A Novel Fault Location Algorithm for Multi-Terminal Transmission Lines without Using Source Impedances

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Presented to the
36th Annual Western Protective Relay Conference
October 20-22, 2009
Spokane, WA, USA

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Abstract

This paper presents a new method to find fault location on a two- or three-terminal transmission line. The method uses phase currents and voltages recorded by digital protection or digital fault recorder at the line terminals. The advantage of the method is that accuracy of calculated fault location is immune to fault resistance and mutual coupling inductance from other paralleling circuits. Positive sequence impedance of the line is only requirement as setting value to locate the fault. The new method has been verified with numerous actual fault data and it can be used to provide efficient tool for line fault patrolling purpose in field.

Keywords: Algorithm, Mutual inductance coupling, Fault location, Transmission line.

1.0 Introduction

There are a great number of digital protections equipped on power transmission lines in Hydro One grid. Fault location scheme has been embedded in typical digital line protections. However, the digital relays often can not report accurate fault location due to many factors, such as fault resistance, zero sequence mutual inductance coupling, multi-terminal sources in-feeding and etc.

Even though many methods have been developed to locate the fault, Takigi algorithm based on single-ended voltage and current is a standard solution in most of digital line protections [1]. The method generally uses voltages and currents at the relay location of one side of the line. Information from remote end is not used due to unavailable communication or other factors. The advantage of the single-ended method is that the relay can report fault location immediately after the fault occurs. The disadvantage of the method is that a significant estimate error appears when mutual coupling between paralleling circuits or other factor mentioned above exists. The error of reported results is often too high to be acceptable for fault patrolling purpose.

Many algorithms have been proposed to compensate or model the effect of mutual coupling from other lines. However, the mutual coupling effect is a very complex issue. At Hydro One, it is very common that more than two circuits parallel with each other. The paralleling circuit may have different voltage levels. They also do not parallel in entire way of line in fact. It also is not feasible to introduce current or voltage from other circuit to relay at faulted circuit. These factors make it very difficult to model or compensate effect of mutual coupling from other circuits.

[2] proposed a fault location algorithm for parallel lines based on negative sequence currents and voltages from each terminal. It is very obvious that the calculation result is

immune to mutual coupling from other lines. However, the algorithm uses source impedances behind the digital protection at each terminal. For a complex transmission grid, the source impedance may not be a fixed parameter like line impedance. The equivalent source impedance varies with fault location. Deviation on setting will result in significant calculation error.

This paper proposes a new algorithm for fault location for two- or three-terminal transmission lines. The algorithm uses currents and voltages recorded by digital protection relays or digital fault recorders at each end of the line. The accuracy of calculated fault location is not affected by fault resistance and mutual coupling inductance from other paralleling circuits. Only positive sequence impedance of lines is required as unique setting value.

Even though the algorithm uses fault data from remote terminals, synchronization of sampling is not required as the proposed method provides a way of aligning the asynchronous sampling data from relay at each terminal. The fault data can be obtained from different types of microprocessor-based relays or digital fault recorders.

Unlike some of other algorithms based on mutual coupling model, this algorithm is built to eliminate effect of mutual coupling from other circuit. Therefore, accuracy of model of mutual coupling does not affect result of the fault location.

The new algorithm is mainly used for offline calculation of fault location. It has been validated with numerous actual fault data.

Because both phase-to-phase fault and three-phase fault do not create trouble for fault location calculation, only single phase to ground fault is discussed in this paper.

