Travelling Wave Fault Location

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QUALITROL® Defining Reliability

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Categories of Fault

Faults can be divided into three types

- Permanent faults – normally rare but need finding and fixing fast
- Intermittent faults – can be re-closed but can occur again. Eg damaged insulation, vegetation
- Transient faults – can be re-closed. Caused by random events eg lightning, bush fires.

Intermittent and transient faults were not taken too seriously but there is an increasing awareness over power quality and system stability issues that are driving a need to reduce the number of line trips.

You need accurate fault location to find these faults

The need for fault location

It is generally accepted that accurate fault location on overhead lines is necessary at transmission voltages (>100KV) to:

- Reduce downtime
- Allow the implementation of preventive maintenance at known trouble spots to avoid further trips and voltage dips
- Reduce costs and manpower requirements – no need for multiple line patrols or use of helicopters.
- Minimises extra costs involved in maintaining system security during the plant outage.

The traditional methods of fault location have been based on impedance techniques now commonly incorporated in digital relays and fault recorders.

Problems with Impedance

Impedance techniques have been used for the past 35 years. They are now conveniently available in digital protection relays and fault recorders. Problems arise when:

- The fault arc is unstable
- The fault resistance is high and fed from both ends
- Circuits run parallel for only part of the route

Accuracy is dependent on:

- VT and CT response
- The assumption that the line is symmetrical
- A lumped equivalent circuit used in the algorithms
- Filtering of harmonics and DC offsets – more difficult with reduced data window caused by faster clearance times (5 cycles or less)
- Line parameters

Accuracy of Impedance

Typically **1 to 15%** of line length but it can be worse depending on fault type.

Phase to phase faults give best performance.
Phase to earth faults with high fault resistance can result in large errors.
Actual error increases with line length.
Compensation required for mutual coupling on double circuit lines
Compensation required for end source impedance.

On a 200Km line the error could be from 2Km to 30Km

There is a need for a better system

History of Travelling Waves

First reported for use on overhead lines in 1931 but it was not until the 1950s that practical systems were developed.

Different operating modes were defined, Type A, B, C and D

Types B and C require pulse or signal generating circuitry. Commercial equipment based on this available in the 1960s

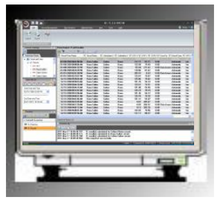
Modern equipment is based on Type D - a double ended measurement.

Application of TWS (Travelling wave system)

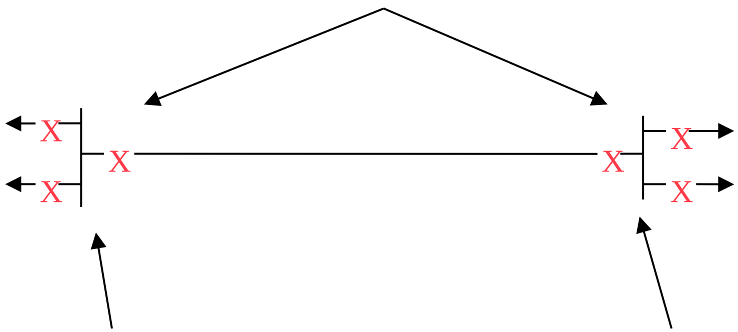
- Best on interconnected overhead lines
- Uses a double ended technique to allow automatic calculation and display of fault position
- Accuracy not affected by the factors that cause problems to impedance methods
- Accuracy not affected by line length
- Works for all types of faults including open circuit faults
- Works on series compensated lines, lines with tapped loads, underground cable circuits and lines with teed circuits

Application of Double Ended Method

Double ended accurate fault location system for interconnected transmission lines

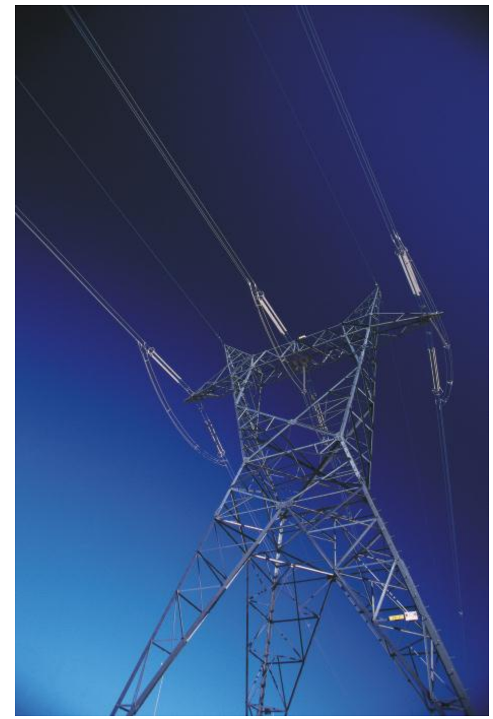


Permanent and
Intermittent Faults

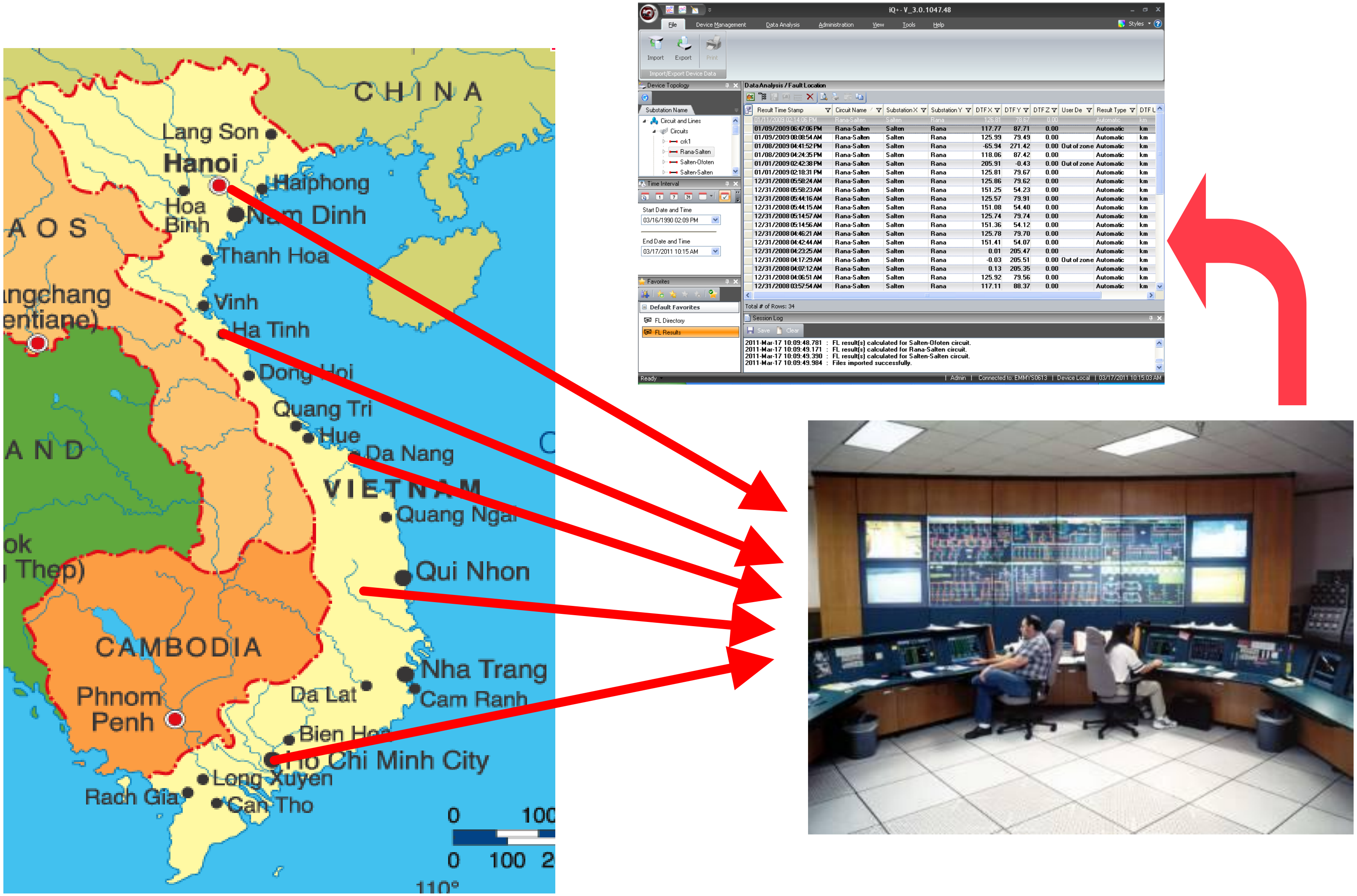


TWS-FL8

TWS-FL1

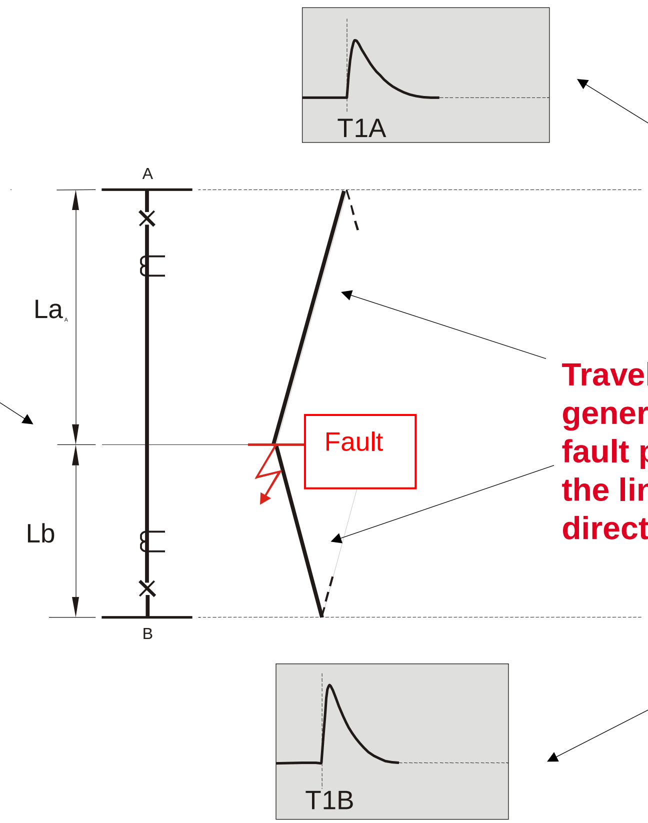


Typical Application



Double Ended Method of Fault Location

The distance to fault is proportional to the difference in arrival time (T1A – T1B), the length of line (La+Lb) and the propagation velocity

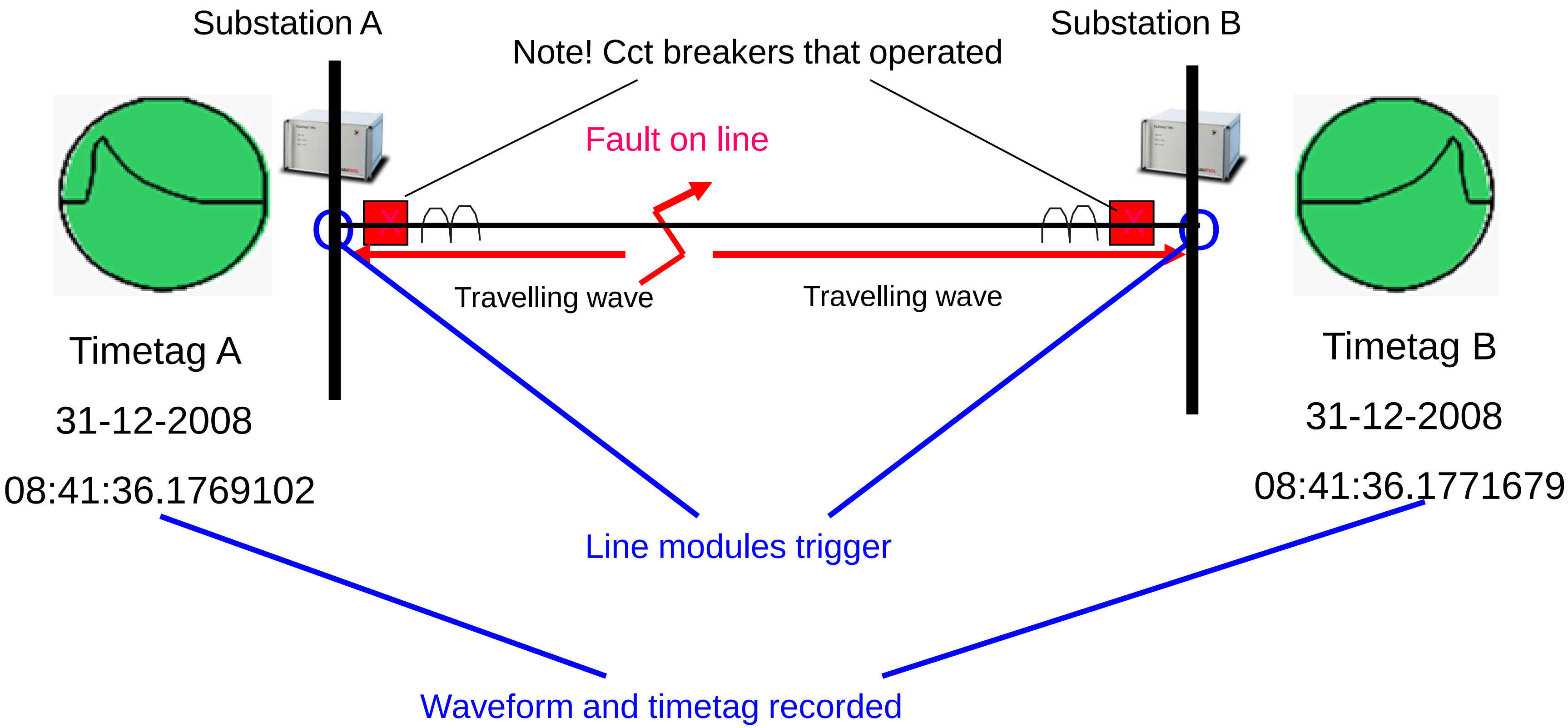


Traveling waves generated by the fault propagate along the line in both directions

