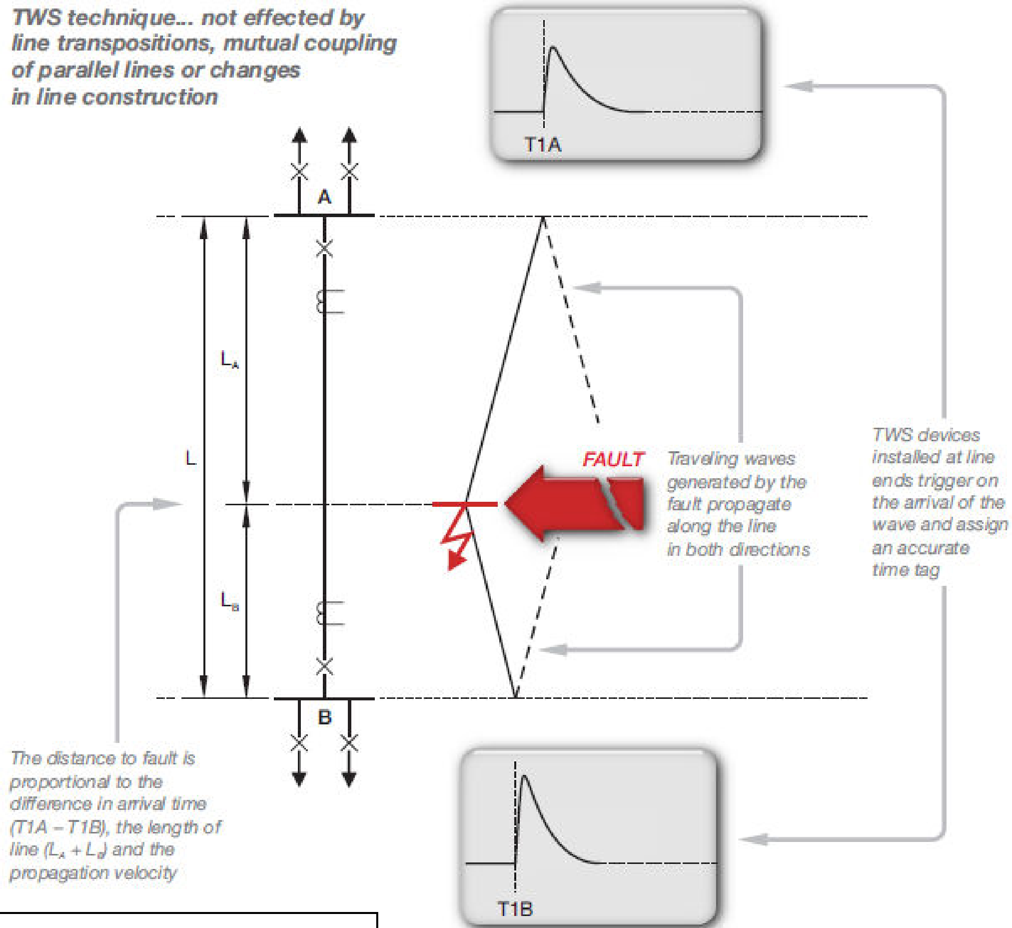
Faults on overhead transmission lines can be divided into three categories, permanent faults, intermittent or recurring faults and transient faults. Permanent faults are normally rare but when they do occur it is essential to locate them fast to instigate repairs. Most faults on overhead networks are 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 with the growing regulatory pressure to maintain quality of supply and with more stringent consequences should an 'intermittent' fault turn into a 'permanent' fault, there is a growing awareness that ALL line trips are important and require analyses. There is 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.

Traditional methods of fault location have been based on impedance methods but the accuracy and consistency of the results for different types of fault does not provide sufficient confidence to know which tower has the cracked insulator or which span has tree growth close by. There is a need for a better system based on travelling waves.

Travelling Wave Technique

Modern travelling wave systems (TWS) use a double ended (Type D) method for fault location that does not rely on operator intervention to determine distance to fault. Results are automatically calculated and immediately available for use. The power arc at the fault site and the resulting step change in voltage generates a travelling wave that propagates along the line in both directions to the line ends. TWS fault locators positioned at the line ends accurately tag the arrival time of the waves using GPS as a reference. These time tags are sent to a central location where they are used to calculate distance to fault using the line length and the velocity of propagation. Further details are given in Figure 1.