2.0 Fault Location Algorithm for Two-Ended Circuit

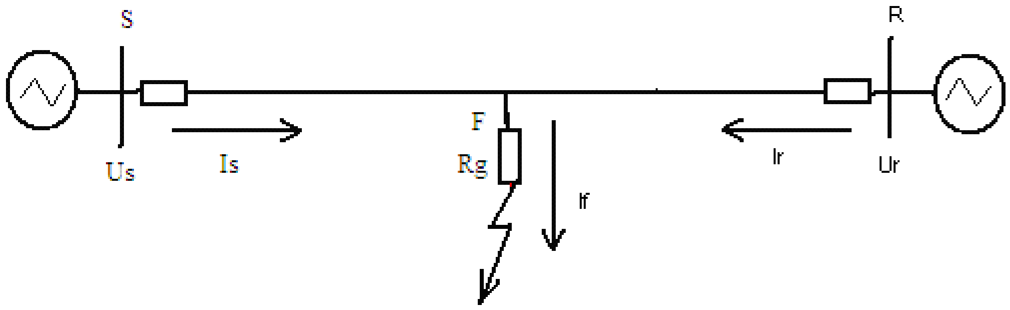

Figure 1 Two-Ended System

For a two-ended line as shown in Figure 1,
At terminal S:

$$U_{\varphi FS} = U_{\varphi S} - I_{\varphi S} \cdot mZ_{1L} \tag{1}$$

At terminal R:

$$U_{\varphi FR} = U_{\varphi R} - I_{\varphi R} \cdot (1-m)Z_{1L} \tag{2}$$

Where, for single phase to ground fault, e.g., AG fault,

$$\begin{aligned} U_{\varphi FS} &= U_{AFS} - U_{0FS} = U_{1AFS} + U_{2AFS} \\ U_{\varphi FR} &= U_{AFR} - U_{0FR} = U_{1AFR} + U_{2AFR} \\ U_{\varphi S} &= U_{AS} - U_{0S} = U_{1AS} + U_{2AS} \\ U_{\varphi R} &= U_{AR} - U_{0R} = U_{1AR} + U_{2AR} \\ I_{\varphi S} &= I_{AS} - I_{0S} = I_{1AS} + I_{2AS} \\ I_{\varphi R} &= I_{AR} - I_{0R} = I_{1AR} + I_{2AR} \end{aligned} \tag{3}$$

Subscripts 0, 1 and 2 in (3) and later equations stand for zero, positive and negative sequences respectively. mZ_{1L} is positive sequence line impedance between terminal S and fault point F. At the point F, voltage calculated with fault data recorded by relay S and R must be equal. After considering alignment of relay S and R data, we have

$$U_{\varphi S} - I_{\varphi S} \cdot mZ_{1L} = (U_{\varphi R} - I_{\varphi R} \cdot (1-m)Z_{1L}) \cdot e^{j\delta} \tag{4}$$

Where, δ is sampling synchronization compensation angle between two terminals. It represents phase difference between data sampled by two relays sample to a voltage or current. δ keeps unchanged as power load varies and fault occurs if every digital protection uses a fixed sampling rate.

Sampling synchronization compensation angle δ can be calculated by using non-faulted phase quantities.

$$U_{\Psi S} - I_{\Psi S} \cdot Z_{1L} = U_{\Psi R} \cdot e^{j\delta} \tag{5}$$

For example, for phase A to ground fault,

$$\begin{aligned} U_{\Psi S} &= U_{BS} - U_{CS} = (a^2 - a) \cdot (U_{1S} - U_{2S}) \\ I_{\Psi S} &= I_{BS} - I_{CS} = (a^2 - a) \cdot (I_{1S} - I_{2S}) \\ U_{\Psi R} &= U_{BR} - U_{CR} = (a^2 - a) \cdot (U_{1R} - U_{2R}) \end{aligned} \tag{6}$$

Therefore,

$$e^{j\delta} = \frac{U_{\Psi S} - I_{\Psi S} \cdot Z_{1L}}{U_{\Psi R}} \tag{7}$$

Similarly, we can calculate δ for phase B or C to ground fault.

From (4), we have,

$$m = \frac{U_{\varphi S} - (U_{\varphi R} - I_{\varphi R} \cdot Z_{1L}) \cdot e^{j\delta}}{(I_{\varphi S} + I_{\varphi R} \cdot e^{j\delta}) \cdot Z_{1L}} \tag{8}$$

According to (7) and (8), it is not necessary to calculate value of δ because only $e^{j\delta}$ instead of δ is needed in (8).

