Traveling Wave Fault Location Experience at Bonneville Power Administration

Armando Guzmán, Veselin Skendzic, and Mangapathirao V. Mynam, Stephen Marx, Brian K. Johnson

Abstract-- **Faults in power transmission lines cause transients that travel at a speed close to the speed of light and propagate along the line as traveling waves (TWs). This paper shows how these transients can be used in a protective relay to enhance its fault locating function. These relays detect in-zone line faults and use TW- and impedance-based algorithms to optimize the estimation and reporting of the fault location. The TW- and impedance-based algorithms complement each other to provide accurate fault location estimation for all internal faults, independent of the fault incidence angle. This paper presents the details and experiences of a field application of these relays on a 161 kV voltage transmission line at Bonneville Power Administration (BPA).**

Keywords: **Fault location, GPS, protective relay, traveling wave.**

I. Introduction

THE Bonneville Power Administration (BPA) has been using traveling wave (TW) technology to locate faults in their extra-high voltage (EHV) transmission networks since the 1950s [1]. In the 1960s and 1970s, BPA installed an automated fault locating system that used microwave communications to send the TW arrival information to the master terminal for fault location estimation [2]. References [3] and [4] describe the development and field evaluation of the performance of a digital fault locator for high-voltage direct current (HVDC) lines that uses voltage and current measurements from one line terminal to estimate the fault location. Using voltage and current measurements, we can calculate incident and reflected waves. Applications based on incident waves are immune to the effects caused by termination impedances. In 1987, BPA started to use Global Positioning System (GPS) time information to measure the arrival of the TWs [5].

Later on, utilities like BPA used dedicated TW-based fault locating devices that sample the currents or voltages at sampling rates greater than 1 MHz [6]. Some of these devices also include fault disturbance recording and are capable of reporting accurate fault location results [7].

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Numerical protective relays include fault location estimation algorithms based on the line impedance and voltage and current measurements. In most applications, these relays only use measurements from the local terminal. Some relays also use information from the remote terminal to estimate the fault location. Using information from the local and remote terminals minimizes errors due to mutual coupling with adjacent lines, system nonhomogeneity, and fault resistance [8] [9]. For some scenarios, such as series-compensated lines and short-duration faults, the impedance-based fault locating methods are challenged and utilities require more accurate estimation than traditional relays provide [10].

This paper discusses the basic principles of TWs, a protective relay that estimates fault location using TW information, and the benefits of having TW fault location estimation within a protective relay. We also share the field experiences from an installation on a BPA 161 kV transmission line.

II. Basic Principles of Traveling Waves in Transmission Lines

A fault on a transmission line generates TWs that propagate from the fault location to the line terminals with a propagation velocity that depends on the inductance and capacitance of the line. Fig. 1 shows the equivalent circuit of a segment with length Δx of a two-conductor transmission line. The circuit includes the resistance R, inductance L, conductance G, and capacitance C of the line in per unit of the total line length [11].

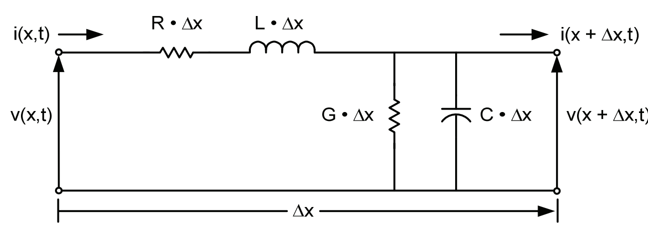

Fig. 1. Equivalent circuit of a segment of a two-conductor transmission line.

We use Kirchhoff's voltage law, shown in (1), and Kirchhoff's current law, shown in (2) for the first line mode, to relate the voltages and currents at locations x and x+Δx.

$$\begin{aligned} v(x,t) &= R \cdot \Delta x \cdot i(x,t) \\ &+ L \cdot \Delta x \frac{\partial i(x,t)}{\partial t} + v(x + \Delta x, t) \end{aligned} \tag{1}$$

$$i(x,t)=G \cdot \Delta x \cdot v(x+\Delta x,t) + C \cdot \Delta x \frac{\partial v(x+\Delta x,t)}{\partial t} + i(x+\Delta x,t) \quad (2)$$