TWS devices also capture and store waveforms and it is possible, in some cases, to manually measure between initial and reflected travelling waves (pulses) to determine fault position. This single ended (Type A) method, however, is not reliable as reflected pulses from the fault site are not always recognisable. Analysis of waveforms and trigger points is useful for 'calibrating' a line whereby normal transients from switching can be used to check line length or velocity factor.



LA = [L + (T1A-T1B).v] / 2

LB = [L + (T1B -T1A).v] / 2

V = propagation velocity

Figure 1 Type D Travelling Wave Technique

Accuracy of TWS Method

The accuracy of the distance to fault calculation is dependent on the GPS time tag, the line length and the velocity of propagation.

The speed of propagation on an overhead line is the speed of light (300m/µs) and is not affected by conductor type or size, tower construction or phase transpositions.

The line length is provided by the Utility and is normally a summation of all the point to point distances between each tower. This 'physical' line length does not include sag and to compensate a default velocity of 98.98% (297m/µs) is used.

Most existing TWS equipment has a GPS time tag accuracy of 1 µs with a resolution of 100ns. Field results have shown that accuracy of around 200m is achievable. This is independent of fault type and line lengths less than 800Km. The latest TWS equipment has a GPS time accuracy of 100ns with a resolution of 10ns giving a theoretical accuracy of around 30m. Recent switching trials in the Far East have returned an accuracy of 45m but a more typical accuracy would be 60m after 'calibrating' the line as explained previously. Note that other errors can be introduced by any differences in the length of the cabling from protection CT to relay room at each end of the line.

In general the existing TWS equipment is accurate to one span and the new to one tower.

Benefit of Great Accuracy

Reliable, consistent accuracy to one span or one tower gives Operation Engineers the confidence to send repair teams to the right location first time. It also allows intermittent or transient faults (those that successfully reclose) to be mapped with sufficient detail to establish trends such as polluted or damaged insulators, encroaching tree growth or bird activity. A few instances at the same location can trigger a line inspection and possible remedial action taken before a permanent fault develops. An example of a damaged insulator is shown below in Figure 3.

Question:

A structure experienced 4 self-clearing faults in 1 year. Is it in the best **interest of your company** and **reliability** to visually inspect that structure for damage that may eventually result in a non-clearing fault?

Figure 2 – Location of a Damaged Insulator

The damage could not easily be seen – the linesman needed the exact tower location to carry out the detailed inspection.

Many transient faults are often classed as caused by lightning because there are no other obvious explanations. In the US TWS fault results have proved to correlate very well with lightening detection schemes [1]. Knowing that a line trip was close to a lightning strike is good reason to classify it as such but a few years ago Public Service New Mexico categorised line trips as lightning that were later found to be due to bird activity after inspections driven by TWS results.

The Need for Communications

The double ended Type D method of fault location does require information to be collected from each end of the line to allow the automatic calculation of distance to fault - communication to a central location is essential. The most common methods of remote communications are via an ethernet connection or via a dialup modem to vendor based software packages that calculate and display results. In some Utilities where neither of these are available or reliable GSM or GPRS modems have been used based on the mobile phone services. Another alternative that is being considered in the US is use of the substation SCADA channel. In this mode the TWS device can use a standard protocol, like DNP, to send trigger time tag information to the SCADA master via the RTU. Special software then has to be added to the SCADA master to combine this data from each of the line ends with line length and speed of propagation to calculate distance to fault.

Monitoring the Travelling Waves

Many TWS systems are retrofitted to existing substations so it is essential that TWS installation is easy and non-intrusive. At substations where more than one line is connected to the busbar and the terminating impedance is low compared to the line surge impedance it is best to monitor the current component of the travelling wave from the secondary side of the protection CT. Small split core current clamps are placed around the CT wiring in the protection panel and connected to the TWS as shown in Figure 3. An air gap is introduced to reject low power frequencies. A GPS antenna must be mounted on the roof with a clear view of the sky as shown in Fig 4.

