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Location of Underground Cable Transitory Faults

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***Abstract*—Formulation of distance to fault of transitory, sub-cycle, behavior is discussed with detailed circuit modeling and its principle of utilizing only discrete voltage and current samples available at the substation. The formula is derived for a reactance value as the distance from the equivalent circuit to fault location with voltage injection and superposition with the terms of net fault voltage and net fault current. The steps for implementing the derived formula in practical application are detailed, and the test result of seven single line-to-ground faults of underground cable with actual substation measured data is discussed.**

***Keywords*: Transitory fault, sub-cycle fault, superposition, fault voltage injection, fault location.**

I. Introduction

MOST fault location algorithms rely on phasor information of voltage and current and utilizing line impedance or reactance as the main variable as fault distance. The phasor, by definition, is obtained from steady-state sinusoidal signal of voltage and current. Therefore, the fault location algorithms wait, after the on-set of the fault which, without exception, first manifests a transitory behavior, for the start of the steady-state period of fault signals and, then, using the steady-state sinusoidal signals of, for example, two or more cycles, they calculate the magnitudes and phase angles of the signals to produce phasor information of the signals for determining the impedance or reactance value to the fault [1 – 4].

However, a great portion of faults, especially in underground cables, exhibit behaviors without steady-state signals but also with fewer than 2 cycles of an abnormal signal period before returning to normal operation. Many, if not all, faults under this category manifest their abnormal signal behavior for 1 cycle or even one-half cycle period [5].

These types of faults are often called transitory or intermittent faults since they are not permanent faults but may be precursors of permanent faults to come. Therefore, the correct location of transitory intermittent faults is crucially important in prevention of faults and unscheduled outages. However, conventional fault location algorithms cannot locate these types of faults.

The first objective of this paper is to introduce, as a continued effort on the subject of sub-cycle ground fault location [6], fault location formulation and circuit modeling of transitory faults of double line faults with and without ground involvement (termed DLG and DL, respectively), which are more commonly found in overhead lines.

The second objective is to report the result of tests of the SLG fault location formula on real cable faults. Even though interested readers can refer the reference [6] for the details of the transitory single-line-to-ground (SLG) fault location in principle and location formula; however, because of the importance of full understanding the concept on the SLG fault location for the further development of to the DL/DLG faults, a brief summary on the transitory fault location of SLG is discussed in Section II. Then, in Section III, fault location formulas for DL/DLG of transitory nature are described. Section IV describes the test of the formula on SLG cable faults with real data acquired from San Diego Gas & Electric (SDG&E), followed by the conclusions of the paper in Section V.

II. Transitory SLG Fault Location

In the analysis and derivation of the fault location formula, we follow the present practice and design of the substations of SDG&E from which recordings are made and fault signals are obtained. In particular, the substation transformer(s) are Y-connected and direct grounded and a 3-phase capacitor bank is connected to the substation bus. The substation measurement is conducted on the bus therefore the measured voltage is the bus voltage and the measured current is the current from the main source which may indicate the combined current from multiple circuits connected to the bus.

Suppose that a single line to ground fault occurs on phase A at the location x of the line served by the assumed substation. The situation can be equivalently expressed for each phase, as illustrated in Fig. 1, with a sinusoidal source E_s with source inductance L_s, parallel capacitance C of substation capacitor bank, the inductance of the circuit from the substation to the location of the fault, L_{line} (or "LF") and the inductance of the circuit from the fault location to the end of the circuit, L_r. The only variables measurable at the substation, through CTs and PTs, are the current flowing through the source impedance and the bus voltage across the capacitor C. The approach calculates the inductance to x, LF, by using only the substation measured voltages and currents.

At the fault inception at time t=0 (or t=tF), the fault voltage at x becomes zero by the assumption of zero fault resistance.

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The voltage zero incident can be represented by an injection of the negative polarity of the normal voltage at x, $-v_{ax}(0)$, into the location x to the system. Also, since our interest is only in the change of voltage and current, termed "net fault voltage and net fault current" due to the fault, we deactivate the source voltage while keeping $-V_{ax}(0)$ or $-V_{ax}(tF)$ between x and the ground by the principle of superposition. V_{aF} and I_{aF} are the net phase A fault voltage and current, respectively, at the substation bus contributed only by the injected voltage source. The injected voltage at x is the same as the normal voltage at the bus at time tF since there is no current flowing in the normal (no-fault) situation. In other words, $V_{ax}(tF) = V_{aN}(tF)$.

