6147 N94-30652

DEVELOPMENT OF AN ACCURATE TRANSMISSION LINE FAULT LOCATOR USING THE GLOBAL POSITIONING SYSTEM SATELLITES

Harry Lee
B.C. Hydro and Power Authority
Burnaby, B.C. Canada

Abstract

A highly accurate transmission line fault locator based on the traveling-wave principle has been developed and successfully operated within B.C. Hydro. A transmission line fault produces a fast–risetime traveling wave at the fault point which propagates along the transmission line. This fault locator system consists of traveling wave detectors located at key substations which detect and time tag the leading edge of the fault–generated traveling wave as it passes through. A master station gathers the time–tagged information from the remote detectors and determines the location of the fault. Precise time is a key element to the success of this system. This fault locator system derives its timing from the Global Positioning System (GPS) satellites. System tests confirmed the accuracy of locating faults to within the design objective of ± 300 meters.

INTRODUCTION

Operating an electric system that includes long transmission lines passing through rugged terrain poses difficult challenges for operations personnel. The B.C. Hydro system is characterized by major hydroelectric generation sites that are separated by large distances from load centers. Confirming the location of transmission line faults typically involve a combination of helicopter and ground patrols both of which may be difficult or impossible to execute due to adverse weather conditions – which is usually the time when transmission line faults occur. A method for quickly and accurately locating transmission line faults has been a much desired tool for control center operators who must act quickly to determine locations of system disturbances in order to direct the work of search and repair crews.

Use of commercially available fault location tools such as fault–locating digital relays and digital fault recorders on the B.C. Hydro 500 kV system have produced limited successful results. Factors such as high ground resistance, series capacitor banks, etc. reduce the effectiveness of these fault location systems. To address the problem of accurate fault location under these conditions, a traveling wave based fault location system has been developed and successfully operated on the B.C. Hydro 500 kV system.

FAULT LOCATION METHODS

Time Domain Reflectometers

Early fault locators were based on pulse radar techniques. These devices known as time domain reflectometers (TDRs), are commonly used for locating faults in buried cables where visual inspection is not possible without excavation. This technique makes use of a "probe" pulse that is launched into one end of the cable and relies on the pulse being reflected back to the source due to an electrical discontinuity at the faulted location. The fault location is determined by measuring the time delay from launching the pulse and receiving its reflection. There is, however, little interest in applying this method to overhead transmission lines. Several factors make this technique impracticable:

Unlike cables which are physically and electrically uniform throughout its length, overhead lines have inherent discontinuities such as tower structures, conductor variations, etc. that cause unwanted secondary reflections which interfere with detecting the reflected "probe" pulse.

The faulted line must be taken out of service to conduct testing and special precautions must be taken to ensure mutual inductance effects from healthy adjacent lines and nearby energized equipment does not pose a safety hazard.

The fault must be permanent (e.g.. solid short or open conductors) to ensure a strong reflected signal. Difficult to find faults such as ice build–up, galloping conductors, etc., conveniently disappear by the time the fault location equipment can be mobilized and put into service.

B.C. Hydro has used time domain reflectors on transmission lines for many years before largely abandoning this technique due to its complexity and small gains.

Impedance–Based Fault Location Methods

The largest area of development on fault location methods are those based on the measurement of system frequency (60Hz) signals. These methods make use of information from the transmission lines that are already available for protective relaying purposes (i.e. line voltage and current). In the most general sense, these techniques analyze the impedance characteristics of the line to determine the fault location.

Early fault locators were based on the reactance method where fault location is determined by measuring the ratio of the reactance of the faulted line at the source end to the unfaulted line reactance, the assumption being that the fault impedance is purely resistive. More complex algorithms make use of pre– and post–fault conditions to reduce the effects of sources (except for the virtual source at the fault) and loads. The development of digital fault recorders and digital protective relays has made it possible to implement better and computationally more complex algorithms. Many of these methods involve simultaneous solutions of non–linear equations which can easily be implemented using iterative techniques.