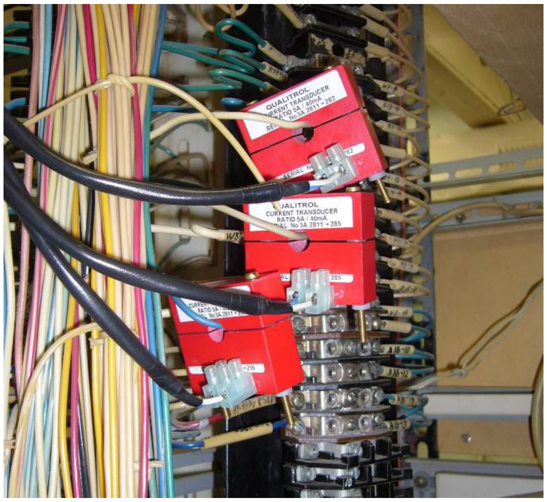


Figure 3 – Collecting ‘Current’ Travelling Waves When the Terminating Impedance is Low

Figure 4 – Roof Mounted GPS Antenna

99% of TWS installations are installed in this way but there is a growing need to monitor lines where either one end terminates in a transformer or a double circuit line feeds a substation and it is possible for one of the lines to be switched out. In such instances where the terminating impedance is high compared to the line surge impedance it is necessary to monitor the voltage part of the travelling wave. The easiest way to accomplish this is to use the line CVT when one is available as shown in Figure 5.

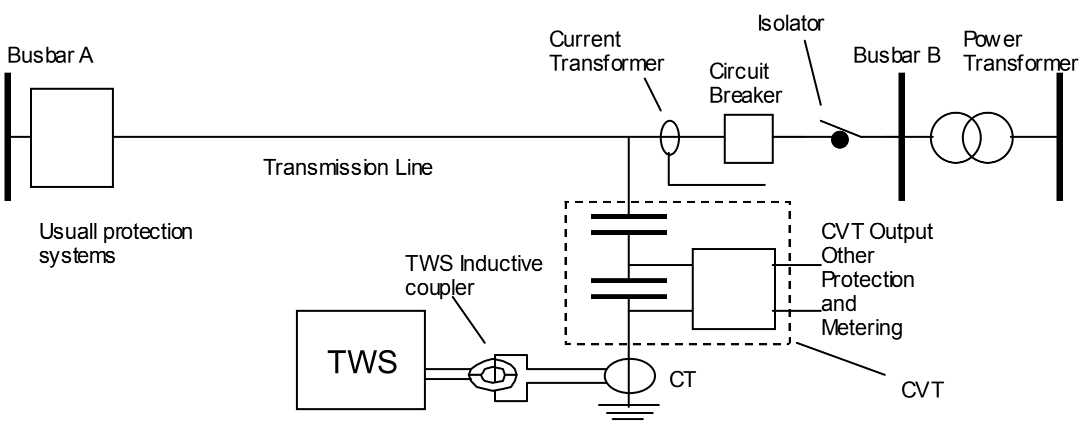


Figure 5 – Collecting ‘Voltage’ Travelling Waves when the Terminating Impedance is High

A toroidal CT is connected into the earth connection of the CVT capacitor stack to monitor the current from the HV line voltage. High frequency components are effectively amplified. The signal is taken to the relay room via a twisted pair screened armoured cable and shorted. A standard split core CT (inductive coupler) as used in the ‘current’ method is then placed around the shorted turn and connected to the TWS. This technique provides good high frequency coupling but it requires a line outage to fit the toroidal CT and the installation of a new length of cable to the relay room.

An example of the use of this ‘CVT’ technique from Russia on a 110KV network is given below in Figure 6. The line L-107 and L-147 had to be monitored but line L-148 is normally out of service and only used if L-147 is switched out. The resulting high terminating impedance at end E meant that the CVT technique was used to monitor the voltage component of the travelling waves on L-147 and L-148. The standard ‘current’ method was used at end A.