TWS devices installed at line ends trigger on the arrival of the wave and assign an accurate time tag

La = [(La+Lb) + (T1A-T1B).v] / 2
V for air insulation = 300m/μs

In-zone fault



Distance to fault calculated: -

Distance from Substation A= [(Line length) + (Timetag A-Timetag B).v] / 2

V for air insulation = 300m/μs

RESULT 34.8km from Sub A 111.4km from Sub B

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TWS Accuracy

Time stamp accurate to 100ns with internal GPS

At the speed of light, 100 nano seconds equals 30 m (98 feet) on an overhead line

With good signals and accurate line length and propagation velocity it is possible to achieve accuracies of 60m.

The result is repeatable fault location within 1 tower / span on all types of fault.

TWS Fault Location to One Span - Works Even When Impedance Methods have Large Errors

Send the repair teams to the right place. Minimize search time and reduce expensive downtime

What is the actual cost of inaccuracy?

TWS Accuracy Check

Results from ESKOM

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

TWS result confirmed to one span. Error on impedance from 1.7% to 23%

Results from Dominion

- 39.07 miles 500KV circuit built on wooden towers.
- 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

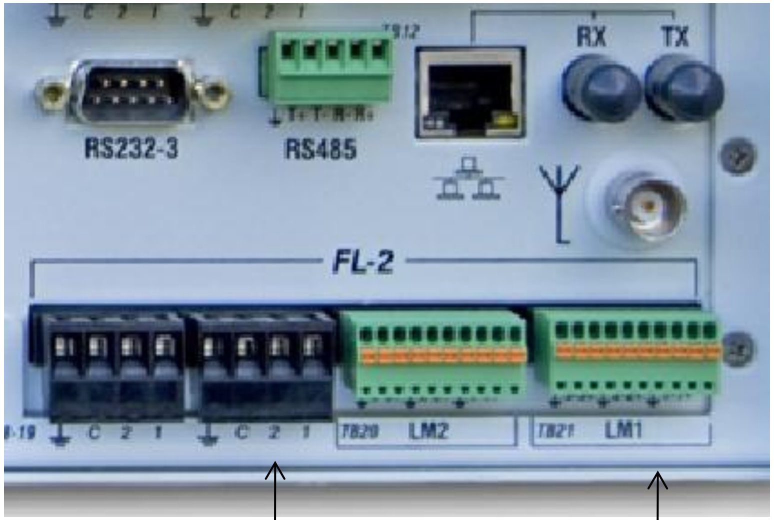
Review of Travelling Wave Implementation

- Commercially available double ended systems for overhead lines since the mid 1990s
- Over 3000 systems installed worldwide returning consistent distance to fault accuracies of one span on intermittent and permanent faults
- New platforms have 100ns clock accuracy from internal GPS receivers giving distance to fault to one tower
- List of results available centrally in the control room for all circuits
- Results obtained from all travelling wave events.
  - Results from line trips can be prioritised and filtered
  - Results from transients passing through the monitored zone can be used to ‘calibrate’ the system – line length versus velocity
  - Detection of incipient faults!
- Latest equipment combines TWS fault location with fault recording that can also return an impedance distance to fault

Filter Results on Line Trips

Two digital inputs per line module Used to flag a line trip

- FL triggers associated with a line trip are flagged as high priority and can set up an auto-call to IQ+ to enact a circuit poll
- DTF results can be filtered on high priority



Benefit - dispatchers can automatically see results from **line trips** on the screen within minutes of a fault

TWS accuracy in all types of weather

Works in fog and at night when helicopters are grounded

Why risk multiple line patrols over dangerous terrain when you can go straight to the spot?

TWS – Consistent accuracy on all Types of Fault

Locate and Verify

Bird excrement faults between conductors
Bird excrement damage to insulators and surge arrestors
Lightning strike location compared to IEEE
Smoke from forest fires
Tree damage

Track intermittent self clearing faults and focus maintenance at the right spot to prevent a major breakdown

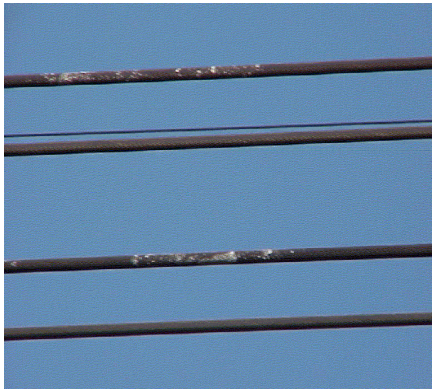
TWS One span accuracy locates damaged insulators

Question:

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

Not possible to pinpoint damage with impedance methods due to inconsistency of results and variable errors

TWS Accurate enough to locate fault damage caused by bird streamers



Assess damage and organise repairs

One span accuracy tracks down tree problems

Go straight to cause of problem to take remedial action and avoid further trips

TWS accuracy pinpoints lightning faults

- **Compare lightning strike information from the IEEE Fault And Lightning Location System (FALLStm) against exact TWS fault location to:**
- Confirm lightning is fault cause:-
- The TWS trigger was caused by an actual lightning strike on the line
- Confirm lightning is not the fault cause:-
- The TWS trigger was caused by induced lightning activity, but not a direct hit

Vital information when deciding whether to reclose a line

Where TWS has added value

- Transmission and Sub Transmission
- Interconnected substations and lines with tees
- Longer lines greater than 100Km
- Difficult terrain with access problems
- Prone to bad weather – lightning, rain, gales
- Old lines – more prone to faults
- Heavily loaded lines - line trips have bigger impact
- Where older relays are used without fault location features
- Where regulators are driving improved performance – minimise voltage dips – reduce customer minutes lost

Travelling Wave Theory

The velocity of propagation of Travelling Waves is determined solely by the insulation medium

$$velocity = \frac{Speed\ of\ Light}{\varepsilon}$$

ε - is the Dielectric Constant which gives:-
300 m/μSec for all overhead lines
150 - 200 m/μSec for underground cables

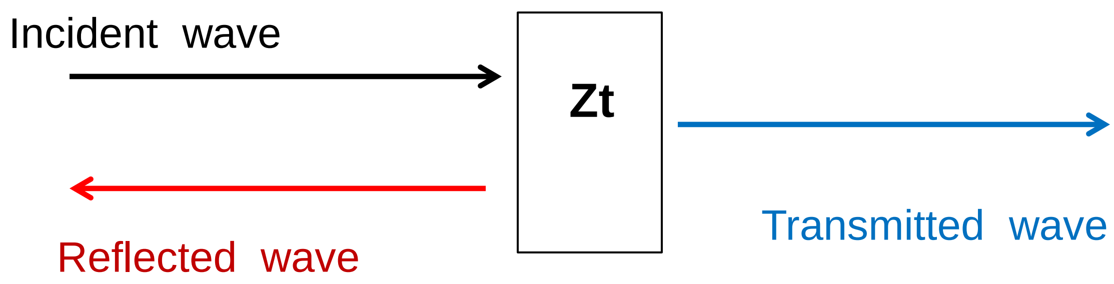
Travelling Wave Theory

Travelling Waves contain *voltage* and *current* components which are related through Ohm's Law

$$I_{wave} = \frac{V_{wave}}{Z_o}$$

Z_o - is the *Surge Impedance* typically :-
200 - 400 ohms for overhead lines
10 - 50 ohms for underground cables

Impedance Discontinuities



Reflected wave = Incident wave x reflection coefficient ρ

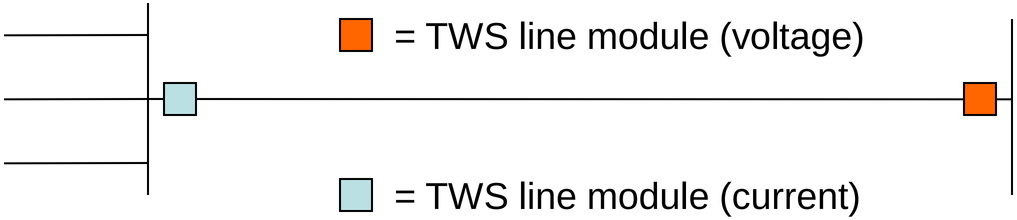
$$\rho_{voltage} = \frac{Z_T - Z_O}{Z_T + Z_O}$$

$$-1 \leq \rho \leq +1$$

$$\rho_{current} = -\rho_{voltage}$$

Magnitude of a TW at a Line End

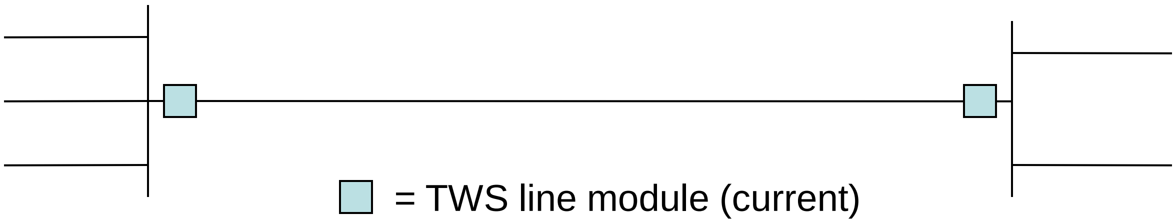
- The Travelling Wave at a Discontinuity (eg a line end) is the Sum of the Incident and Reflected Waves
- When Zt is low compared to Zo then current increases and voltage decreases
- When Zt is high compared to Zo then voltage increases and current decreases



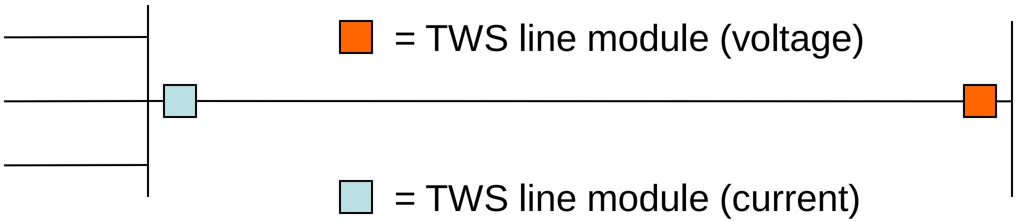
At Transformer feeders it is necessary to monitor Voltage

General Deployment Rules

- TWS must be located at a substation where more than one line is connected to the busbar if linear couplers are used.



TWS can be located at a line end but the voltage component of the wave must be monitored, not the current



Attenuation Through a Substation

- Transmitted wave is the difference between the incident and reflected waves.
- Transmitted wave is divided equally between all the outgoing lines

Transmitted v Incident Wave per Outgoing Line	***n***
1.0	2
0.33	3
0.16	4
0.1	5

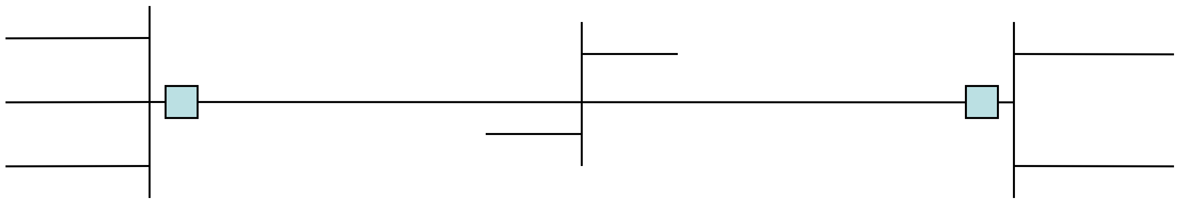
n = number of lines including the faulty line

Figures assume Zo is 300 ohms

Travelling waves severely attenuated through multi line stations

General Deployment Rules

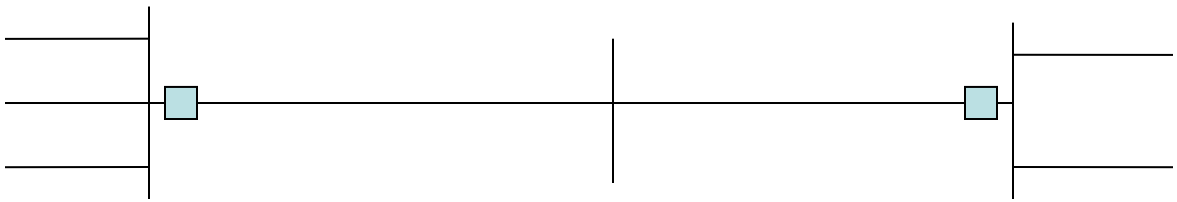
Do not assume a travelling wave will pass through a substation where more than two lines are connected. The wave is attenuated.



