Evaluation of Travelling Wave Fault Locators at Dominion

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Background

Dominion has historically had difficulty in locating faults on 500kV transmission lines. We have studied this problem and have improved our results, but fault locating on these lines is still not as accurate as it is on our 115kV and 230kV lines. To improve our accuracy, we embarked on a pilot project to evaluate the travelling wave method of fault location.

We use digital fault recorders, microprocessor based relays, and system modeling to calculate fault locations. These devices use an impedance-based fault locating algorithm, and as such are susceptible to several sources of inaccuracies. These include changing (due to weather conditions) and varying (due to terrain) ground conductivity. Another problem occurs when the conductors on the line are non homogenous. Static wire segmentation and lack of phase transpositions also affect impedance based location methods.

Theory

Travelling wave fault locators operate independently of ground conductivity and conductor impedance. The basis of their operation is that a step change in voltage occurs at the point of the fault. This step change creates a pulse that emanates from the fault. The time of arrival of this pulse is measured at both ends of the line using a precision GPS synchronized clock. The time of arrival data from each end is compared and a location is calculated using these times, along with the length of the line. The following formula will give the distance:

$$\text{Distance from end A} = \frac{L}{2} + \frac{(TA - TB)}{2} \times V$$

Where:
L = Line length
V = velocity of travelling wave (we use 99.5% speed of light)
TA = time of arrival at end A
TB = time of arrival at end B

Examples (see *Figure 1*):
A fault in the middle of the line will have the same time of arrival at each end since the pulse travels the same distance. Therefore, the location is 50% of the line length.

A fault closer to one end will arrive at the near end first and then at the far end. The difference in time is converted to a distance (the distance that the pulse travels, at the speed of light) based on the above formula.

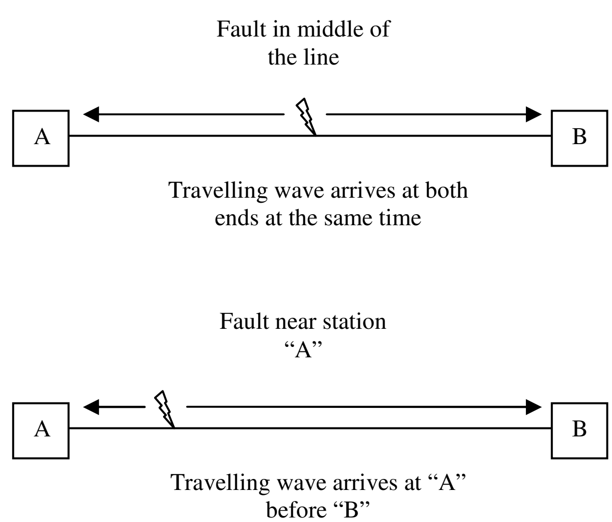

Figure 1 - Travelling wave arrival times.

The Travelling Wave System requires a unit at each end of the monitored line. The output from each unit is a precise time stamp and a waveform file that shows the travelling wave. Only the time stamp is required to perform the fault location calculation. The time stamp is downloaded to a "Master Station" computer that performs the fault location calculation. The travelling wave system does not provide a faulted phase or fault current - only a location.

Pilot line selection process

Once we decided to try traveling wave fault locators, we had to choose somewhere to place the devices. In order to choose the lines for the pilot project, we looked at a number of criteria, such as:

1. Number of operations
2. Relatively long line
3. Geographically diverse
4. Lines with taps
5. Lines with non-homogeneous conductors

We chose three of our 115kV lines based on the above criteria. Our goal was to have the best chance possible of seeing activity so we could evaluate the travelling wave system. Our 500kV lines very rarely operate, so they would not make for a good evaluation of the system.

The lines we chose for the pilot were the following:

22 line - 39.07 mile line of old construction. The line was originally built in the 1920s with wooden towers and one tap line. Ground faults on this line typically have high impedance. Locating faults on this line has been challenging.

27 line - 16.36 mile line with multiple under-built distribution circuits. This line has experienced many faults due to ionized gas flashing over from the distribution circuit.

198 line - 24.59 mile line with taps. One end terminates into the low side of a 500/115kV 90 MVA transformer.