Equations (3) and (4) determine the voltage and current as a function of x and time for the two-conductor transmission line in the time domain as the length of the segment Δx approaches zero.

$$\frac{\partial v(x,t)}{\partial x} = -R \cdot i(x,t) - L\frac{\partial i(x,t)}{\partial t} \quad (3)$$

$$\frac{\partial i(x,t)}{\partial x} = -G \cdot v(x,t) - C\frac{\partial v(x,t)}{\partial t} \quad (4)$$

Based on the techniques presented in [11], [12] and [13], equations (3) and (4) can be rearranged to obtain the voltage wave equation shown in (5) and the current wave equation in (6).

$$\frac{\partial^2 v(x,t)}{\partial x^2} = LC\frac{\partial^2 v(x,t)}{\partial t^2} + (RC+GL)\frac{\partial v(x,t)}{\partial t} + GR \cdot v(x,t) \quad (5)$$

$$\frac{\partial^2 i(x,t)}{\partial x^2} = LC\frac{\partial^2 i(x,t)}{\partial t^2} + (RC+GL)\frac{\partial i(x,t)}{\partial t} + GR \cdot i(x,t) \quad (6)$$

Equations (5) and (6) determine how the voltage and current waves propagate along a two-conductor transmission line.

To analyze the voltage and current TWs in multiphase transmission lines, we used an Electromagnetic Transients Program (EMTP) that models transmission lines considering the changes in the conductor resistance and inductance due to skin effect [11] [12] [13]. Fig. 2 shows how the current waves propagate across a 400 kV line in response to a nominal voltage step change on A-phase and B-phase at the sending end (the step change occurs at t = 0).

III. Traveling Wave Fault Location for Two-Terminal Lines

TW-based fault location provides better accuracy relative to impedance-based fault locating methods. Single end (Type A) and double end (Type D) are the two most common methods for computing fault location using TWs [1]. In this paper, we use the Type D method, which uses the time difference between the first arrived TWs captured at both terminals along with the line length and the wave propagation velocity to compute the fault location. Fig. 3 shows the waves propagating to Terminals A and B following a fault condition on a transmission line.

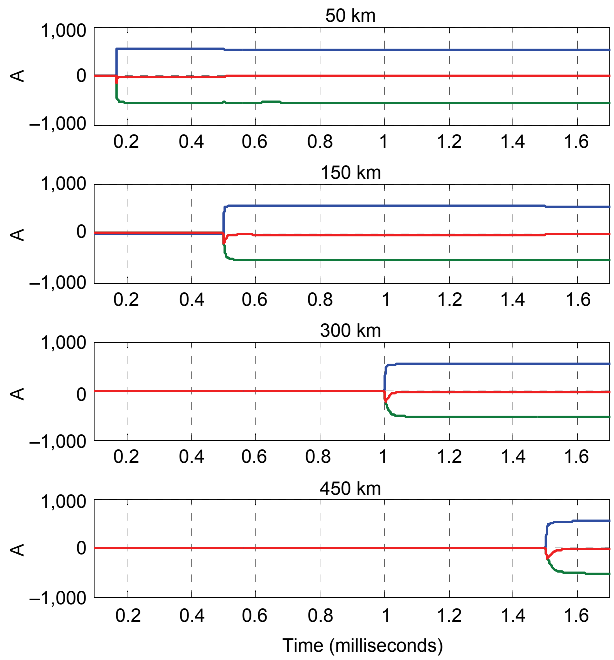

Fig. 2. Current waves at 50, 150, 300, and 450 kilometers traveling on a 400 kV line for a nominal voltage step change at the sending end, where A-phase is green, B-phase is blue, and C-phase is red.

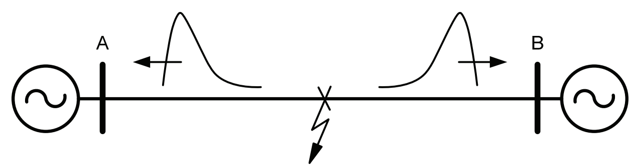

Fig. 3. TWs propagating to Terminals A and B.