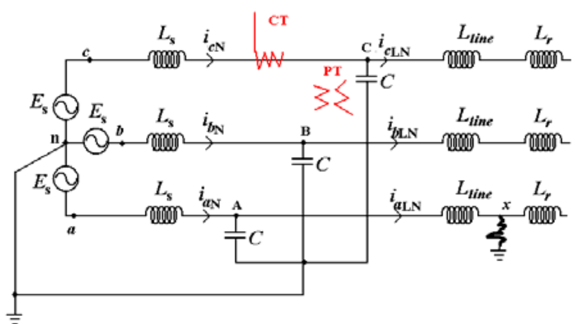

Fig. 1. A SLG fault circuit.

The $V_{aN}(tF)$ injection and superposition principle simplifies the situation to the equivalent circuit of Fig. 2, with all resistive components ignored. The problem now becomes a transient response with the source $-V_{ax}(tF)$ or $-V_{aN}(tF)$ switched on to the circuit at t=0 (or tF).

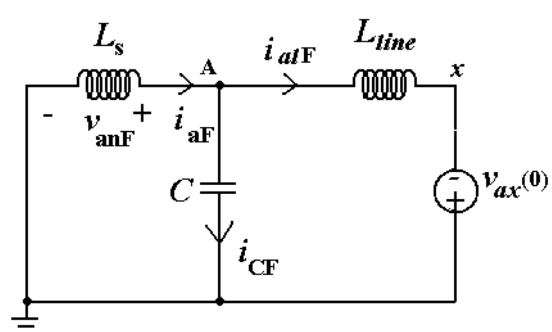

Fig. 2. Equivalent circuit of SLG fault.

From Fig. 2, we can draw following equation for the distance to fault: $LF_A = \frac{V_{anF}(t) + V_{aN}(tF)}{dI_{aF}(t) + C * ddV_{aF}(t)}$, where $dI_{aF}(t)$, $ddV_{aF}(t)$ are the first and the second derivatives of the net fault current and the net fault voltage, respectively.

III. Formula for Transitory DL and DLG Faults

The types of fault described here are more common in overhead lines; however, they cannot be excluded in all cases of underground cable faults. In both overhead lines and cables, the formulas developed in the section equally apply.

A. DL Fault without Ground Involvement ("AB fault")

The case of DL fault without ground involvement is illustrated in Fig. 3 with similar elements used in Fig. 1, for a phase A and B fault ("AB fault"). Fault distance formulas for other line-to-line faults, BC and CA faults, can be similarly derived in the same manner.

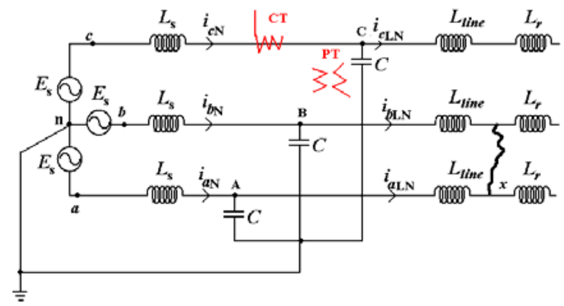

Fig. 3. An AB fault circuit.

The circuit under fault at location x is now simplified to a circuit of Fig. 4 with injection voltage, the voltage between A and B at normal situation at the fault inception time, $V_{abx}(tF)$, and inductors and capacitors of phases A and B only.

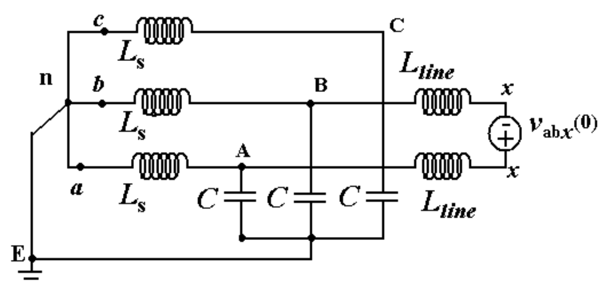

Fig. 4. Simplified AB fault circuit.

As explained with regard to SLG fault formula derivation, the injection voltage Vabx(0)=Vabx(tF) is the same as the normal line-to-line voltage at the bus at time tF:

$V_{abN}(tF)=V_{abx}(tF)$, where $V_{abN}=V_{aN}-V_{bN}$.