Installation Experience

Installing the devices at each station is relatively simple. The unit needs DC power, GPS timing, communications, and an input from the current circuit of the line being monitored. We chose to mount the unit itself in a rack and provide DC. A GPS antenna is also required. This is in addition to any GPS antenna you may have previously installed. The manufacturer recommends using the built-in GPS for timing for the travelling wave unit. The unit comes with a standard 15 meter cable for the GPS antenna. In one instance we had to run the antenna cable several hundred feet to reach to roof of a power station. This required the installation of an amplifier in line with the coax, as well as lower loss coax cable.

The input from the line being monitored, in our case, consists of split core CTs that connect around each phase of the current circuit. The circuit monitored is the same circuit that feeds the line protection relays.

The split core CTs are assembled around the current wire and a piece of insulating material, usually a nylon washer, is placed between the two halves of the CT. With this washer in place, the CTs respond to the higher frequencies of the travelling wave that are produced when a fault occurs and the 60 Hz component can be ignored. The split core CTs come from the factory with a default cable length of approximately 50 feet.

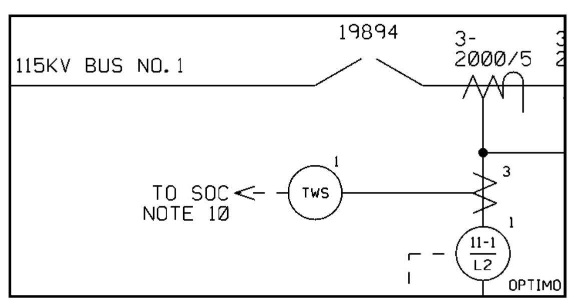

Figure 2 - CT connection for the Travelling Wave unit

In addition to the installation of the equipment in the field, the Master Station program needs information about the line. Communications to each unit must be established and then the line length must be entered as well.

The line length entered is not always the same as the physical length of the transmission line. It should also include the length of the secondary CT wires as well. To be precise, the location given by the TWS system is from TWS unit to TWS unit and includes secondary CT wires as well as the length of the cabling from the TWS unit to the secondary CT circuit. In most of our installations the CT wire length was insignificant, on the order of 100-200 feet. However we do have one installation with about 1500 ft of CT wire.

Commissioning

Commissioning proves that the units are installed properly. Polarity of the split core CTs is verified as well as the line length.

For commissioning, we attempt to create a transient at one end of the line, a known location, and have the TWS units trigger. During commissioning we increase the sensitivity of the TWS trigger so that it is more likely to capture the transient.

We attempt to create a transient during commissioning several ways:

1) Operating a breaker
2) Operating a disconnect switch
3) Operating a line switch
4) Operating a capacitor bank

Synchronous close breakers do not work well since the contacts close very near to the zero crossing of the voltage. We also found that operating gas (SF6) breakers would not create a transient. Oil breakers and disconnect switches, in our experience, provide the best chances for triggering the TWS units at both ends of the line.

Once we had matching triggers then we would compare the results from the master station location to the known location - the disconnect switches. The distance from one end should be zero and the distance from the other end should be the line length. The results would usually be within a few tenths of a mile. With this data, you can then precisely know the electrical length of the line. Many times the line construction data that we have does not necessarily have the exact conductor length. For example, sometimes the last span connecting to substation is not included, and the length between towers is used as conductor length and catenary distance is not considered.

The largest discrepancy we have come across is the 22 line where we had a line length of 39.07 miles in our database, yet we calculated a line length of 39.8 miles during the commissioning process. This is the same line that has a 1500 ft run of CT wire at one end. That alone accounts for almost 0.3 miles of the difference.

Communications Requirements

Since the only data that is required for a TWS fault location calculation to be performed is a time stamp, the communications requirements are relatively low. Initially we had many units on dial up modems and had the master station software polling all the units every four hours. During the automatic polling, only the time stamp data is downloaded. If we want to look at the waveform data, then we manually retrieve it.

In addition to the manufacturer's Master Station program that calculates location and displays waveforms, we poll the units via DNP so that our SCADA system can poll the units directly and have the location data presented on the operator's screen. We have an in house application that polls the units and retrieves the time stamp data and then performs the distance to fault calculation.