= TWS line module (current)

May NOT work

A travelling wave will pass through two substations with one line in and one line out

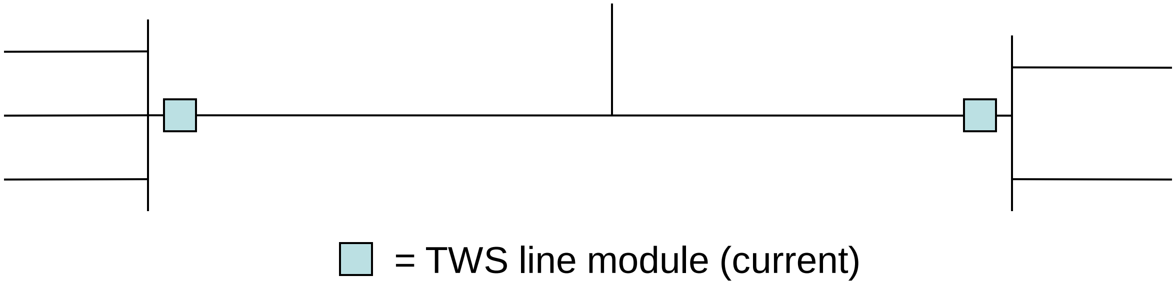


= TWS line module (current)

This OK

General Deployment Rules

Only allow a maximum of one tee connection between two TW devices

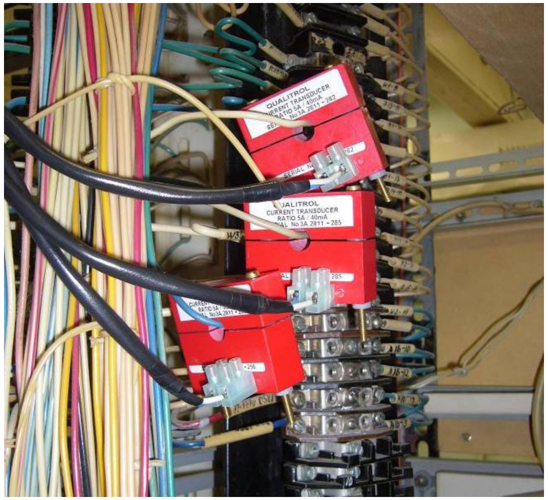


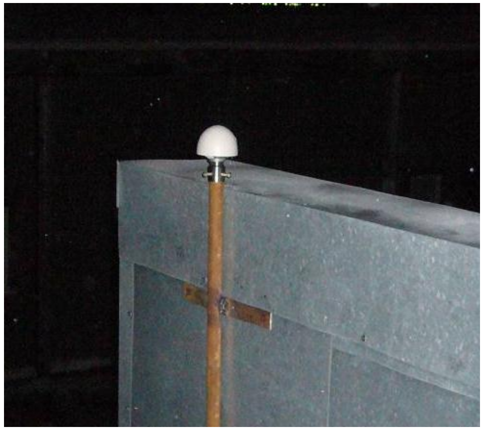
One T only

Remember – a TWS system must have a good comms infrastructure for practical double ended operation

Monitoring Current Travelling Waves

- An easy and non-intrusive method essential for retrofit sites
- Where more than one line is connected to the busbar the terminating impedance is low and the current component of the travelling wave can be used.
- Split core current clamps are placed around the CT secondary wiring
- A GPS antenna is mounted on the roof with a clear view of the sky





Communications to central location – modem, ethernet, GSM/GPRS

Breaker and a Half or Double Breaker Schemes

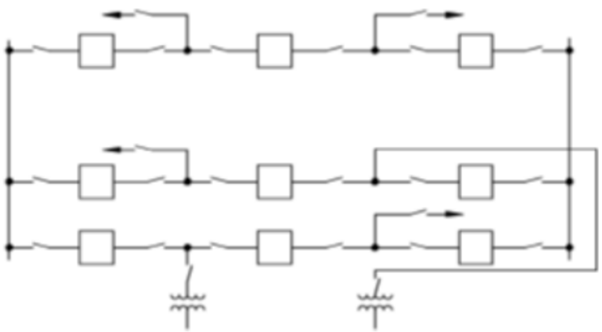


Figure 6: Breaker-and-a-Half

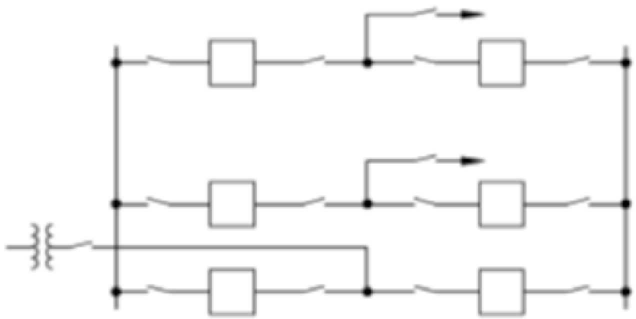
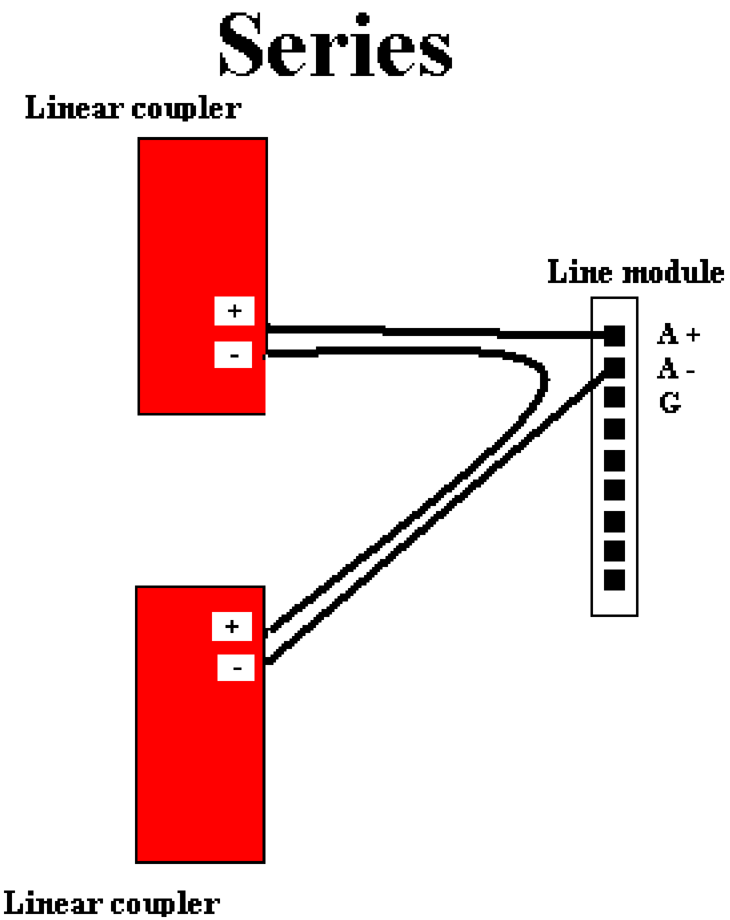


Figure 7: Double Breaker-Double Bus

- Line current is obtained by summating current from 2 x CTs
- This is normally done externally such that a single 3 phase current is connected to the relay / fault recorder
- New relays have two CT inputs – there is no need for external summation

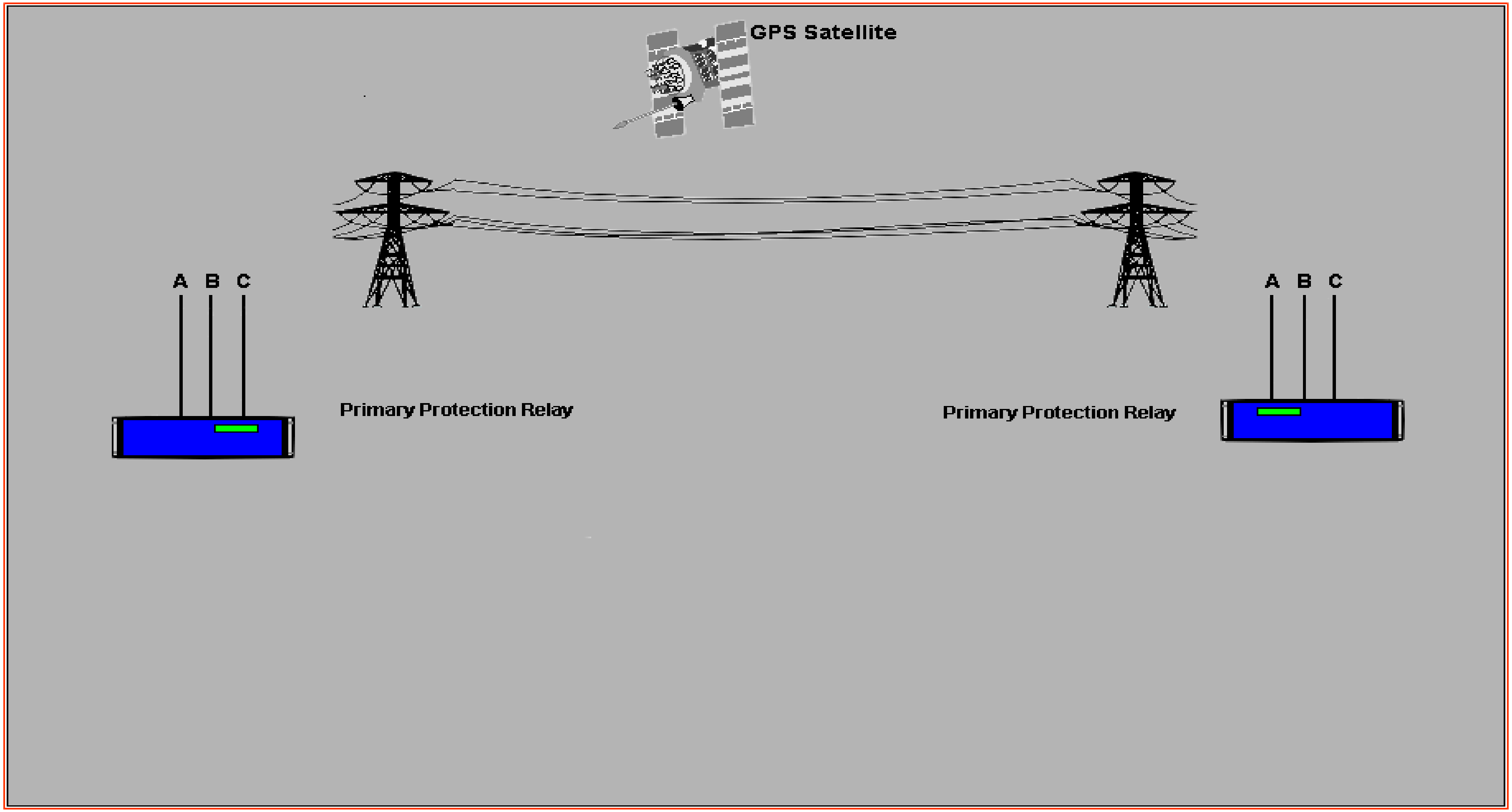
It is necessary to use 2 sets of linear couplers per line module