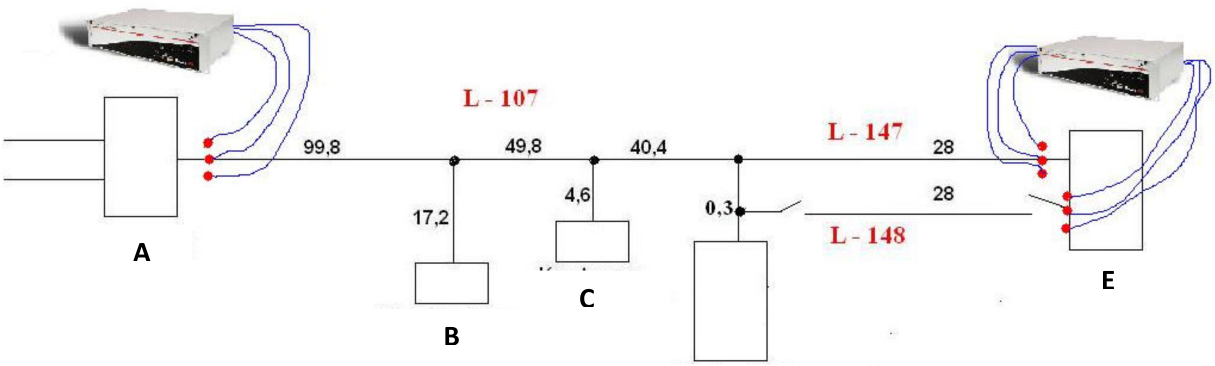
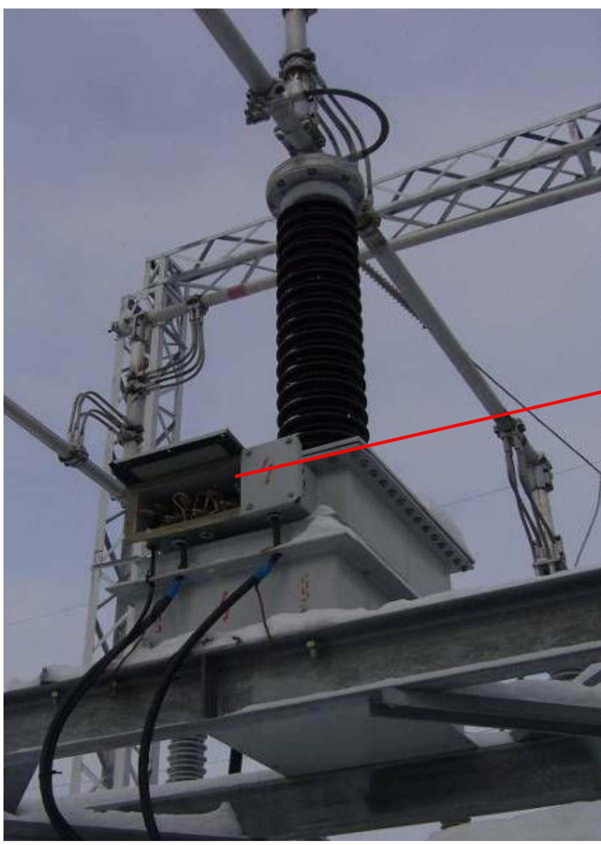


Figure 6 – 110KV network in Russia

An example of one of the CVTs with the toroidal CT installed in the marshalling box is shown in Figure 7.



CVT marshalling box - Toroidal CT around the earth connection of the bottom capacitor

Figure 7 – Installation of Toroidal CT on a CVT at End E

A fault was located in December 2011 just after midnight at 64.5Km from end A. Phase B conductor snapped in the extreme cold of -51˚C. Repair crews went directly to the site.

TWS Results

Double ended Travelling Wave fault location systems have been in use for over 15 years.

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. 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%.

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

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

More recent results have been published from Dominion, a Utility in the USA [2]. TWS devices have been installed on 12 x 500KV circuits. Table 3 compares TWS generated results on one line against lightning data during a storm. Note that the line did not trip. The TWS triggered from travelling waves induced in the line from nearby lightning strikes.

Date	**Time**	**TWS location**	**Lightning Correlation**
4/16/2011	16:01:26.366	57.4 miles	56.2-57.04mi
4/16/2011	16:04:52.976	57.0 miles	55.3-55.9mi
4/16/2011	16:05:27.945	55.5 miles	55.5mi
4/16/2011	16:50:11.458	20.4 miles	20.4-21.2mi
4/16/2011	16:53:36.527	5.5 miles	5.4-6.4mi
4/16/2011	19:54:54.178	46.9 miles	46.6mi
4/16/2011	20:16:27.659	37.8 miles	38.2-38.6mi

Table 3 Lightning Correlation Results on a 500KV circuit – no circuit trips

Table 4 gives results on the Dominion line 22 500KV circuit that is 39.07 miles. This line is interesting since it was constructed in the 1920s with wooden towers and ground faults typically tend to have high impedance. Fault location on this line to date has been challenging. Since installation the TWS has triggered and located all 10 line trips.