Because both zero sequence voltage and current have been eliminated in (3) and (6), only positive and negative sequence quantities are used to assess the fault location, mutual coupling from other circuit does not influence accuracy of fault location. Therefore, the algorithm is suitable for both simple single line and line with other paralleling circuit nearby.

Equation (4) is satisfied without assuming any condition about fault resistance at fault point. Therefore, accuracy of this algorithm is not influenced with fault resistance. From (4) and (8), it is very apparent that positive sequence line impedance Z_{1L} is unique setting value.

3.0 Algorithm to Three-Terminal Line

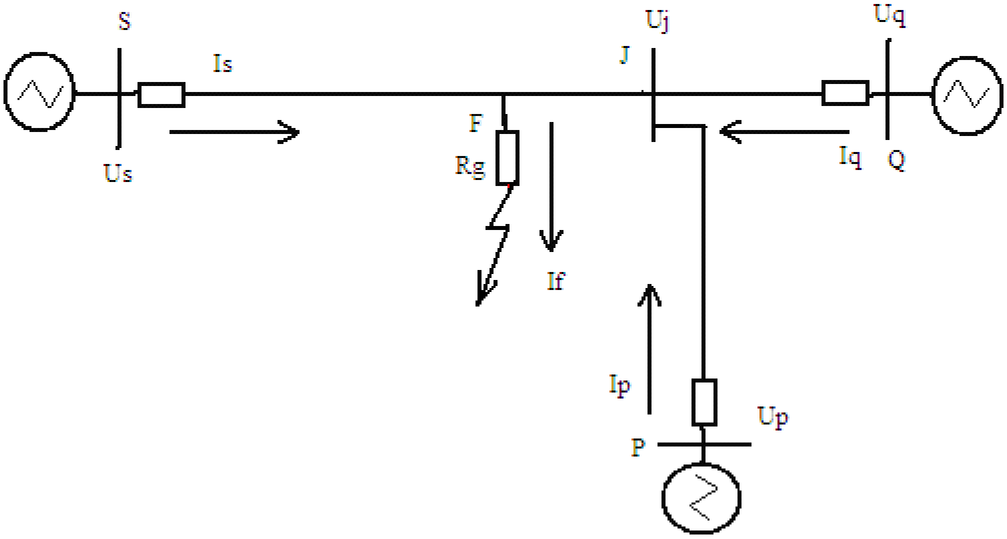

Figure 2 Three-Terminal Power Transmission System

3.1 Faulted Section Selection

For a three-terminal transmission system as shown in Figure 2, first step is to find faulted section. When a fault occurs on section S-J, joint point J voltages calculated with sampling data from terminals P and Q are same as actual voltage. However, calculated voltage of J point based on sampling data of relay at Terminal S is different from actual voltage because the fault insolates two points. The nearer the fault to terminal S, the greater the difference between actual voltage and calculated voltage is. Therefore, faulted section can be selected by method below.

At Terminal S:

$$U_{\varphi JS} = U_{\varphi S} - I_{\varphi S} \cdot Z_{1LS} \qquad (9)$$

At Terminal P:

$$U_{\varphi JP} = U_{\varphi P} - I_{\varphi P} \cdot Z_{1LP} \qquad (10)$$

At Terminal Q:

$$U_{\varphi JQ} = U_{\varphi Q} - I_{\varphi Q} \cdot Z_{1LQ} \qquad (11)$$

Where, for single phase to ground fault, e.g., AG fault,

$$\begin{gathered}
U_{\varphi JS} = U_{AJS} - U_{0JS} = U_{1AJS} + U_{2AJS} \\
U_{\varphi JP} = U_{AJP} - U_{0JP} = U_{1AJP} + U_{2AJP} \\
U_{\varphi JQ} = U_{AJQ} - U_{0JQ} = U_{1AJQ} + U_{2AJQ} \\
U_{\varphi S} = U_{AS} - U_{0S} = U_{1AS} + U_{2AS} \\
U_{\varphi P} = U_{AP} - U_{0P} = U_{1AP} + U_{2AP} \\
U_{\varphi Q} = U_{AQ} - U_{0Q} = U_{1AQ} + U_{2AQ} \\
I_{\varphi S} = I_{AS} - I_{0S} = I_{1AS} + I_{2AS} \\
I_{\varphi P} = I_{AP} - I_{0P} = I_{1AP} + I_{2AP} \\
I_{\varphi Q} = I_{AQ} - I_{0Q} = I_{1AQ} + I_{2AQ}
\end{gathered} \tag{12}$$