Connect Linear Couplers in Series

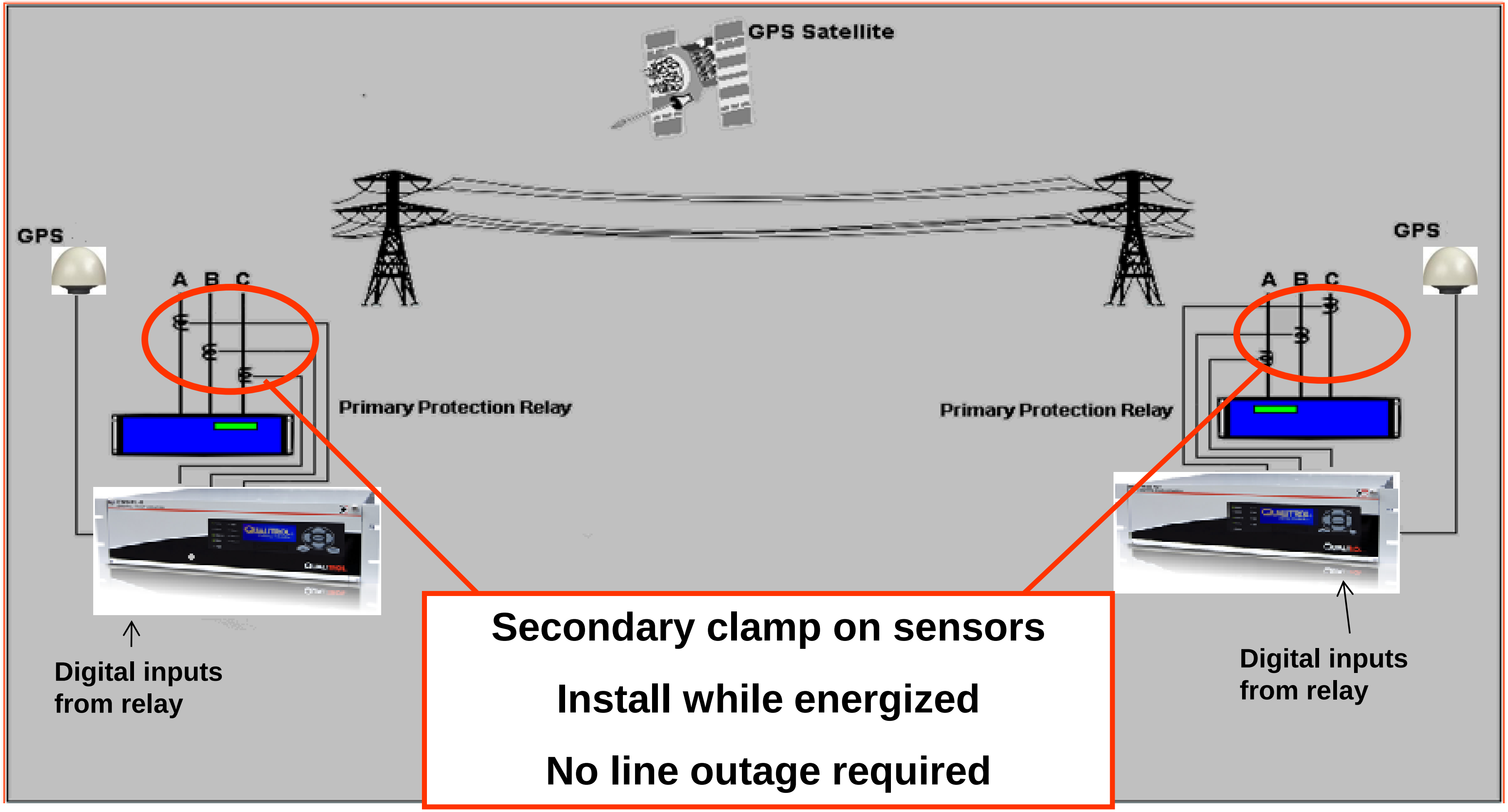


- Linear couplers produce a voltage on the secondary side
- Connect outputs in series to summate outputs