A number of protective relaying manufacturers have incorporated fault location functions as part of their protective relays. B.C. Hydro has made extensive use of these devices on lower voltage lines (230 kV and below). Experience with these fault locating relays have shown some very good results, but occasionally some poor results.

On the 500 kV system where accurate fault location is of much greater importance, the use of series compensation precludes the use of these relays for fault location. In long transmission lines, reactive compensation in the form of a series capacitor is typically inserted at the midpoint of the line to compensate for the line inductance and increase the load carrying capacity of the line.

A fault on a series compensated line produces transient frequencies below the power system frequency that are the result of the natural resonance of the series capacitance and system inductance. The frequency of these oscillations depends largely on the source impedance and can lie close to the power system frequency. These transient frequencies can produce spurious outputs, causing inaccurate fault location.

Traveling Wave Fault Location

Traveling wave fault locators make use of the transient signals generated by the fault. When a line fault occurs, such as an insulator flashover or fallen conductor, the abrupt change in voltage at the point of the fault generates a high frequency electromagnetic impulse called the traveling wave which propagates along the line in both directions away from the fault point at speeds close to that of light. The fault location is determined by accurately time-tagging the arrival of the traveling wave at each end of the line and comparing the time difference to the total propagation time of the line. Refer to Figure 1.0

Unlike impedance-based fault location systems, the traveling wave fault locator is unaffected by load conditions, high ground resistance and most notably, series capacitor banks. This fault locating technique relies on precisely synchronized clocks at the line terminals which can accurately time-tag the arrival of the traveling wave. The performance goal selected by B.C. Hydro is a fault location accuracy of ± one tower span or approximately 300 meters. The propagation velocity of the traveling wave is roughly 300 meters per microsecond which in turn requires the clocks to be synchronized with respect to each other by less than one microsecond.

Precisely synchronized clocks is the key element in the implementation of this fault location technique. The required level of clock accuracy has only recently been available at reasonable cost with the introduction of the Global Positioning System.

IMPLEMENTATION AND TESTING

Evaluation of the fault locator involved the installation of GPS timing receivers at four 500 kV substations, see Figure 2.0. A especially developed Fault Transient Interface Unit (FTIU) connects to the transmission lines and discriminates for a valid traveling wave. The FTIU produces a TTL-level trigger pulse that is coincident with the leading edge of the traveling wave.

A time-tagging input function was provided under special request to the GPS receiver manufacturer. This input accepts the TTL level logic pulse from the FTIU and time tags the arrival of the fault-generated traveling wave. The time tag function is accurate to within 300 nanoseconds of UTC – well within the overall performance requirement of timing to within

1 microsecond.

The fault locator was tested by placing B–phase to ground faults on line 5L82 using a high speed ground switch. Twelve faults were applied to the line and the fault locator successfully located all twelve faults to well within the design goal of plus or minus one tower span (300 meters) accuracy. The results are summarized in Table 1.0.

ADDITIONAL SOURCES OF VERIFICATION

The fault locator responds to any traveling wave impulse with sufficient energy in the 35 kHz to 350 kHz range. These impulses are not limited to those generated by actual transmission line faults. Routine switching of substation equipment also produces similar fast risetime impulses which are also detected and time tagged by the fault locator. These station–generated traveling waves provide an opportunity to test (and calibrate) the fault locator by comparing the measured results against the total propagation time of the line – a known quantity. Traveling waves generated by routine operation of 500 kV equipment at NIC, KLY and ING substations over a period of one year indicated repeatability of fault location measurements to within the one microsecond or 300 meter performance accuracy goal. See table 2.0.

EFFECTS OF SERIES CAPACITOR BANKS

A prime consideration leading to the development a traveling wave fault locator was the use of series capacitor banks has made it very difficult if not impossible for the system frequency (60Hz) or impedance–based fault location techniques to operate properly i.e. fault location using digital relays and digital fault recorders. The high frequency fault-generated traveling waves on the other hand, are not affected by series capacitor banks. There are series capacitor banks installed on lines 5L81, 5L82 and 5L42. Testing using traveling waves generated by reactor switching at NIC and KLY showed the capacitor banks did not have any noticeable effects on the propagation of the traveling waves.