From Figure 2, if a fault falls on section SJ, then

$$||U_{\varphi JS}| - |U_{\varphi JQ}|| > ||U_{\varphi JP}| - |U_{\varphi JQ}|| < ||U_{\varphi JS}| - |U_{\varphi JP}|| \tag{13}$$

Similarly, if a fault falls on section PJ, then

$$||U_{\varphi JP}| - |U_{\varphi JQ}|| > ||U_{\varphi JS}| - |U_{\varphi JQ}|| < ||U_{\varphi JS}| - |U_{\varphi JP}|| \tag{14}$$

Similarly, if a fault falls on section QJ, then

$$||U_{\varphi JQ}| - |U_{\varphi JS}|| > ||U_{\varphi JS}| - |U_{\varphi JP}|| < ||U_{\varphi JQ}| - |U_{\varphi JP}|| \tag{15}$$

If a fault exactly falls on junction J, then

$$|U_{\varphi JQ}| = |U_{\varphi JS}| = |U_{\varphi JP}| \tag{16}$$

When a fault does not fall on any of three line sections, (16) also is satisfied. However, it is not a problem because we will not start calculation of fault location if the fault does not occurs on this circuit.

3.2 Fault Location Algorithm for Three-Terminal Circuit

Similarly with two-terminal system, we can align voltage and current at three ends with non-faulted phase sampling data as below. Let us take a phase A to ground fault as an example.

At terminal S:

$$U_{\Psi JS} = U_{BCS} - I_{BCS} \cdot Z_{1LS} \tag{17}$$

At terminal P:

$$U_{\Psi JP} = U_{BCP} - I_{BCP} \cdot Z_{1LP} \tag{18}$$

At terminal Q:

$$U_{\Psi JQ} = U_{BCQ} - I_{BCQ} \cdot Z_{1LQ} \tag{19}$$

Where, $U_{\Psi JS}$, $U_{\Psi JP}$ and $U_{\Psi JQ}$ are voltages of joint point J calculated with voltage and current samplings of terminals S, P and Q respectively.

If we take terminal S as reference, we have

$$U_{\Psi JP} = U_{\Psi JS} \cdot e^{jp}$$

$$U_{\Psi JQ} = U_{\Psi JS} \cdot e^{jq}$$

That is,

$$e^{jp} = U_{\Psi JP} / U_{\Psi JS} \tag{20}$$

$$e^{jq} = U_{\Psi JQ} / U_{\Psi JS} \tag{21}$$

If a fault occurs on line section SJ, we can establish fault equation similar with (4),

$$U_{\varphi S} - I_{\varphi S} \cdot mZ_{1L} = U_{\varphi J} - I_{\varphi J} \cdot (1-m)Z_{1L} \tag{22}$$

Where,

$$U_{\varphi J} = \frac{1}{2}(U_{\varphi JP} \cdot e^{-jp} + U_{\varphi JQ} \cdot e^{-jq}) \tag{23}$$

$$I_{\varphi J} = I_{\varphi P} \cdot e^{-jp} + I_{\varphi Q} \cdot e^{-jq} \tag{24}$$

From (22), fault location can be found as below.

$$m = \frac{U_{\varphi S} - (U_{\varphi J} - I_{\varphi J} \cdot Z_{1LS})}{(I_{\varphi S} + I_{\varphi J})Z_{1LS}} \tag{25}$$

Similarly, we can find the fault location when a fault happens on other sections.