Now Fig.4 can be again simplified to the circuit of Fig. 5, from which the two current equations at two nodes A and B can be determined:

$I_{alF} = I_{aF} - C * dV_{aF}$ (at node A), and

$I_{blF} = I_{bF} - C * dV_{bF}$ (at node B).

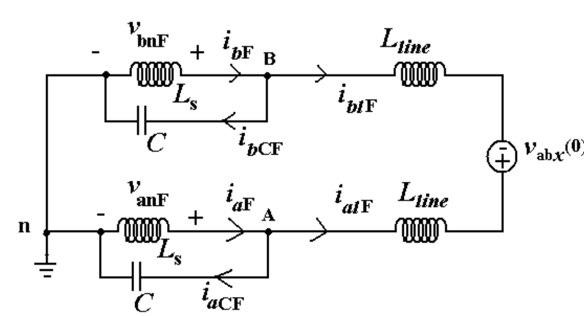

Fig. 5. Further simplified circuit for AB fault.

Then, using the above two equations, the voltage equation around the main loop, not including the capacitors, leads to the following equation for LF:

$LF_{AB} = \frac{V_{aF} - V_{bF} - V_{abN}(tF)}{dI_{alF} - dI_{blF}}$, where dI_{alF} and dI_{blF} are the first derivatives of I_{alF} and I_{blF}, respectively.

Applying the relationships that V_{aF}-V_{bF}=V_{abF} and I_{blF}= -I_{alF}, the LF equation is simplified to:

$$LF_{AB} = \frac{V_{abF} - V_{abN}(tF)}{2*(dI_{aF} - C*ddV_{aF})}.$$

The cases for a three line fault ("ABC fault") are similar to the AB fault formula in the fault distance calculation. Actually, the LF formula for distance to fault for ABC fault is identical to that of AB (or any line-to-line) fault.

B. DL Fault to Ground ("ABE" Fault)

The phase AB to ground fault, "ABE fault" as a typical but equally applicable to other line-to-line-to-ground faults in a 3-phase circuit system is diagrammed in Fig. 6.

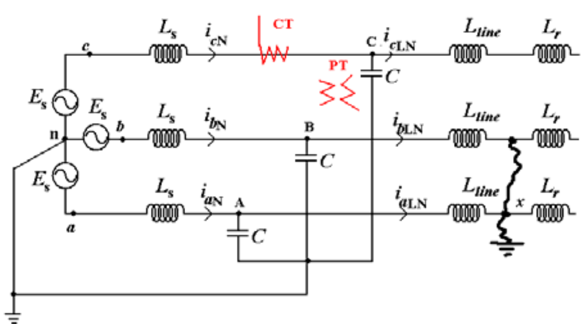

Fig. 6. Circuit diagram of ABE fault.

The circuit diagram of Fig. 6 can be reduced to that of Fig. 7 with the two injection voltages for phase A and B with the same magnitude since the X points are conjoined at the same point in both lines.

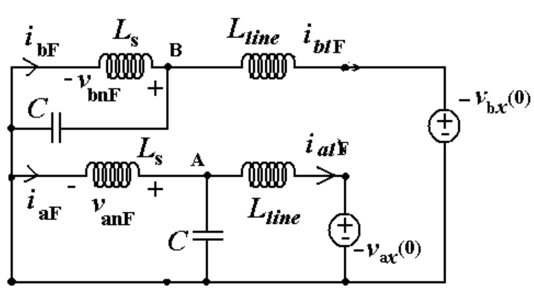

Fig. 7. Simplified circuit diagram of ABE fault.

The two independent voltage equations around the main loop and the inner loop, respectively, generate two equivalent fault distance formulas for LF, each identical to that of phase A (or B) SLG fault. Specifically, the equivalent two voltage equations for LF are determined to be:

$$LF_{ABE} = \frac{V_{aF} + V_{aN}(tF)}{dI_{aF} - C*ddV_{aF}} = \frac{V_{bF} + V_{bN}(tF)}{dI_{bF} - C*ddV_{bF}}.$$

The fault distance formula for three line-to-ground fault ("ABCE fault") turns out to be, by applying the same analysis and circuit simplification approach applied in the ABE fault example, the same as that of a SLG fault:

$$LF_{ABCE} = \frac{V_{aF} + V_{aN}(tF)}{dI_{aF} - C*ddV_{aF}} = \frac{V_{bF} + V_{bN}(tF)}{dI_{bF} - C*ddV_{bF}}.$$

IV. Test of Fault Location Formula with Real Data

This section discusses the preliminary test of the formula drawn for transitory SLG faults with real data obtained from the Creelman substation of SDG&E. However, before the reporting of the test result, algorithmic structure and the steps of applying the formula are first described, followed by the source of the real data.