TWS Implementation



TWS Implementation

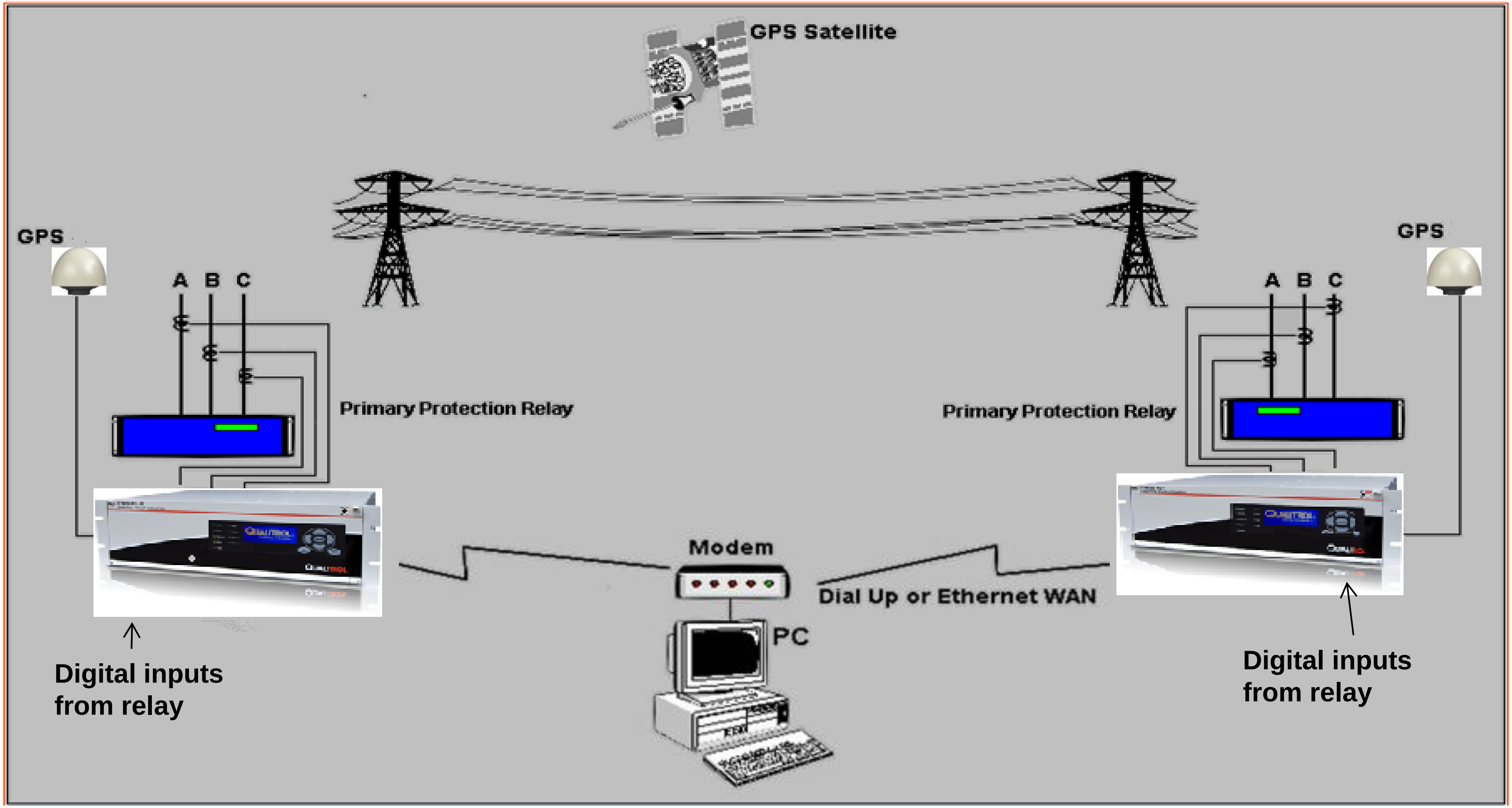


Secondary clamp on sensors

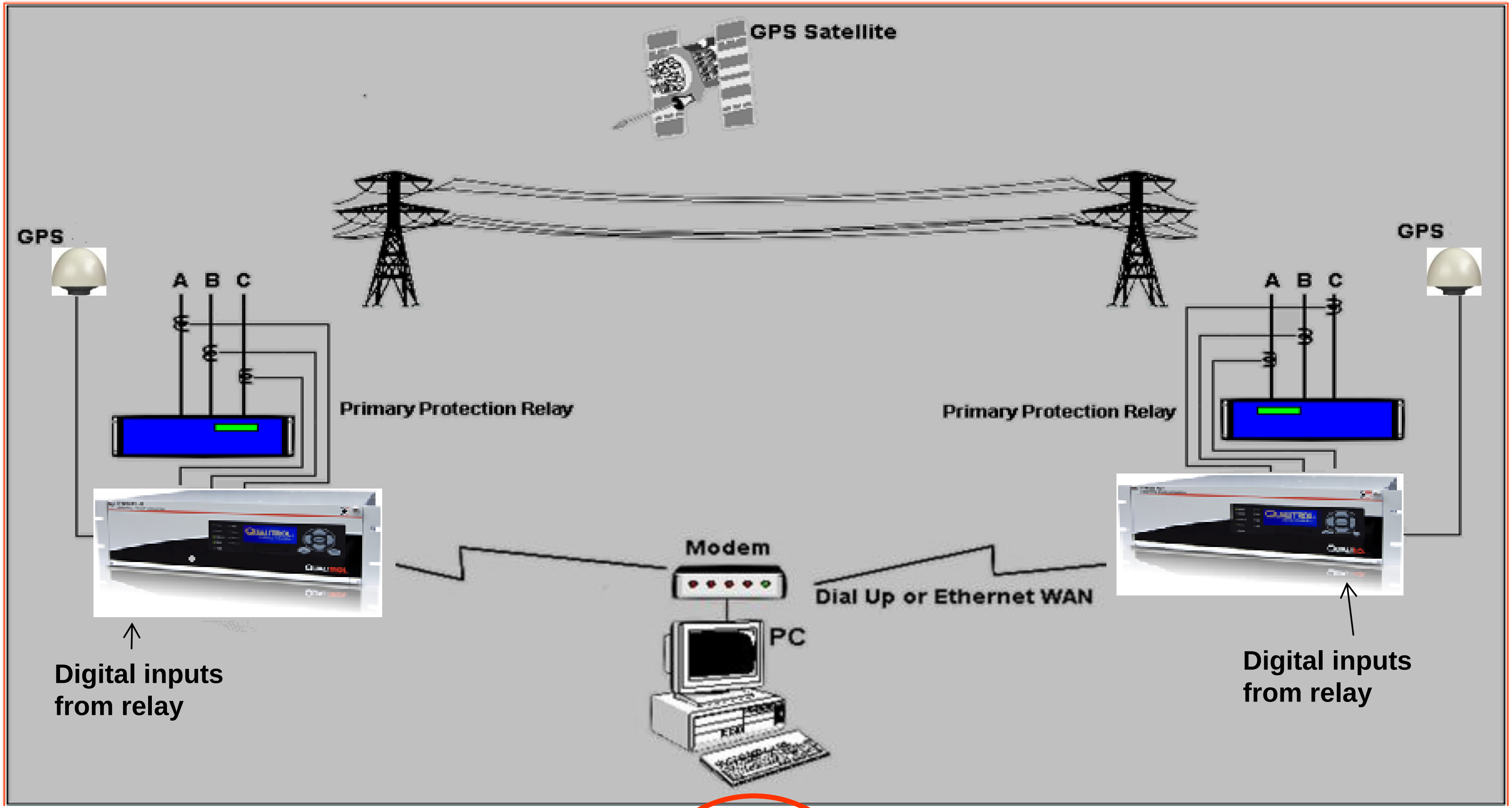
Install while energized

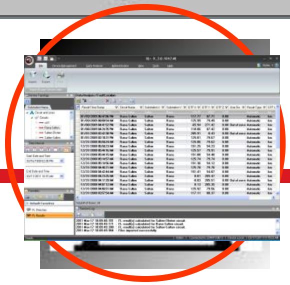
No line outage required

TWS Implementation

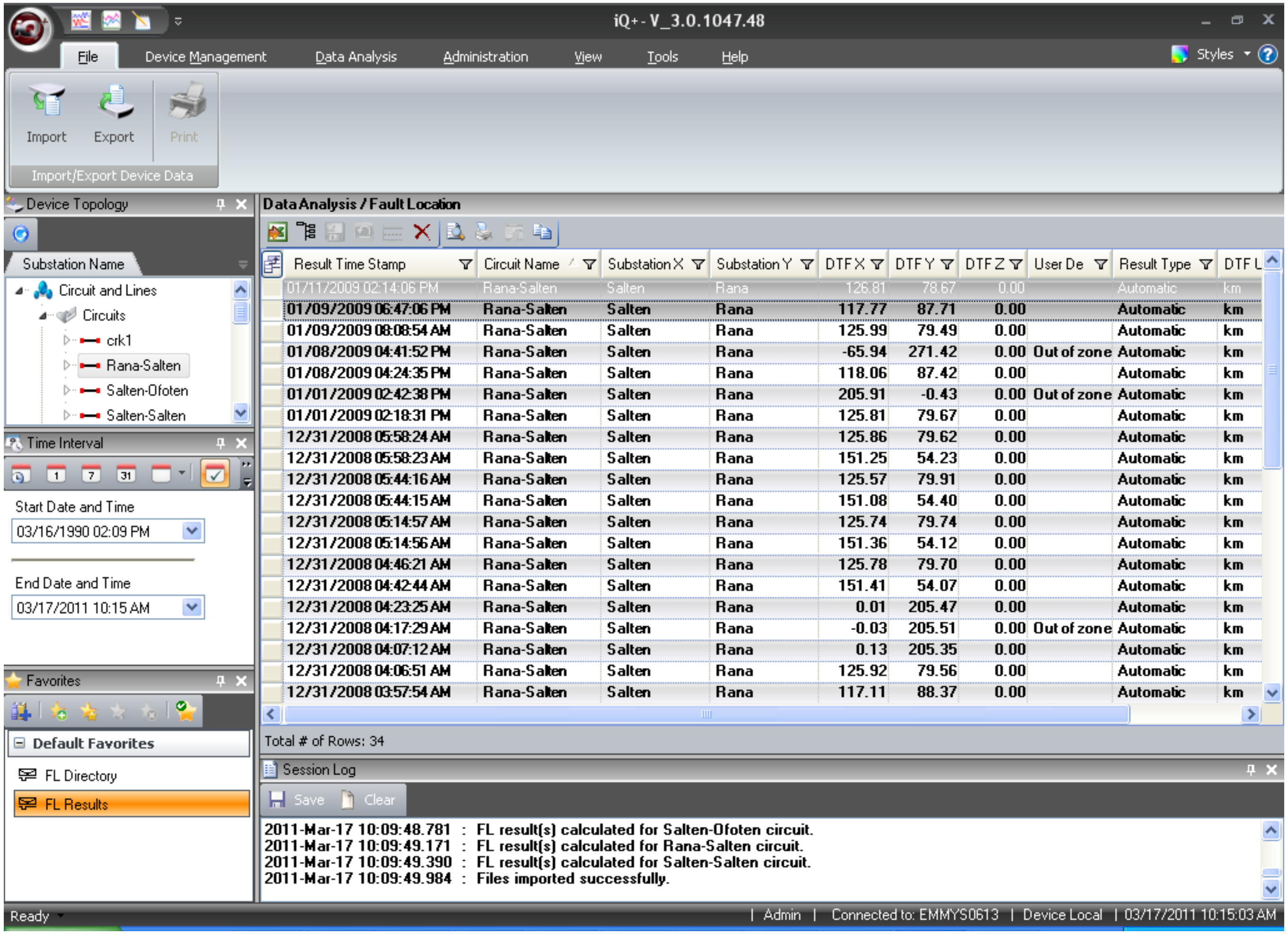


TWS Implementation



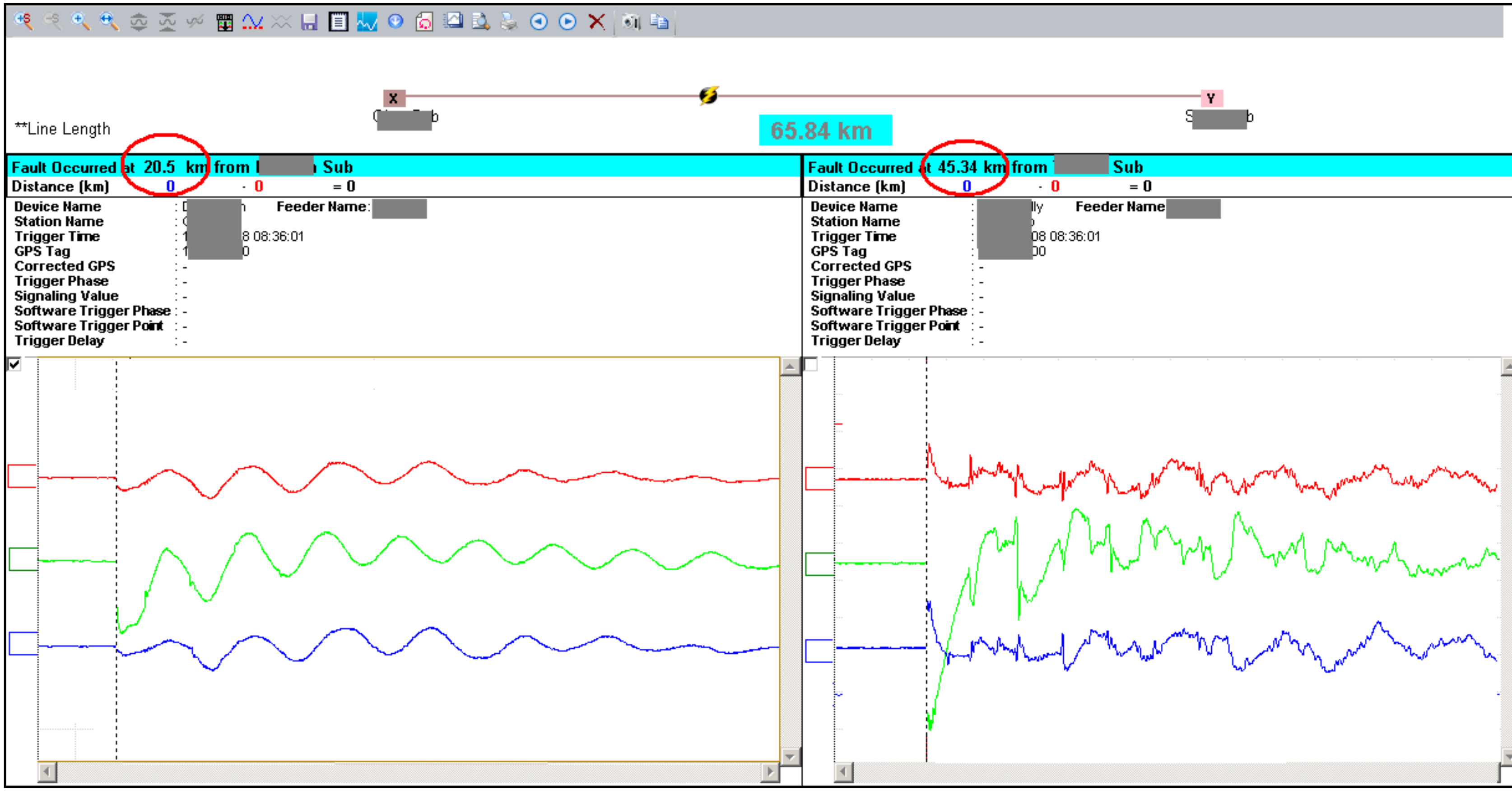


Example of Distance to Fault Results



Result Time Stamp	Circuit Name	Substation X	Substation Y	DTF X	DTF Y	DTF Z	User De	Result Type	DTF L
01/11/2009 02:14:06 PM	Rana-Salten	Salten	Rana	126.81	78.67	0.00		Automatic	km
01/09/2009 06:47:06 PM	Rana-Salten	Salten	Rana	117.77	87.71	0.00		Automatic	km
01/09/2009 08:08:54 AM	Rana-Salten	Salten	Rana	125.99	79.49	0.00		Automatic	km
01/08/2009 04:41:52 PM	Rana-Salten	Salten	Rana	-65.94	271.42	0.00	Out of zone	Automatic	km
01/08/2009 04:24:35 PM	Rana-Salten	Salten	Rana	118.06	87.42	0.00		Automatic	km
01/01/2009 02:42:38 PM	Rana-Salten	Salten	Rana	205.91	-0.43	0.00	Out of zone	Automatic	km
01/01/2009 02:18:31 PM	Rana-Salten	Salten	Rana	125.81	79.67	0.00		Automatic	km
12/31/2008 05:58:24 AM	Rana-Salten	Salten	Rana	125.86	79.62	0.00		Automatic	km
12/31/2008 05:58:23 AM	Rana-Salten	Salten	Rana	151.25	54.23	0.00		Automatic	km
12/31/2008 05:44:16 AM	Rana-Salten	Salten	Rana	125.57	79.91	0.00		Automatic	km
12/31/2008 05:44:15 AM	Rana-Salten	Salten	Rana	151.08	54.40	0.00		Automatic	km
12/31/2008 05:14:57 AM	Rana-Salten	Salten	Rana	125.74	79.74	0.00		Automatic	km
12/31/2008 05:14:56 AM	Rana-Salten	Salten	Rana	151.36	54.12	0.00		Automatic	km
12/31/2008 04:46:21 AM	Rana-Salten	Salten	Rana	125.78	79.70	0.00		Automatic	km
12/31/2008 04:42:44 AM	Rana-Salten	Salten	Rana	151.41	54.07	0.00		Automatic	km
12/31/2008 04:23:25 AM	Rana-Salten	Salten	Rana	0.01	205.47	0.00		Automatic	km
12/31/2008 04:17:29 AM	Rana-Salten	Salten	Rana	-0.03	205.51	0.00	Out of zone	Automatic	km
12/31/2008 04:07:12 AM	Rana-Salten	Salten	Rana	0.13	205.35	0.00		Automatic	km
12/31/2008 04:06:51 AM	Rana-Salten	Salten	Rana	125.92	79.56	0.00		Automatic	km
12/31/2008 03:57:54 AM	Rana-Salten	Salten	Rana	117.11	88.37	0.00		Automatic	km

Result from UK

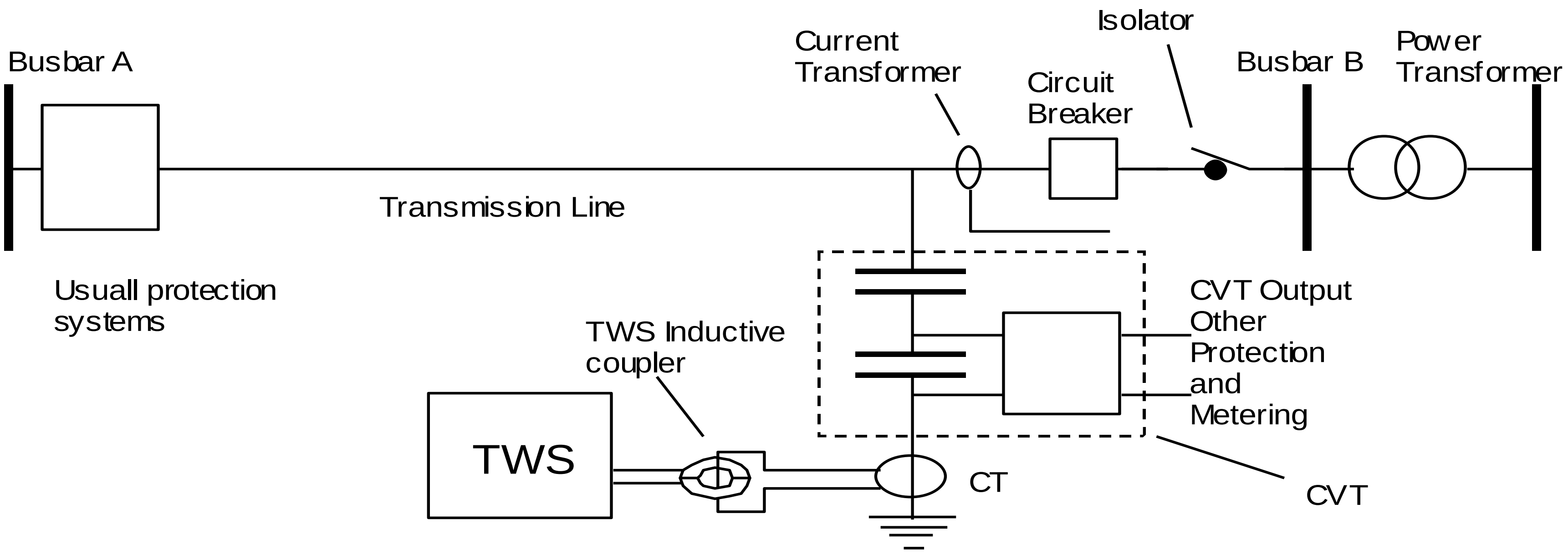


Automatic DTF Calculation using Double Ended Type D Method

Waveform analysis

High Impedance Terminations - CVT

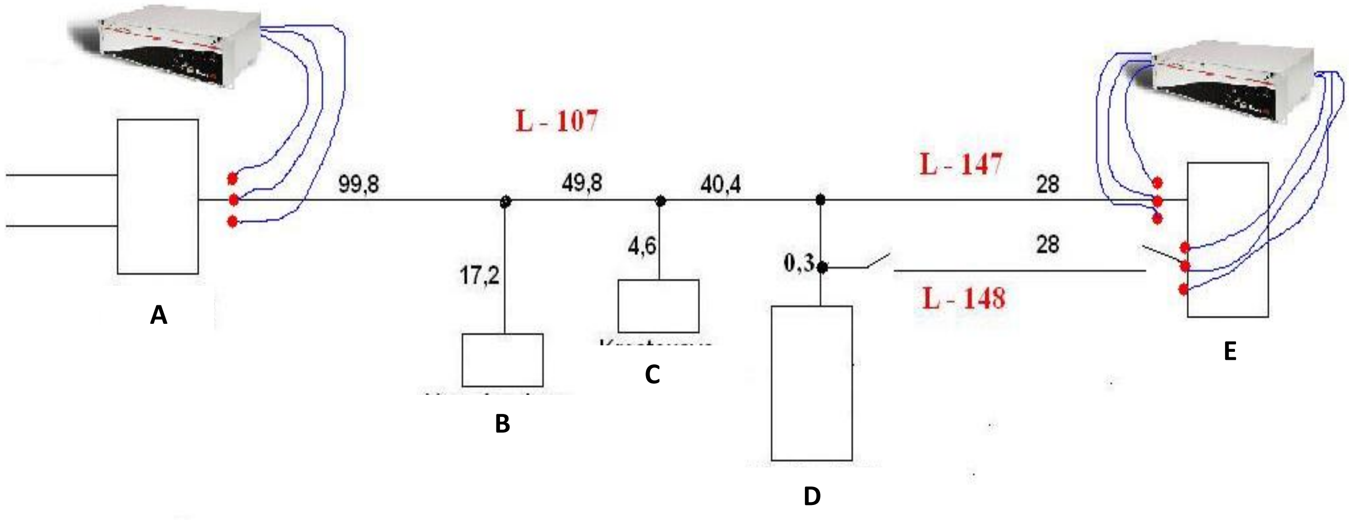
- Need to monitor lines terminated in a transformer or a double circuit line where it is possible for one line to be switched out
- The voltage part of the travelling wave is monitored when the terminating impedance is high
- Easiest way is to use the line CVT when one is available.