4.0 Examples

The fault location algorithms proposed above are validated with actual fault data recorded by micro-processor-based line protection in Hydro One grid. Fault causes actually were found according to re-calculation result.

4.1 115kV Three-Terminal Parallel Transmission Lines

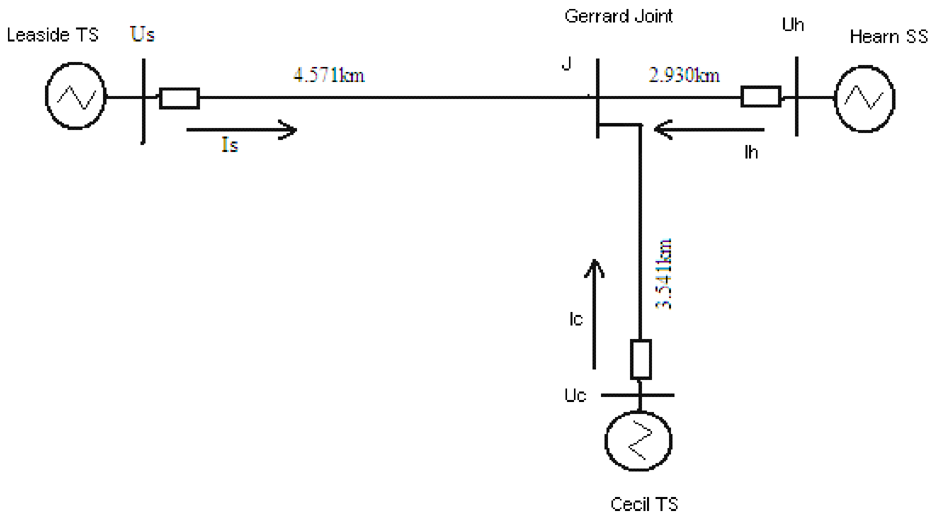

Figure 3 Three-Terminal Parallel Circuits

A single phase C to ground fault occurred on 115kV circuit as shown in Figure 3. Other parallel lines are not shown.

Fault location results reported by digital line protections at each terminal were:

Leaside TS: 7.87km;

Hearn SS: 2.80km;
Cecle TS: 1.66km.

Because three relays indicated conflict fault location results, the new algorithm was used to re-calculate the fault. The fault was found according to new calculation result. Following shows some faulted section decision and fault location result.