Actual location miles	TWS miles	Relay miles	DFR miles	FALLS miles	Aspen miles	Date	Time	Cause
19.8	19.8		17.5			12/3/2008	0:18:00.000	Conductor burned off
13.4	13.6		12.6			1/18/2009	21:26:50.568	Car hit guy support
Unknown	18.4					6/23/2009	1:27:55.150	Undefined
2.33	2.4					6/25/2009	22:38:47.872	Snake
32.3	31.5				29.75	8/30/2009	12:46:24.309	Found buzzard feathers
17.64	17.8/17.9	14.8	17			3/18/2010	2:25:00.000	Car hit pole
Unknown	18.7	16.9	18.3		18	5/4/2010	18:56:00.000	Unknown
18.2	18.2	16.57	17.8			6/22/2010	4:21:00.000	Arrester
Unknown	18.5	16.9	18.3			8/9/2010	15:55:32.841	Unknown
37.15/34.96 (?)	33.6			32.06		7/6/2011	18:41:32.122	Two blown arrestors

Table 4 Results from a 39.07 mile 500KV circuit from Dominion

Another interesting result was on a 275KV line in Scottish Power where an insulator hanger broke and the conductor fell onto the lower cross arm. Figure 8 shows the TWS waveforms from each end of the line and in this instance it is possible to identify the reflected pulse from the fault. Figure 9 shows the damage at the tower,

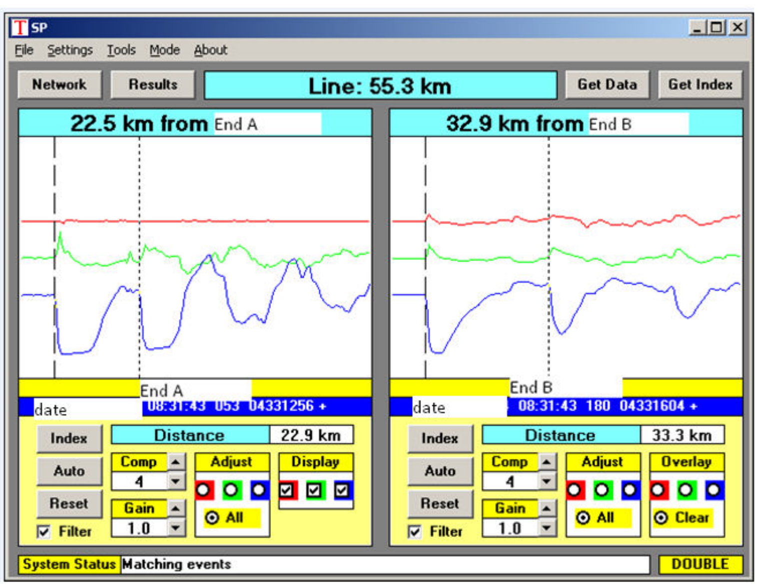


Figure 8 TWS waveforms from each end of the line

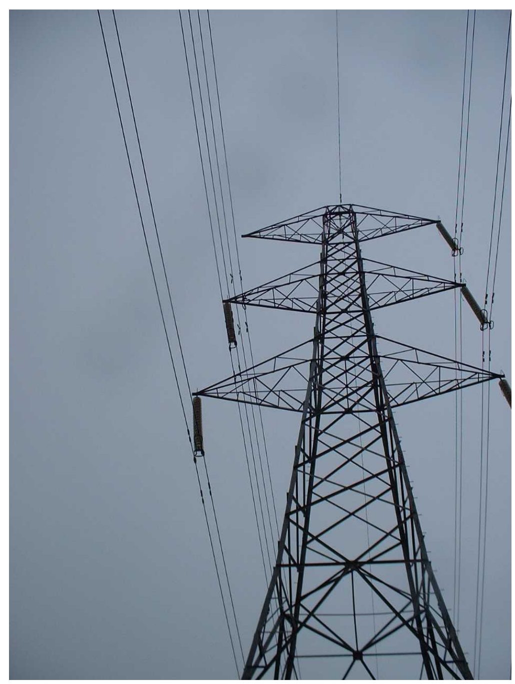


Figure 9 Top left conductor fallen onto lower cross arm

Actual fault 33Km from end B – TWS automatic location 32.9Km

Conclusions

The double ended TWS system has proved to be an effective and viable method of providing accurate, automatic distance to fault results that allow operators to rapidly deploy repair teams to the fault site, undertake remedial action to reduce the instance of transient / intermittent faults and restore faulted networks to original operating conditions as soon as possible.

Future work is aimed at deploying the method more effectively on lower voltage systems with more line taps / branches and where transformer feeders are more prevalent. The analysis software will be improved to provide an easier user interface for circuits with up to 6 'tee' connections. Alternative transducers for collecting the voltage component of travelling waves from line ends where CVTs are not present are also being investigated.

References

[1] 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

[2] Orndorf, R.M 'Evaluation of Travelling Wave Fault Locators at Dominion', Fault and Disturbance Analysis Conference, Atlanta, April 2012