This DNP / SCADA application is still a work in progress.

Site Selection

We learned that not all locations are suitable for the split core CT method of obtaining the travelling wave. If a station is a pass through with a single breaker or a high impedance transmission transformer, then there may not be enough of a signal for the unit to detect. The travelling wave is reflected 180° out of phase and has a canceling effect on the incoming wave. The 198 line (115kV) at present is terminated at one end into a 500/115 kV transformer.

An alternate method is available for these locations. This alternate method involves connecting directly to the line potential devices to obtain the signal. Since it involves connecting directly to the coupling device, it requires an extra run of wire in the switchyard, which could require much more expense if extra conduit is needed for the cable. Dominion has not had any experience with the voltage method of travelling wave detection.

Another consideration for placement of the TWS units is how tap lines on the monitored line are handled. When there are taps on a line and a fault occurs on a tap and not on the main line, the fault appears to the TWS system as if it occurred at the point where the tap is connected to the line. In other words the travelling waves appear to emanate from the tap point. This behavior can be confusing if you are not aware of it. If you have another device, such as a DFR or digital relay, then you can use the TWS information to narrow the location to a specific tap. Then use your system modeling program and traditional impedance algorithms to provide a location on just that tap section of the line.

In Service Anomalies

We have encountered issues with the units sometimes triggering too much. There is a sensitivity adjustment that sets the level at which the unit triggers. We normally set this at the middle of the range. Some installations require that this be adjusted because the unit is triggering too much.

We have one particular station where the unit will trigger whenever a particular carrier set transmits. At first we thought that it was the RF from the carrier set, but after testing at the station it seems that when the set is keyed the power supply is creating a spike on the DC system that is being induced on the CT signal cables. This has not been fixed as of this writing.

Quite often the units will trigger for lightning, even when the line itself does not operate. One example occurred several days after the new line was energized. A large group of thunderstorms moved through the area and there were several triggers and fault locations generated for the line. We compared the locations to lightning locations given by the FALLS system. The results are shown in **Table 1**.

Table 1 - Lightning only events during storm

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

Results and Comparison

The tables in appendix A show the comparison to other forms of fault location that we have available. Only fault operations are included in this list. These tables only contain data from the original three 115kV pilot test lines. Where multiple locations are shown, the fault location method produced more than one location. This occurs when a location is given on the initial fault and on a subsequent reclose attempt.

The results on the 22 and 27 lines clearly show the accuracy of the travelling wave system. These lines are more challenging than most since there are stations and lines tapped off of these lines. Our intended application is 500 kV lines that do not have taps.

On the 22 line the TWS has calculated a location for every fault event. The 27 line had no data for two of the sixteen faults, and one of those was during a hurricane. The 198 line has provided three locations out of a total of seven faults.

The 198 line is an example of a less than ideal location to use the current method of detecting the travelling waves. The one end that terminates into a single 500/115 kV transformer does not consistently provide a good signal for the system to detect. This may be a good location to use the voltage method where the signal for the travelling wave unit is obtained from the line coupling capacitors. Our experience on this line so far has been that when the system provides a location it is accurate, however it doesn’t always provide a location. There was a big storm that came through the area on October 13, 2011 that operated the line twice, but the system did not provide locations for those events. It did trigger several times during the storm but the times were several minutes off from the actual trip events. We had a fault on the line on December 11, 2009 as shown in Table 4, the TWS location appears to be off by quite a bit. However, in this case the fault was on a tap of the line and the location given by the system was a location that is precisely the point at which the tap connects to the line. A map of the 198 line is shown in Figure 3. This shows that the TWS gave a correct location (the tap point), although by only looking at the mileage given, one might assume that this location was wrong. We have had two other faults on this line where the TWS system gave a location that correlated well with other fault location methods, but the actual fault was never found.

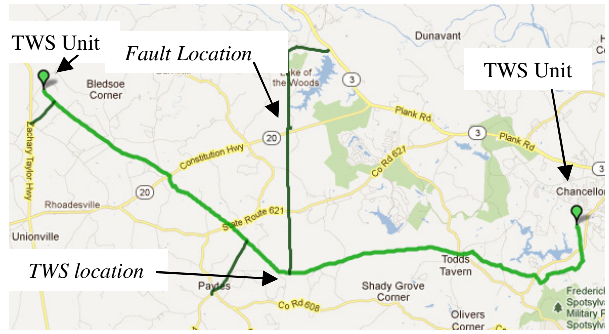

Figure 3 - 198 Line fault on tap section. The TWS correctly located to the tap point.