DISTORTION AND ATTENUATION OF TRAVELING WAVES

The accuracy of fault location depends on the ability to accurately time tagging the arrival of the traveling wave at each line terminal. The traveling wave once generated, is subject to attenuation and distortion as it propagates along the transmission line. Attenuation occurs due to resistive and radiated losses. Distortion of the waveform occurs due to a variety of factors including bandwidth limitations of the transmission line, dispersion from different propagation constants of phase–to–phase and phase–to–ground components, etc. These effects combine to degrade the quality of the "leading edge" of he traveling wave at large distances from the fault inception point. The accuracy of time tagging the traveling wave diminishes for the substations far away from the fault. Experience with the evaluation system has shown that the traveling wave is relatively "undistorted" for distances less than 350 km. To effectively reduce the effects of attenuation and distortion requires traveling wave detector installations spaced at regular intervals. For B.C. Hydro, this translates to installing fault location equipment at fourteen out of nineteen 500 kV substations.

EFFECTS OF SELECTIVE AVAILABILITY

Selective Availability (SA) is the intentional degradation in accuracy of the GPS signal which is applied at the discretion of the U.S. Department of Defense. The result is a pseudo-random wander of the navigation and timing data. To overcome this effect requires the use of a special military–authorized GPS receiver. Selective availability when "switched on" reduces the accuracy of civilian GPS timing receivers from ± 100 nanoseconds to ± 300 nanoseconds, which is still within the allowable tolerance for the accuracy of the fault locator. Selective availability is not considered to be a problem for the purposes of fault location.

CONCLUSION

Testing of the fault location system has produced results meeting the design goal of plus or minus 300 meter accuracy. Based on successful experience with the evaluation system, B.C. Hydro has allocated funding for implementing this fault locator throughout the 500 kV system. This project, which is currently underway, involves the installation of GPS-based timing units and traveling wave detectors at fourteen 500 kV substations and a master polling station and console at the System Control Center.

ACKNOWLEDGEMENTS

The author wishes to thank the Bonneville Power Administration for supplying the design of the traveling wave detector (the Fault Transient Interface Unit) and whose pioneering work on traveling wave fault location provided inspiration for this project.

Table 1.0

Fault Locator System Test

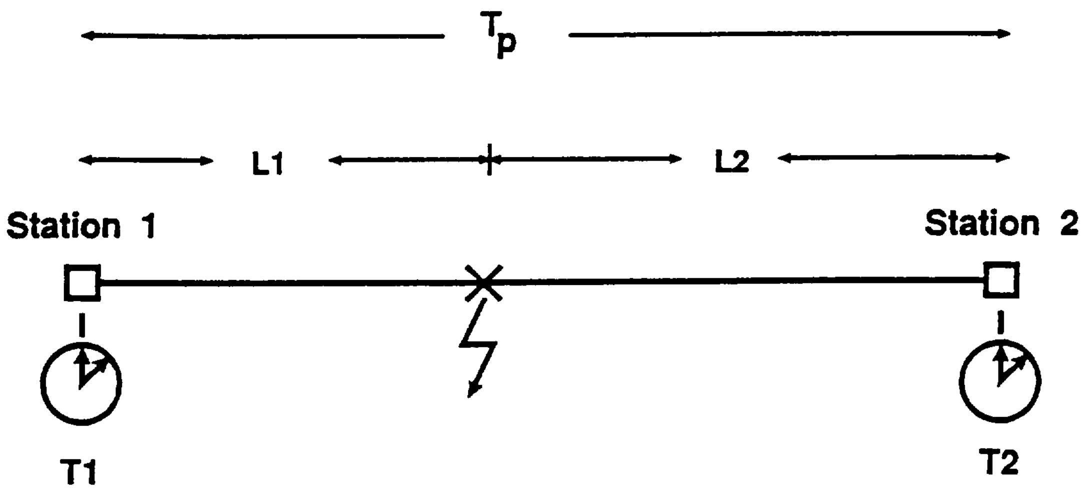
Calculated cumulative arc length from NIC substation to the fault = 131,694.5 meters.