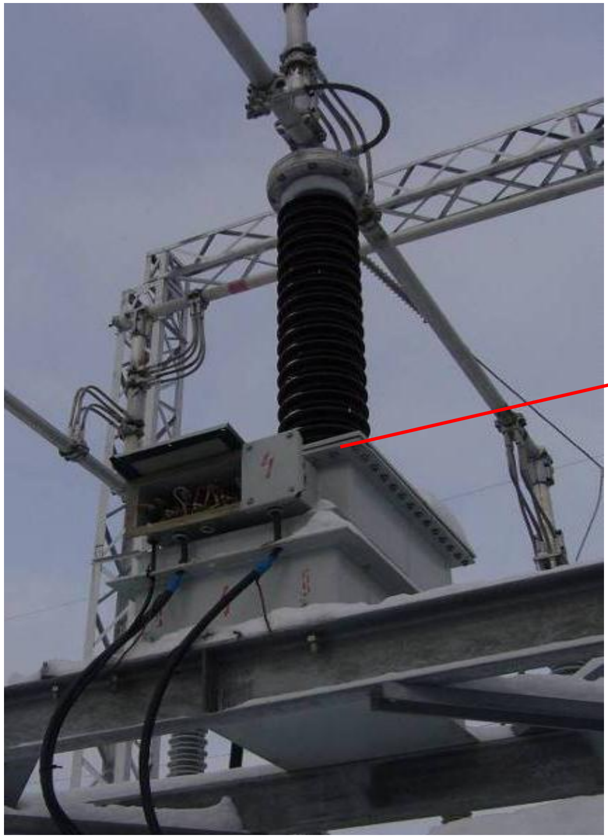
Disadvantage is that a line outage is needed

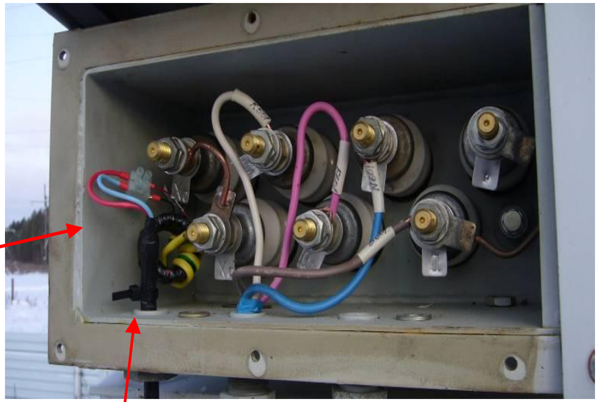
Example from Russia – 110KV network

- 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.



CVT Connection in Russia



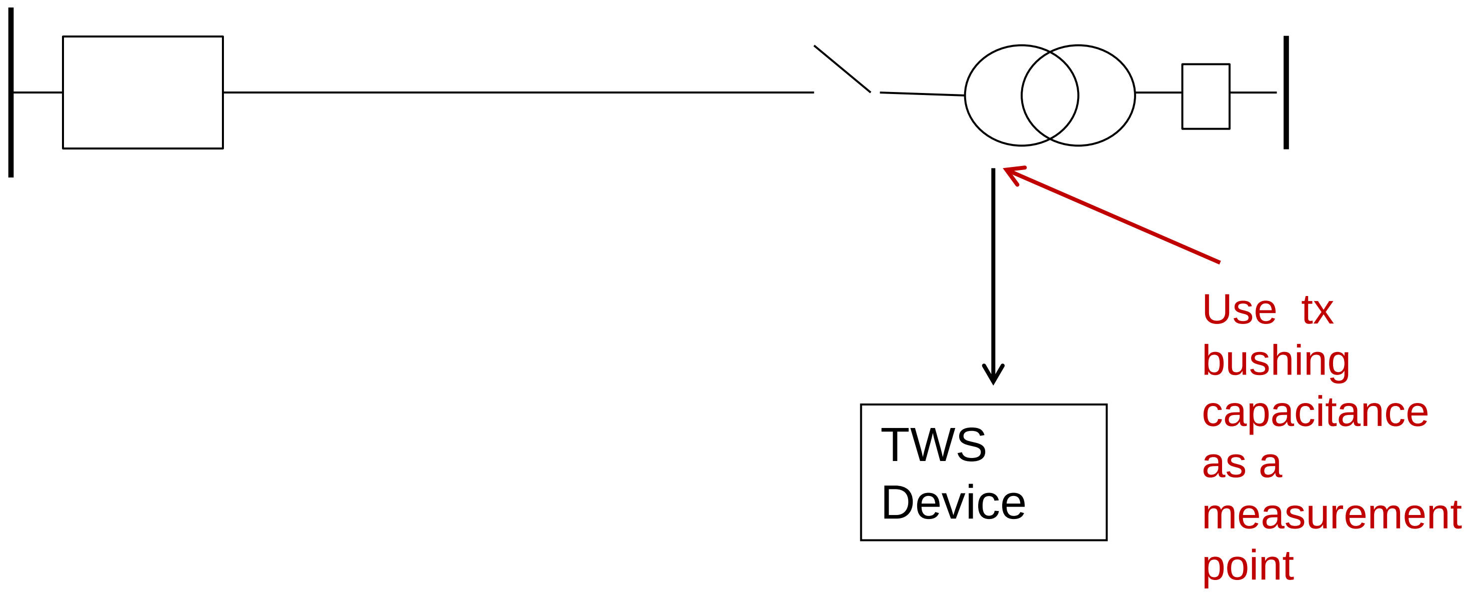


CVT marshalling box - Toroidal CT around the earth connection of the bottom capacitor

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.

What if there is Not a CVT

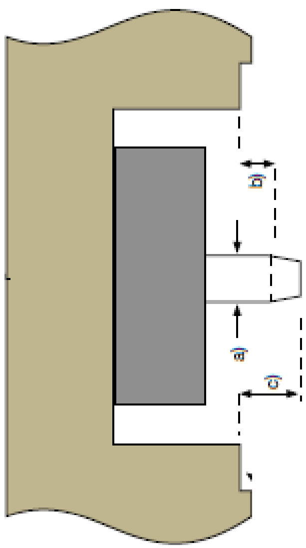
- Very often a CVT is not available at a line end
- An alternative coupling point is the tapping point on the transformer HV bushing

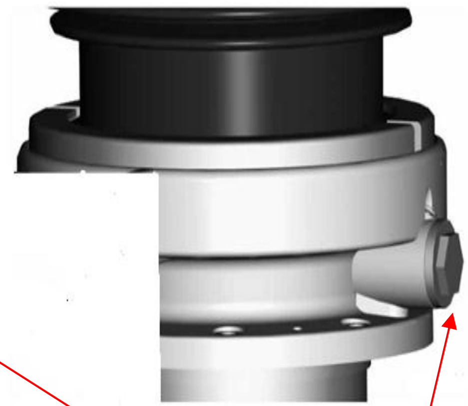


Disadvantage is that a line outage is still needed

Transformer Bushing Coupler

Below is a coupler for an ANSI Type A bushing tap.





Tap point on lower part of bushing

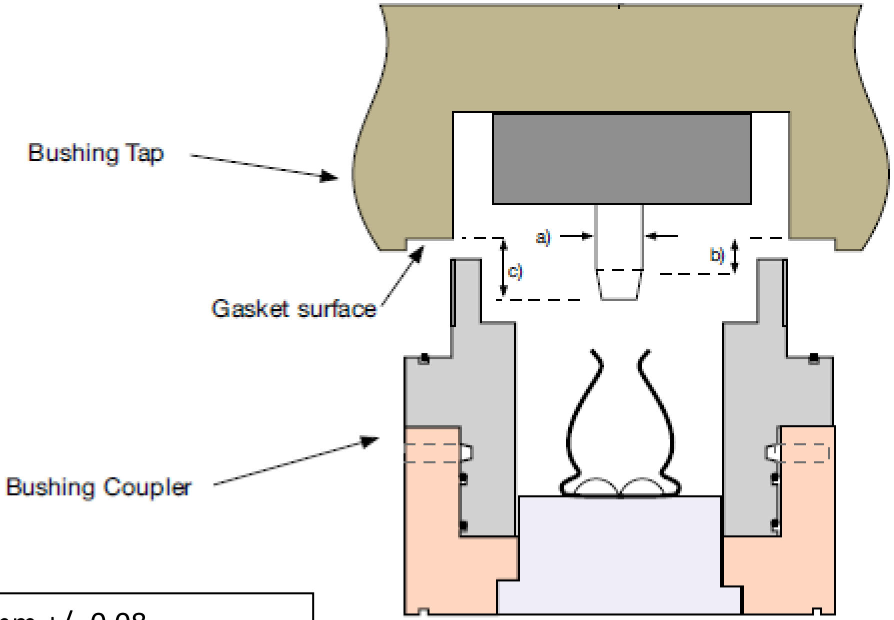
Bushing coupler (not to scale)

Cannot remove the cover with the bushing live

ANSI Type Bushing Tap

Coupler is made in 2 parts – the ‘adapter’ and the ‘body’

Different adapters can be designed for other type of bushings



a= 7.95mm +/- 0.08
b> 5mm
c< 19mm

Coupler fitted to a 138KV Transformer in the US

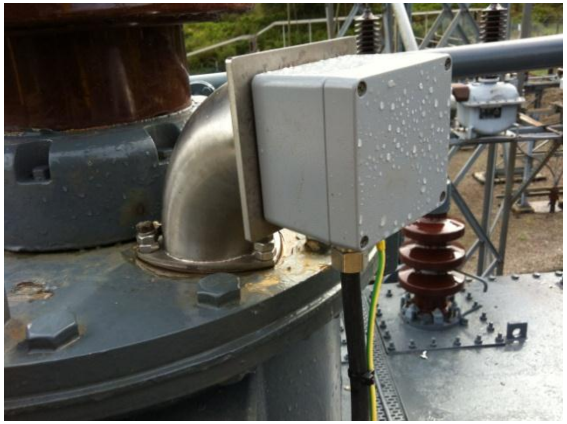
Note that the body should be twisted round so the cable connection is downward to prevent water ingress!