A. Computational Algorithm for SLF Fault Location

From the SLG fault distance formula, it is apparent that application of the formula needs (i) net fault voltage $V_{aF}(t)$ and current $I_{aF}(t)$, (ii) the voltage at fault inception $V_{aN}(tF)$, and (iii) the first discrete derivative of the net fault current $dI_{aF}(t)$ and the second discrete derivative of the net fault voltage $ddV_{aF}(t)$.

Therefore, the first step is to derive net fault values for voltage and current. The captured raw data of voltage and current are to be split into two data components, separated by the fault inception time stamp: synchronized pre-fault data and post-fault data of a full cycle length or more. Synchronization of both data sets is very important because the former is subtracted from the latter for the net fault value. The synchronization is established in the following manner. First, the normal data over the entire captured data length can be obtained by getting a full cycle of pre-fault samples and then by concatenating the same 1 cycle after the full cycle pre-fault samples repeatedly until the combined sample number is the same as that of the captured raw data. Second, the entire captured raw samples, including the 1 cycle pre-fault normal sample in the beginning, are used as the fault data. Then, the net fault data are obtained by subtracting the normal data from the fault data, sample by sample. On the other hand, the value of voltage at the fault inception time becomes the initial phase voltage, $V_x(0)$ or $V_{aF}(tF)$, the negative of which is the injected voltage source in the injection and superposition analysis.

The second step is differentiation of net fault current and voltage. Among many first derivative formulas for discrete value, we choose to use the second order centered difference formula, due to reduced sensitivity to the random white noise components contained in the raw data, which at time step *n* is expressed by:

$$dI_{aF}(n) = \frac{I_{aF}(n+1) - I_{aF}(n-1)}{2*\Delta t}.$$

For the second differentiation for the net fault voltage, we choose to use the above first derivative twice.

The third and last step calculates the fault distance LF (in reactance) using the parameters produced in the previous steps. Note that in the normal situation, since the net fault voltage and net current or its derivative are close to zero, the output of the formula would produce infinity or indeterminate distance to the fault. Therefore, we expect to see very spiky outputs of distance in normal conditions but consistent outputs in faulted conditions.

B. Description of the Real Data

To collect testing data for the developed transitory SLG fault location formula, from the year 2006 Creelman Substation outage list, we downloaded cable related event data captured by a power quality monitor, called PQnode, via PQView data management system. The PQnode installed at each of the two buses, North and South Buses, at the Creelman Substation captures triggered and periodic steady-state waveforms with simultaneous sampling rate of 128 points per 60Hz cycle for 3 phase voltages, 3 phase currents, and residual current.

In the triggered capture, set to respond to the voltage or current magnitude change of +/- 10% or more, 2 cycles of pre-triggered event waveforms and 12 cycles of post-triggered event are recorded. The data collected from the PQnodes but of multi-cycle permanent faults have been used by a third party to test a conventional impedance (or reactance) algorithm [7].

From the downloaded data of cable related events, we found seven outage events which closely matched with the cable damage events of the list that last less than 2 cycles of time. They were all from the South bus of the substation in the circuits of #973, #971, and #970. Each of the seven events is summarized below with event time, circuit number, faulted phase, cause, and fault distance.

Event 1: 05/06/06 14:55, #973, C, Cable Rack, 4.08 miles.
Event 2: 05/15/06 06:16, #973, C, Cable, 1.93 miles.
Event 3: 08/21/06 09:35, #973, B, Cable, 5.02 miles.
Event 4: 12/15/06 21:41, #973, C, Cable, 5.02 miles.
Event 5: 07/31/06 06:32, #971, A, Cable, 5.07 miles.
Event 6: 02/05/06 14:20, #971, A, Cable, 4.05 miles
Event 7: 07/22/06 19:56, #970, B, Cable, 2.76 miles.