Test	Fault Locator Output (meters)	Difference from Est. Value (meters)
1	131,725	30
2	131,819	124
3	131,721	26
4	131,803	108
5	131,800	105
6	131,834	139
7	131,730	35
8	131,697	2
9	131,829	134
10	131,806	111
11	131,810	115
12	131,814	119

Table 2.0

Fault Locator Response to Travelling Waves Generated by Routine Switching of Substation Equipment

Line	Estimated T_p (μsec)	Measured T_p (μsec)
5L87	501	499
5L44	66	67
5L82	850	851
5L81	900	896
5L45/42	901	901



The distance to the fault from the line terminals is given by:

$$L_2 = \frac{T_p + \Delta T}{2} \times V_p \quad \text{and} \quad L_1 = \frac{T_p - \Delta T}{2} \times V_p$$

Where V_p is the velocity of propagation for the line and $\Delta T = T_2 - T_1$.

Figure 1.0 Principle of Operation

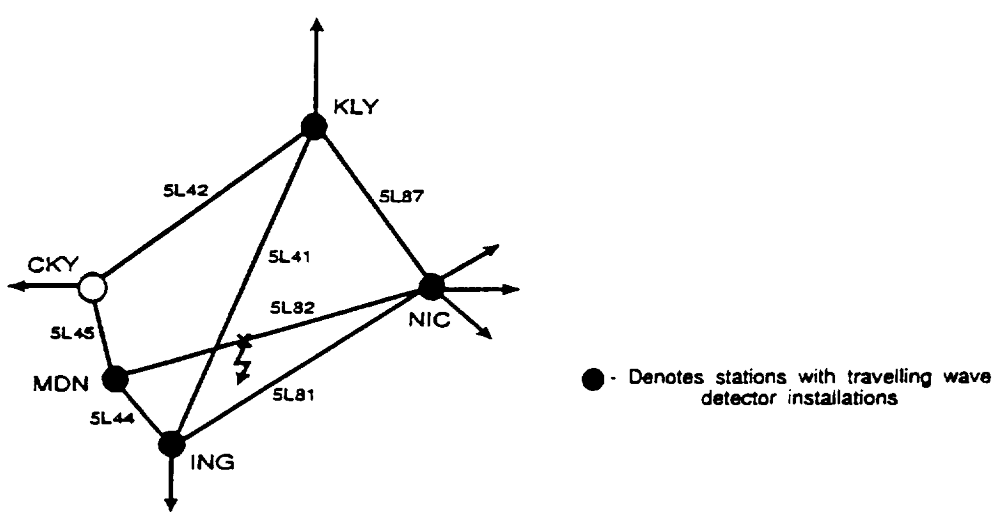


Figure 2.0 Fault Locator Installations and Testing

QUESTIONS AND ANSWERS

Thomas Becker, Air System Technology, Inc.: Have you found any naturally occurring phenomena that produce signals on the line that would appear to be a failure?

Harry Lee: Lightening is one thing that we are really interested in locating. That is something that we have never been able to do in the past. Other than that, there hasn't been much else naturally occurring, if you may mean the effects of solar radiation.

Thomas Becker: No, lightening is probably a great example.

Harry Lee: Lightening is what we do want to locate. It is not too much of a problem for us, these other extraneous sources of travelling waves, because we do have our regular instrumentation that tell us when the line is tripped out. And using that, coupled with this fault locator system, it can effectively field throughout.

Thomas Becker: Is the line switching done automatically based on these fault locators? Or is it then suggested to an operator to actually unload that line and transfer something?

Harry Lee: The two systems operate independently. As I said, we do have our protection systems which monitor faulted conditions, basically short circuits, overloads, high current, low voltage, that type of detection scheme. And that automatically trips the line out of operating circuit breakers. At that point, the operator will then look through the fault locator system to try to pinpoint where the fault occurred. So the two operate independently. The fault locator doesn't initiate corrective tripping.

Thomas Becker: It would seem fairly easy for a cascade of events to occur if you were not prepared for that sort of thing.

Harry Lee: That's right. And those things do happen unfortunately.