Integrity of Bushing Earth Maintained

The earth for the bushing tap is routed through a toroidal CT and connected back to the coupler body and hence to the general mass of earth. No other components are placed in series that might impair the integrity of the earth connection at a later data

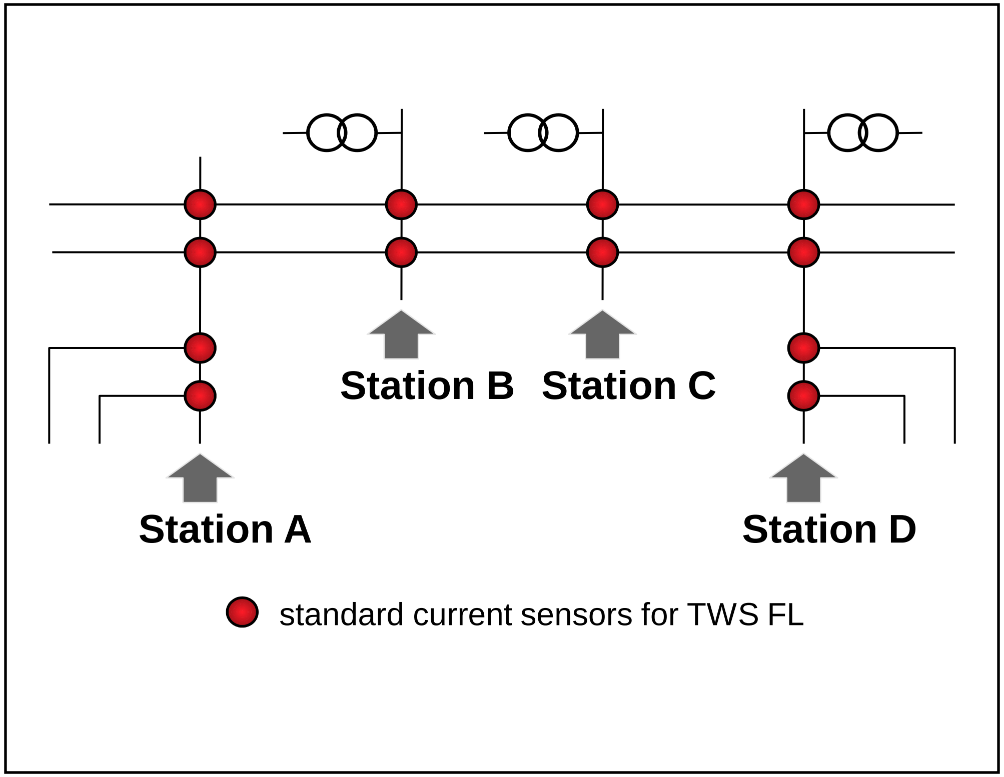
Other Types of Bushing Tap

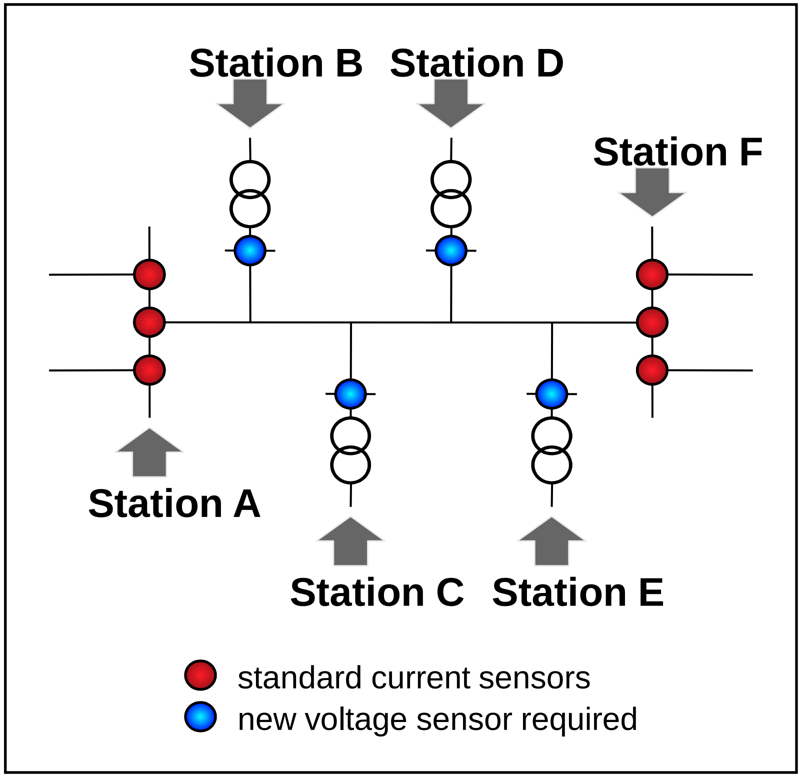
132KV / 300A
Bushing from
Brush



132KV / 600A
Bushing from
English Electric

Transmission v Sub Transmission





Typical transmission system
Multiple lines at each station - 2 ended circuits

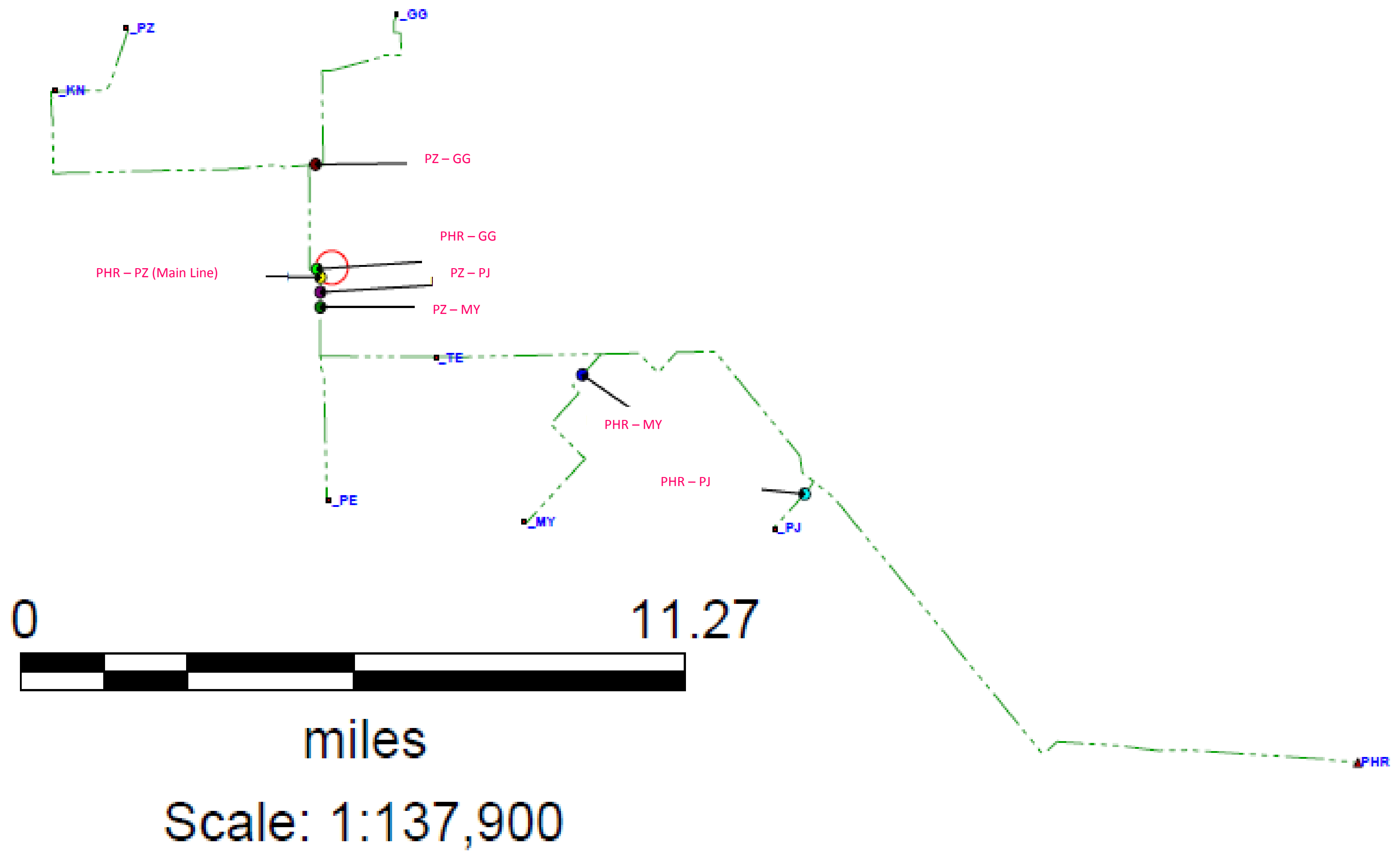
Typical sub transmission system
Single lines at stations - multi ended circuits

Support for Multi Ended Circuits

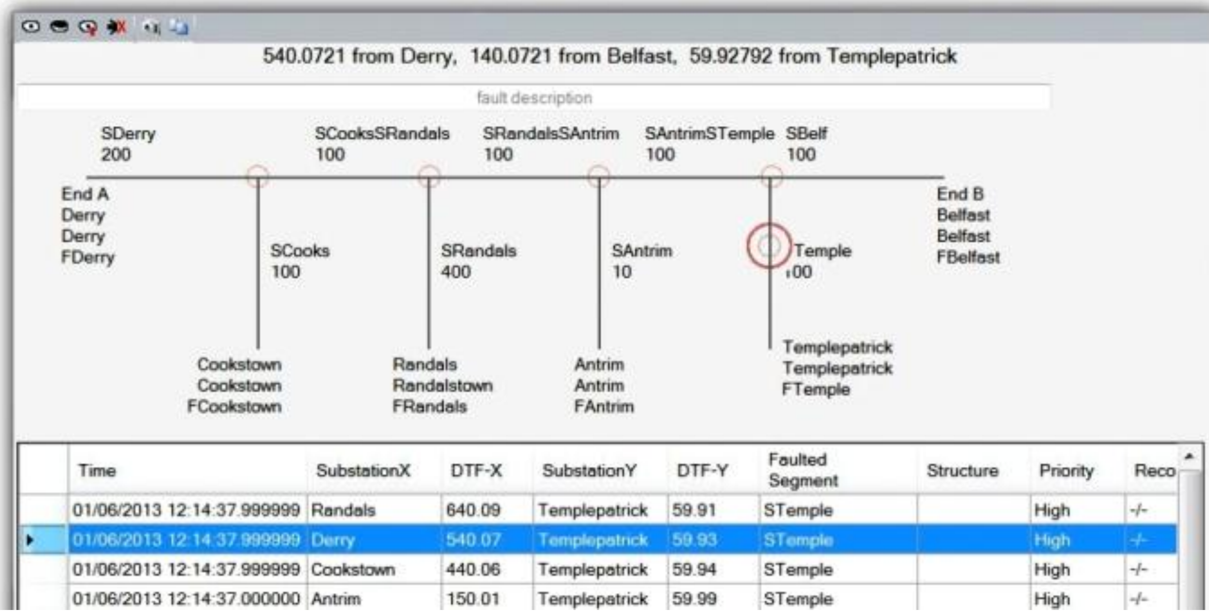
- Each ‘Tee’ position attenuates the transmission of a travelling wave
- Not all TWS devices will detect a fault on a multi branched circuit
- Different combinations of devices will produce distance to fault results for the same event
- New software will support up to 6 ended circuits based on a combination of a graphical and conventional list view of fault position

Extending support to 6 ended feeders for sub transmission networks

Example of a 138KV 6 ended circuit



Graphical Output of 6 Ended Analysis



A larger red ring marks the fault site

Management of cable sections

- The TWS principle works on cable circuits.
- A different velocity factor needs to be used, 50% of overhead line
- Accuracy better but still not good enough to dig a hole!

Example of a joint failure on a 12.45Km, 33KV cable connection to a windfarm - locations were obtained for a month before the main flashover and circuit trip

Result Time Stamp	DTF X	DTF Y	User Descripti
13/05/2013 18:57:29.160	12.35	0.10	Trip
09/05/2013 21:43:02.652	12.34	0.11	Spit
09/05/2013 21:43:02.592	**12.33**	**0.12**	**Spit**
09/05/2013 21:43:02.574	**12.35**	**0.10**	**Spit**
23/04/2013 12:15:24.722	12.34	0.11	Spit
23/04/2013 12:15:23.600	**12.35**	**0.10**	**Spit**
23/04/2013 12:15:22.588	12.32	0.13	Spit
23/04/2013 12:15:20.516	**12.35**	**0.10**	**Spit**
23/04/2013 12:15:19.255	12.36	0.09	Spit
22/04/2013 15:36:09.128	**12.35**	**0.10**	**Spit**
15/04/2013 14:09:58.585	12.30	0.15	Spit

Fault 114m from end Y

Management of cable sections

- Results from out of zone system transients showing the differences between these results and those from the fault

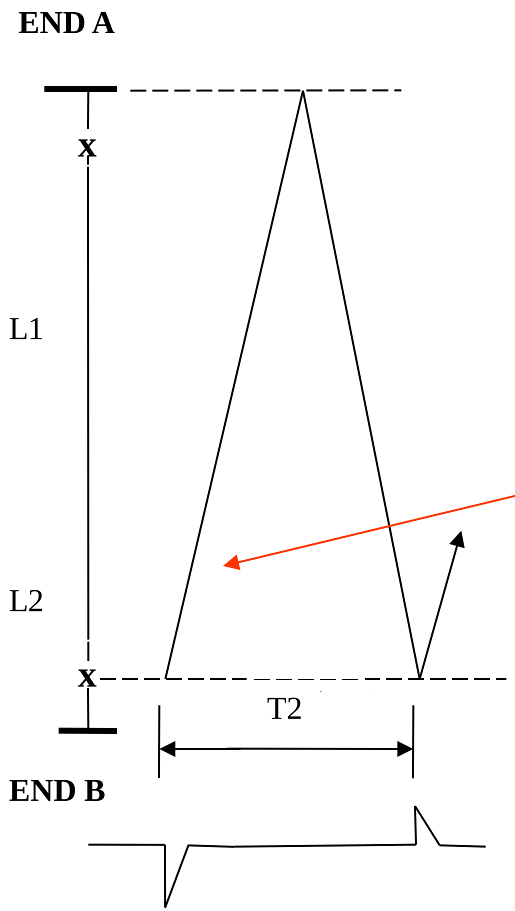
Result Time Stamp	DTF X	DTF Y	User Descripti
13/05/2013 18:57:28.989	12.49	-0.04	
13/05/2013 18:57:25.865	12.39	0.06	
02/05/2013 20:18:59.439	0.10	12.35	
02/05/2013 14:32:24.540	-0.07	12.52	
09/03/2013 17:36:46.193	12.38	0.07	
09/03/2013 17:29:53.466	12.37	0.08	
09/03/2013 17:26:38.419	12.43	0.02	
09/03/2013 17:23:00.636	12.42	0.03	
09/03/2013 17:21:56.714	12.41	0.04	
09/03/2013 17:19:55.915	12.41	0.04	
09/03/2013 17:15:04.148	12.38	0.07	
09/03/2013 17:13:15.131	12.38	0.07	