Since we have been installing these units on the 500kV system, we have had one 500kV fault on an interconnect line, and the location given by the TWS system was on the section of line that belongs to another utility. Their patrol did not find anything, so the accuracy for this event could not be determined.

<u>Conclusions</u>

The travelling wave system has performed very well for us and consistently provides accurate fault locations, when applied properly.

Fault location accuracy is good, regardless of fault type. Many times, only the initial fault will produce a location because of staggered reclosing, which leaves one end open during the reclose attempt.

Based on the results of these pilot lines, we decided to move forward with the installation of TWS units on all new 500kV transmission lines.

References

Jeff Littman, Dave Angell, and Dr. Phil Gale "Traveling Wave Fault Location System, Principles of Operation and Field Experience", presented at the 1995 Fault and Disturbance Analysis Conference, November 9, 1995, in Arlington, VA

Hathaway TWS MkV User Manual, #40-8534-01

About the author

Robert Orndorff has worked at Dominion since 1984. He spent 11 years as a field relay technician and in 1997 transferred to the Fault Analysis department where he currently works. Current responsibilities include maintaining and configuring Dominion's Digital fault recorders, event retrieval and analysis from smart relays and DFRs.

Robert is an IEEE member and has been a member of the Transient Recorder's User Council (TRUC) since 2002.

Appendix A - Fault data

Table 2 - 22 line events

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 3 - 27 Line Events

Actual location miles	TWS miles	Relay miles	DFR miles	FALLS miles	Aspen miles	Date	Time	Cause
Unknown	9.1	9.11		8.76		6/20/2008	0:01:04.395	Lightning
3.2	3	4.93				7/28/2008	5:36:00.000	Found dead Heron
9.52	9.3					9/3/2008	12:48:13.000	Ground switch
3.7	No data		4.1			11/12/2008	13:51:00.000	Distribution
4.42	4.3					12/11/2008	7:36:00.000	Under built distribution arrestor
6.1	5.6					8/5/2009	21:38:00.000	Ground switch
6.75	6.4			6.65		8/5/2009	22:43:08.224	Ground Switch Lightning in Dist
Unknown	2.1	10.3		11.37		8/6/2009	0:39:00.000	-194 KA Lightning
5.07	4.9/4.6				5.2	11/12/2009	17:59:00.000	Tree limb
2.81	2.7	2.89				1/3/2010	0:48:00.000	Insulator
7.7	7.1					2/17/2010	17:49:00.000	Car broke pole
15.67	15.8/15.7					4/23/2011	1:20:00.000	Ground switch
5.08	5.3/5.2	5.56	5.15			4/28/2011	17:50:11.160	Osprey nest
9.9	No data	9.4	10.10			8/27/2011	20:28:46.249	Hurricane
6.4	5.7/6.1		5.8			9/28/2011	17:00:05.024	Tree limb / Storm
Unknown	12.4/12.7			12.25		9/28/2011	18:30:00.562	-118 KA Lightning

Table 4 - 198 Line Events

Actual miles	TWS miles	Relay miles	FALLS miles	Aspen miles	Date	Time	Type	Cause
Unknown	No data	15.9		16	7/14/2008	20:46	BG	Unknown
Unknown	No data	2.2	2.2		8/22/2009	02:07:00.440	ABG	-52 KA Lightning
16.8	11.5(Tap)			15.99	12/11/2009	12:22:00.000	BG	Third Party contact
Unknown	12.5		12.4/12.2		8/25/2011	16:52:27.176	AG	Lightning
Unknown	10.9	11.1	11.1		9/3/2011	11:47:08.952	PPG	-64 KA Lightning
Unknown	No data	4.8	200KA		10/13/2011	02:56:16.928	AG	-200 KA lightning
4.0	No data	3.9	3.57		10/13/2011	02:58:29.968		-240 KA lightning