C. Testing Results with the Real Data

The first step of the process is to read the captured raw data which contains at least 1 cycle of normal and several cycles of post-disturbance waveforms of voltages and currents. Fig. 8 shows the raw waveforms in phase voltage (scaled down by 10), phase current, and residual current, for all 7 events.

Then, the net fault data are obtained by subtracting the normal data from the fault data, sample by sample. Fig. 9 depicts the net fault voltages, net fault currents, and net residual fault currents of the respective faulted phase, of the events.

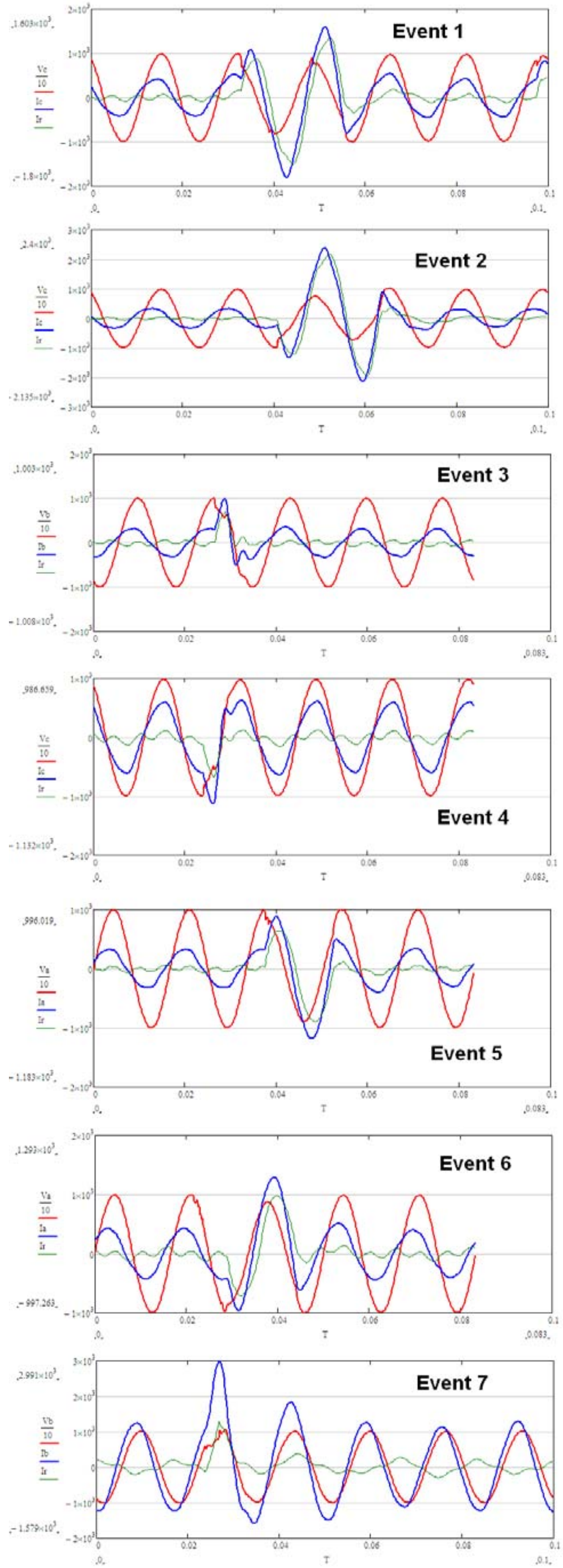

Fig. 8. Voltage and current waveforms of the seven events.

Finally, Fig. 10 shows the results of fault distance in reactance for each of the events. Since the fault distance calculation of the approach produces reactance values, the direct comparison with the actual events' distances in mile is difficult.