Measurement devices at the line terminals detect the TWs and accurately time-stamp the arrival of the wave using a common time reference (e.g., IRIG-B or IEEE 1588). The typical time-stamping accuracy is better than 1 microsecond, which translates to ±0.1 mile (±161 m) in fault location error. The TW-based fault location is computed using (7).

$$TWFL = \frac{LL + (TwaveA - TwaveB) \cdot c \cdot LPVEL}{2} \quad (7)$$

where:

- TWFL is the TW-based fault location.
- LL is the line length.
- TwaveA is the TW arrival time recorded at Terminal A.
- TwaveB is the TW arrival time recorded at Terminal B.
- c is the speed of light.
- LPVEL is the propagation velocity of the TW in per unit of the speed of light.

The TW propagation velocity is a key parameter in the fault location calculation and is typically obtained from line parameter estimation programs. We can also estimate propagation velocity using TW measurements with the following:

- Local TW information recorded during line or reactor energization tests.
- Local and remote TW information recorded during external faults.

Voltage and/or current measurements can be used to capture the TWs. The adequate frequency bandwidth of current transformers (CTs) makes current TWs better suited for this application than voltage TWs measured at the secondary terminals of the step-down transformer of the capacitance coupled voltage transformer (CCVT) [14]. Typical installations have communications between the substation and the control center, where computer-based analysis tools retrieve the TW information captured at the line terminals and compute the fault location. In this paper, we discuss installations where protective relays exchange TW information obtained from the phase currents and automatically calculate the fault location at the line terminals within a couple of seconds after the fault.

IV. TW Fault Location in Protective Relays

A. Benefits of TW Fault Location in a Protective Relay

Numerical protective relays have included fault location estimation based on voltage and current measurements and line impedance since 1982 [15] [16]. While this approach provides estimations within 2 percent of the line length, there are cases where mutual coupling, fault resistance, and system nonhomogeneity can cause large errors. In these cases, the impedance-based fault locating methods in protective relays can be improved using local and remote (double-end) measurements [8] [9].

Because of the importance of locating faults to avoid fault reoccurrences and the high cost associated with finding line faults, utilities require accurate fault locating devices for all applications. For this reason, some utilities have installed dedicated devices that detect the time of arrival of TWs at the line terminals and estimate the fault location using this information [6] [17]. While these devices provide more accurate fault location estimation than relays that use impedance-based methods to estimate the fault location, there are cases where they cannot estimate the fault location when faults occur at or close to the voltage zero crossing.

Protective relays that include both impedance-based and TW-based fault location have the advantage of providing fault location even in cases where the TW amplitude is too low for reliable detection (e.g., faults that occur at voltage zero). In these cases, the relays estimate the fault location using line impedance and local and remote voltage and current measurements. If the remote measurements are not available, the relay estimates the fault location using local measurements only, thus providing robust response with the best possible accuracy under all fault conditions.

B. Relay-to-Relay Communications

The relay discussed in this paper uses a 64 kbps channel that exchanges currents for differential protection purposes. The relay takes advantage of this bandwidth and includes TW information within the data packet without affecting the performance of the differential element. The relays exchange the times of arrival of the TWs and use this information to estimate the fault location, make the results available at the relay location, and send the results to the control center within a couple of seconds after the occurrence of the fault.

V. Field Installation

A. Fault Location Experience

BPA owns and operates Goshen and Drummond substations. The Goshen-Drummond line is operated at 161 kV, and according to the BPA system data book, its line length is 72.77 miles. This transmission line is located in eastern Idaho close to the Wyoming border (see Fig. 4). The line shares a right of way with two other 161 kV lines for approximately 4.75 miles. Then it shares the right of way with another 161 kV line for the next 17 miles. The line was originally built for 115 kV and was later upgraded to 161 kV without changing conductors or insulators.

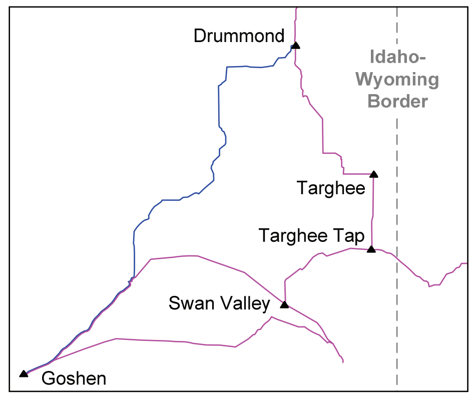

Fig. 4. Goshen-Drummond 161 kV line (blue) and neighboring 161 kV lines (magenta).