Measurement of line length

- The TWS/DSFL is triggered by energising a dead line
- The waveform is analysed and line length measured by identifying a reflection from the far open circuit end
- A good method to check the length of the line including sags and changes in elevation
- Known as a Type E test

A precise line length checks improves fault location accuracy and maximises the benefits

Type E Method for confirming line length



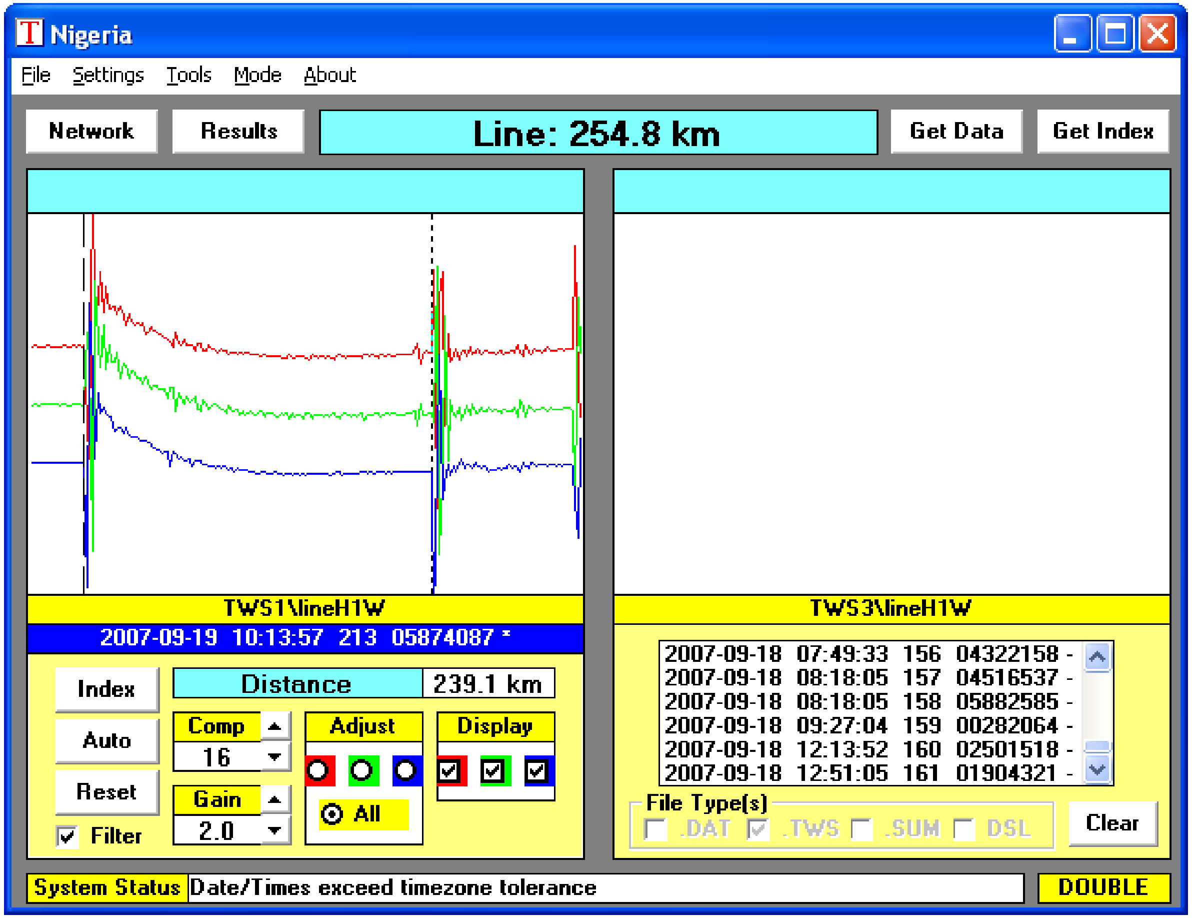
Often used on a trial to show the system is working

Far end must be **open and isolated** (mechanical break with a disconnector)

Closing the circuit breaker at End B to energise the dead line launches a wave that reflects from the far open circuit end

Line Length = [T2 x v]/2

Result from TWS in Nigeria (Base Station software)



Type E Test – Line re-energised from TWS1 end with far end of line open and isolated

Another way of ‘calibrating’

Travelling waves occur on a transmission system due to routine switching of circuit breakers and capacitors, out of zone faults and induced lightning strikes

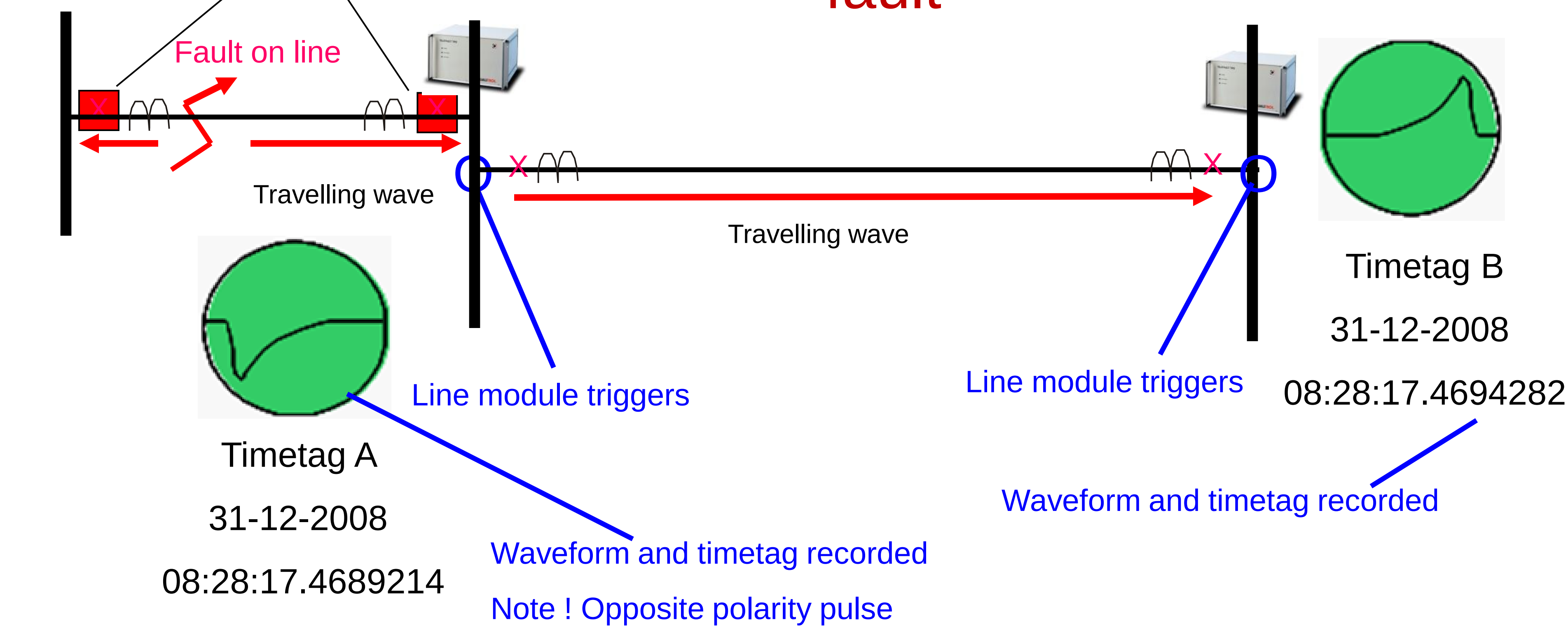
An ‘out of zone’ travelling wave can pass through a line and trigger the TWS fault locators as it enters and leaves the zone

The resultant distance to fault should read 0m from one end and line length from the other

It is possible to ‘calibrate’ the ‘circuit’ by adjusting line length or propagation velocity in the circuit details

Note that the line length given by the Utility is nearly always a physical point to point length that does not include sag or elevation changes. This also relates to the distance between towers. If there is certainty on the line length then adjust the velocity to get the right answer.

Out of zone fault



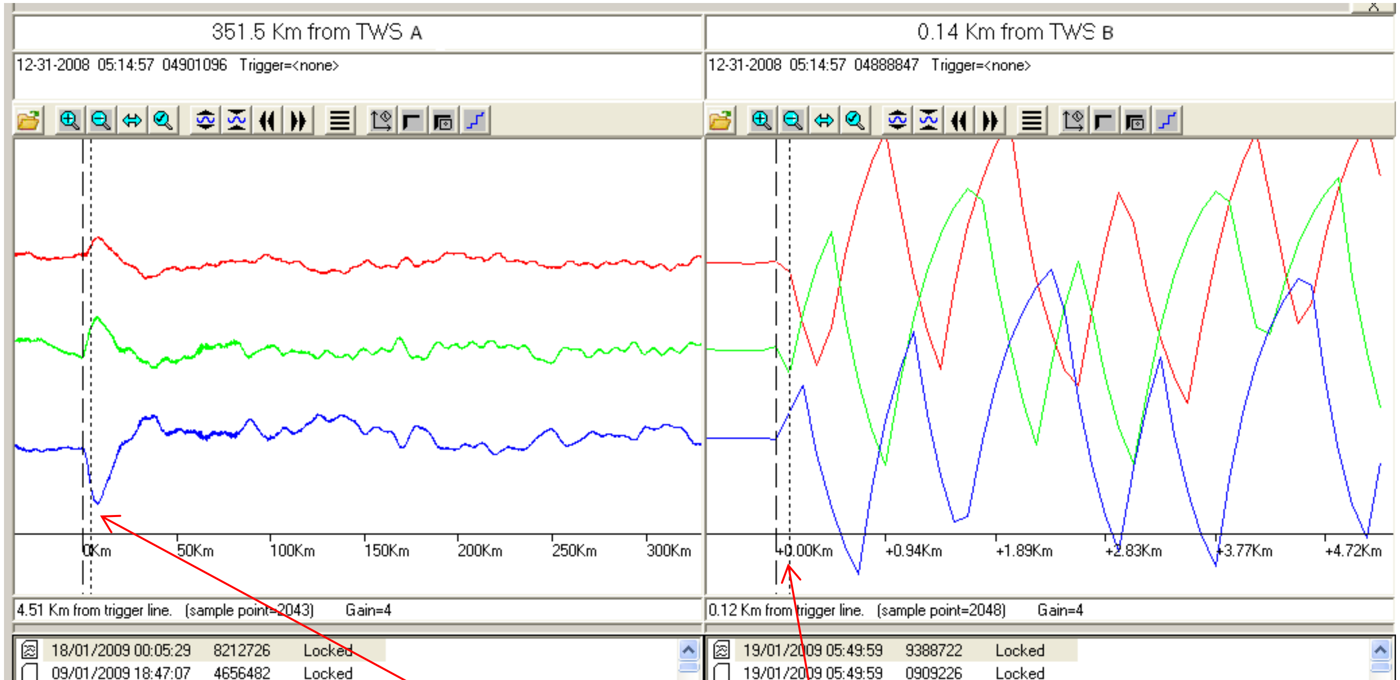
Distance to fault calculated: -

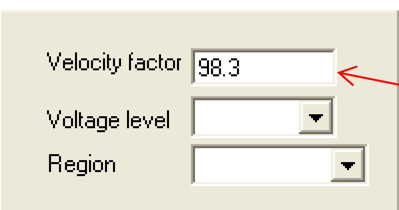
Distance from Substation A= [(Line length) + (Timetag A-Timetag B).v] / 2

V for air insulation = 300m/μs (**decrease value to compensate for sag**)

RESULT 0.0km from Sub A 146.2km from Sub B

Example of calibrating against out of zone incident





Adjust velocity in circuit properties

Small signal levels often means the trigger point must be realigned

Summary

- TWS fault location is more widely used because of the accuracy and consistency of the distance to fault results.
- Virtually all installations have been at transmission where it is normal to have multiple circuits connected to a busbar. As such it has been possible to use current transients derived from the secondary of the protection CT
- On sub transmission networks it is more common to encounter transformer feeders where voltage transients must be monitored due to the high terminating impedance.
- Two methods are possible using a capacitor PT or transformer bushing taps