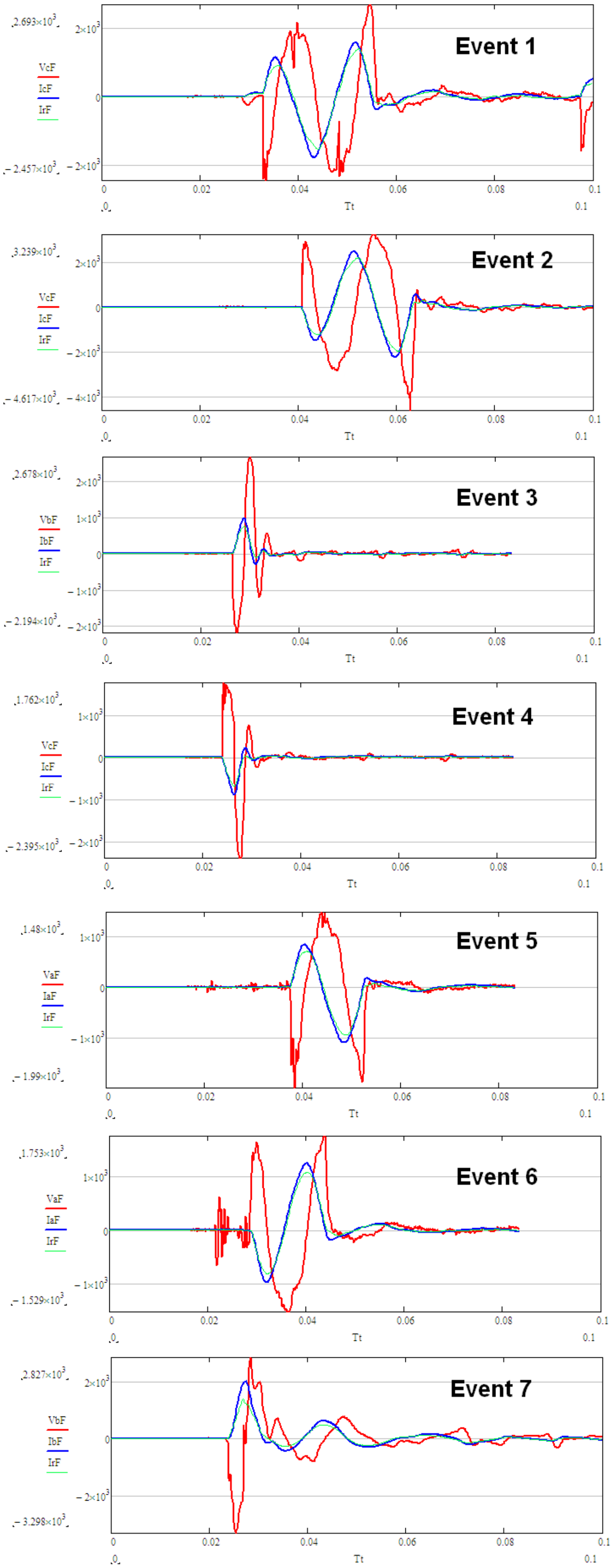

Fig. 9. Waveforms of net fault voltages and net fault currents of the events.