After the 161 kV upgrade, the line experienced over 40 faults over five years. The most common causes of faults on this line include the following:

- Galloping conductors clashing because of the wind.
- Farmers spraying fertilizers on the conductors and insulators.
- Flying projectiles hitting the conductors and insulators.

The Goshen-Drummond line is composed of four different tower structures. The line is spanned across 18 sections.

Fig. 5 shows the one-line diagram that includes the Goshen-Drummond line and relay CT connections. Notice that the line termination at Drummond is an autotransformer.

B. Traveling Wave Device Installation

On April 4, 2012, BPA installed two relays with TW locating capability on the Goshen-Drummond 161 kV line, as shown in Fig. 5. These relays are capable of exchanging TW information via a communications channel and estimating fault location in real time. The event records generated by the relays include the TW phase currents and time-stamp information.

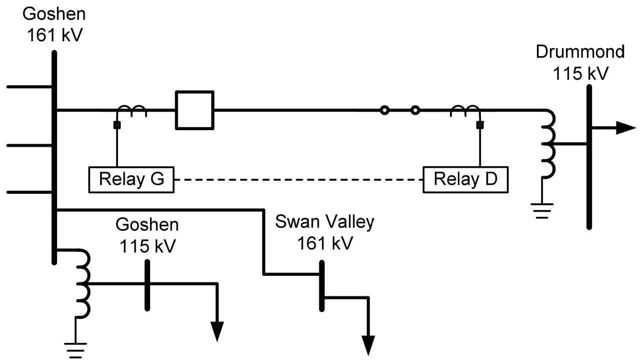

Fig. 5. Transmission network that includes the Goshen-Drummond line.

C. Propagation Velocity and Line Length

As previously mentioned, double-end TW fault location relies on the line length and propagation velocity settings along with the measured time difference between the arrival times of the TWs captured at both terminals of the transmission line.

We measured the propagation velocity based on the line length and travel time of the waves. We estimated travel time using the TW information that we captured during line energization. We energized the line from Goshen while the terminal at Drummond was open and captured the event reports to determine the wave propagation velocity.

Fig. 6 shows the phase currents filtered using an analog band-pass filter, preserving the high-frequency content and rejecting the fundamental frequency content; the currents are sampled at 1.56 MHz.

We used the time stamps corresponding to B-phase pole closing and the reflected wave from the open terminals to calculate the propagation velocity. We show the propagation velocity calculations in (8) and (9), with travel time equal to 790.605 microseconds and line length equal to 72.77 miles.

$$\text{LPVEL} = \frac{2 \bullet \text{LL}}{\text{Travel time}} \bullet \frac{1}{c} \tag{8}$$

$$\text{LPVEL} = \frac{2 \bullet 72.77 \text{ miles}}{790.605\ \mu\text{s}} \bullet \frac{1}{186282.39705 \text{ miles/s}} \tag{9}$$

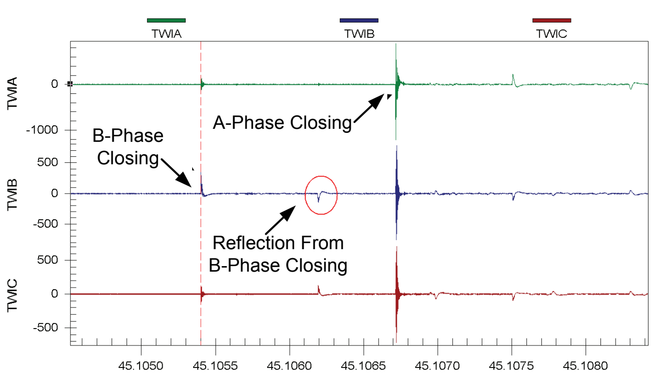

Fig. 6. TW phase currents captured during line energization.

D. Power System Faults and Fault Location Estimates

1) Event 1: C-Phase-to-Ground Fault

The first fault occurred on April 24, 2012. Fig. 7 and Fig. 8 show the TWs captured at the Goshen and Drummond terminals for the C-phase-to-ground fault.