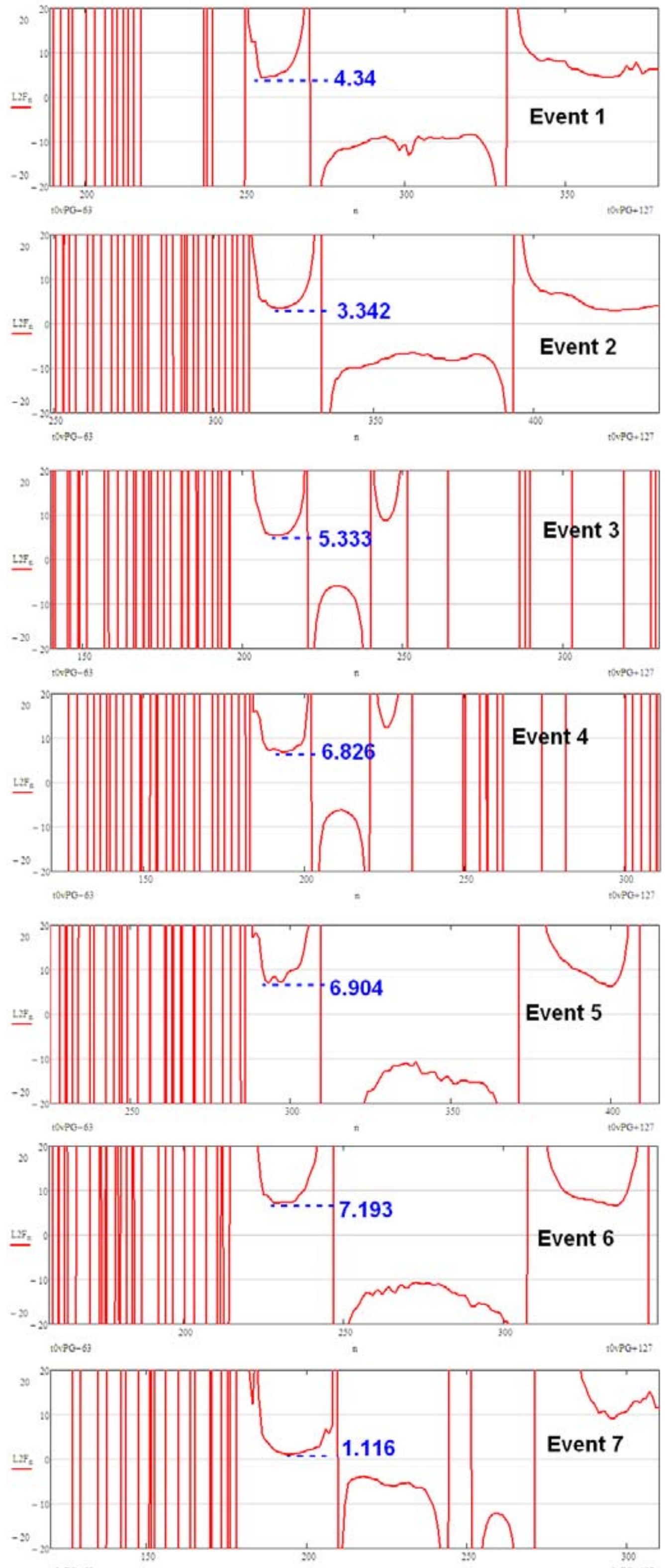

Fig. 10. Fault distance calculation result of each of the seven events.

However, it is clear that the same distanced events do not produce the same reactance values (5.333 for Event 3 and 6.826 for Event 4). Also, even though the farther distance fault of Event 1 has bigger reactance value (4.34) than that of Event 2 (3.342), it is not clear if there is any linear relationship in the reactance value to the distance in mile.

So next we plotted a graph of the calculated fault distance in reactance versus the indicated fault distance in mile (Fig. 11) to see if we can draw relationship between the two and to assess the validity of the fault distance formula developed in the paper. Even though we can say that they are roughly in linear relationship, it is still premature if the "linear" relationship can stand with more event analyses. However, there is promise that the developed formula would help, in the long run, with locating intermittent cable faults before they develop to permanent faults.

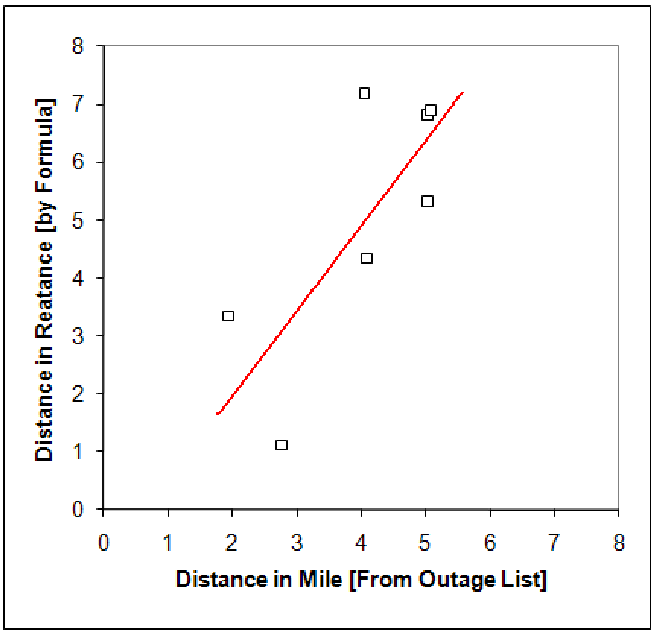

Fig. 11. Calculated fault distance vs. true fault distance

V. Conclusions

We reported the formulation of sub-cycle transitory fault location for all types of faults by employing a time-domain approach with conventional injection method at the faulted location and the superposition principle to calculate the line inductance to the fault using only the voltage and current signals measured at substation. The steps and processes of the formula for practical application was detailed along with preliminary test results with seven actual sub-cycle SLG faults involved in underground cables. The relationship between the calculated reactance to fault and the given fault distance in mile, given in the outage listing, was not clearly determined due to the limited number of events, even though a linear relationship can be claimed to exist. More testing is needed to better assess the validity of the proposed formula for fault distance of sub-cycle faults.

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