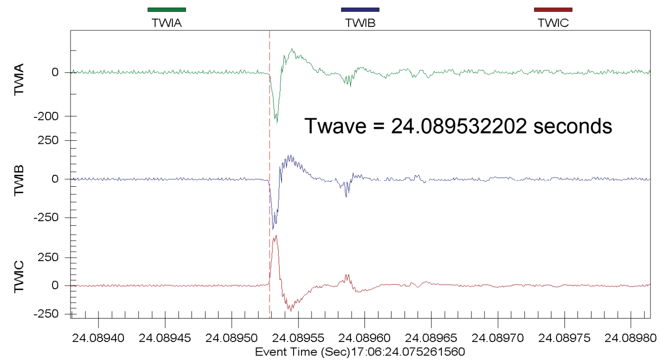

Fig. 7. Phase currents at Goshen for the C-phase-to-ground fault at 67.91 miles from Goshen terminal.

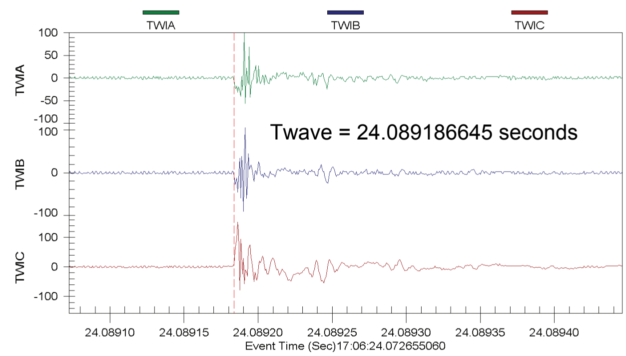

Fig. 8. Phase currents at Drummond for the C-phase-to-ground fault at 67.91 miles from Goshen terminal.

Based on the measured TW arrival times, we estimated from (7) a fault location of 68.19 miles from the Goshen terminal. When the line crew patrolled the line, they found a damaged insulator at 67.91 miles from the Goshen terminal. The line crew reported that the cause of the insulator damage could be a flashover. The relay uses nanosecond resolution for time stamping the TW arrival to minimize the error in fault location estimation.

2) Event 2: B-Phase-to-Ground Fault

The second fault occurred on May 11, 2012. This permanent fault was caused by a lead projectile hitting the B-phase insulators at a high speed. Fig. 9 and Fig. 10 show the high-frequency components of the phase currents captured at both terminals.

We estimated a fault location of 37.98 miles from the Goshen terminal. The line crew found the fault at 38.16 miles from the Goshen terminal. Fig. 11 shows one of the damaged insulators in the insulator string.

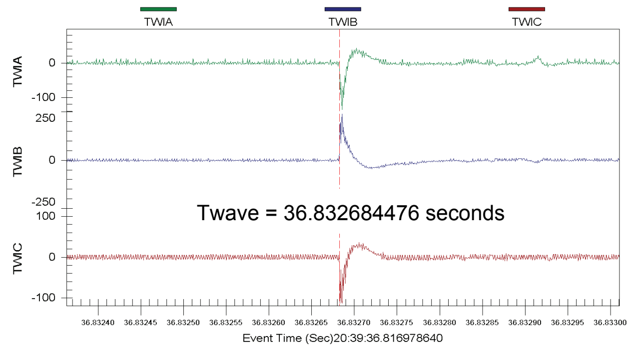

Fig. 9. Phase currents at Goshen for the B-phase-to-ground fault at 38.16 miles from the Goshen terminal.

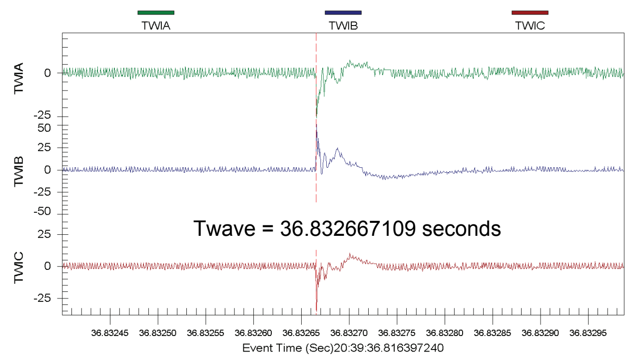

Fig. 10. Phase currents at Drummond for the B-phase-to-ground fault at 38.16 miles from the Goshen terminal.

Fig. 11. Damaged insulator at 38.16 miles from the Goshen terminal.

3) *Event 3: B-Phase-to-Ground Fault*

The third fault was on May 26, 2012. Fig. 12 and Fig. 13 show the high-frequency components of the phase currents captured at both terminals.

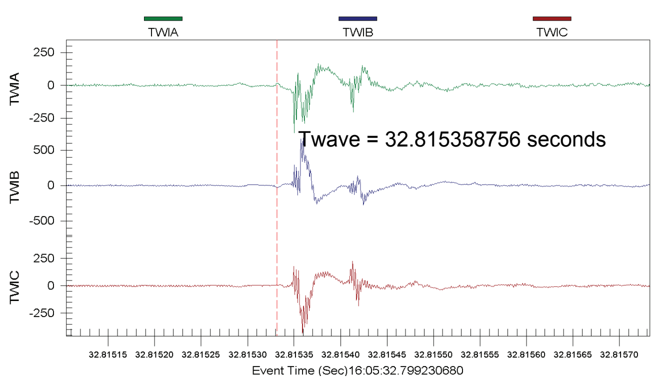

Fig. 12. Phase currents at Goshen for the B-phase-to-ground fault at 66.86 miles from the Goshen terminal.

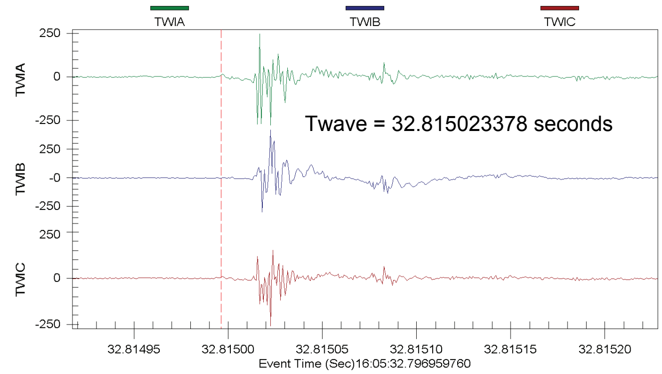

Fig. 13. Phase currents at Drummond for the B-phase-to-ground fault at 66.86 miles from the Goshen terminal.

Based on the prestrikes recorded at the Goshen terminal, it is suspected that the fault was due to lightning.

We estimated a fault location of 67.25 miles from the Goshen terminal. The line crew found the fault at 66.86 miles from Goshen.

4) *Summary of Results*

Table I provides the TW fault location for the three events discussed and additional events, we show the actual fault reported fault location reported by BPA along with the error in miles.

TABLE I. REPORTED FAULT LOCATIONS AND ASSOCIATED ERRORS

Event Number	Faulted Phase	TW-Based Estimated Distance	BPA Reported Distance	Error
1	C	68.19 miles	67.91 miles	0.28 miles
2	B	37.98 miles	38.16 miles	–0.18 miles
3	B	67.25 miles	66.86 miles	0.39 miles
4	B	61.42 miles	61.50 miles	-0.08miles
5	ABC	50.56 miles	50.18 miles	0.38 miles
6	BG	59.04 miles	59.04 miles	0.00 miles

VI. CONCLUSIONS

Travelling wave fault location techniques have been used for decades in the power industry, largely as separate stand alone systems. Microprocessor based relays normally use impedance based fault location methods. Adding travelling wave fault location capabilities within the protective relay to complement the impedance based fault location allows the relay to estimate fault location for faults any point in the voltage waveform within a couple of seconds, without the need for using an additional computer and software.

Results of field cases were presented to demonstrate that the travelling wave fault locating capability allows relays to locate faults to within a tower span in several fault events, including faults lines with mutual coupling where impedance based methods had challenges in the past. The travelling wave fault location capabilities were added to a line current differential relay and there was no need for additional secondary wiring and communications equipment.

VII. References

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