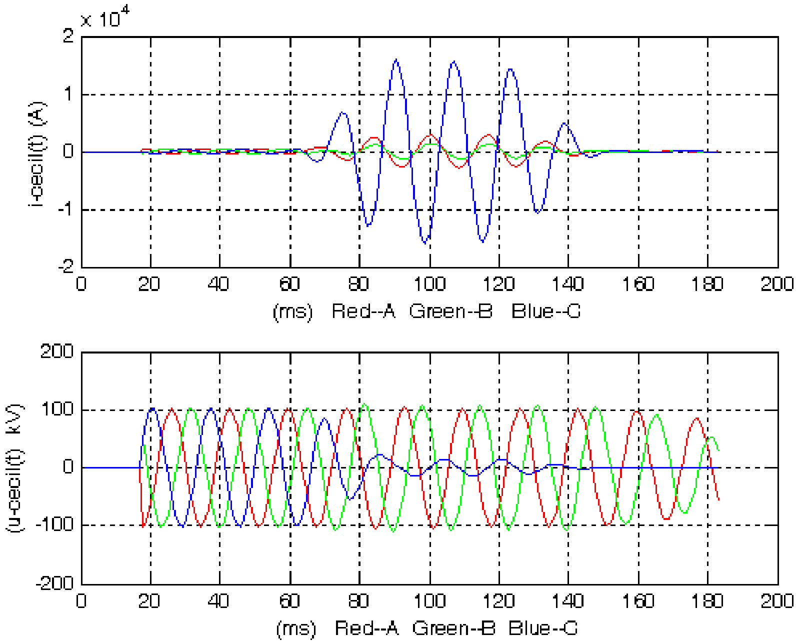

Figure 4.a Currents and Voltages at Cecil

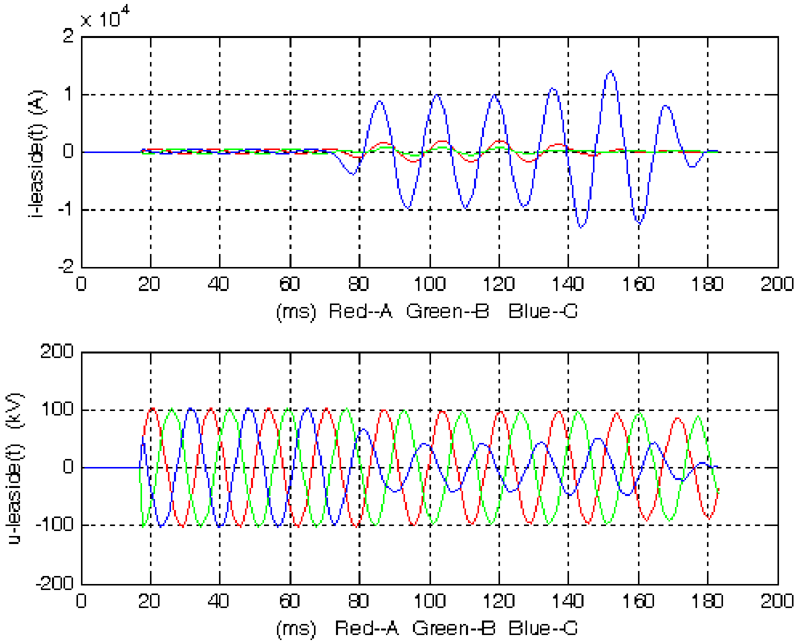

Figure 4.b Currents and Voltages at Leaside

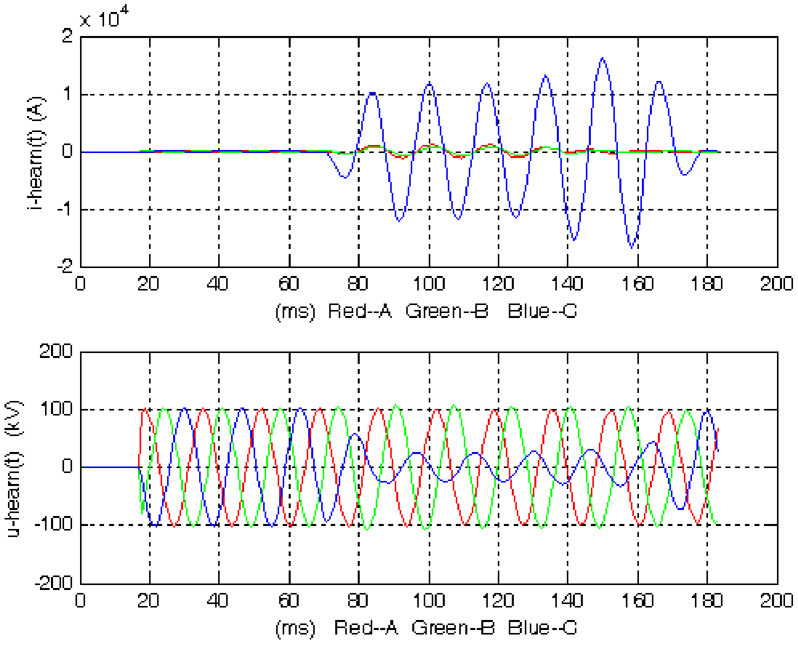

Figure 4.c Currents and Voltages at Hearn

The fault voltages and currents recorded by protections at three terminals were shown in Figure 4a, 4b and 4c.

Figure 5 shows non-faulted phase voltages at Joint Gerrard calculated with sampling data from each terminal by using (17), (18) and (19). The top waveforms are instantaneous values and low waveforms are magnitude values of the voltages.

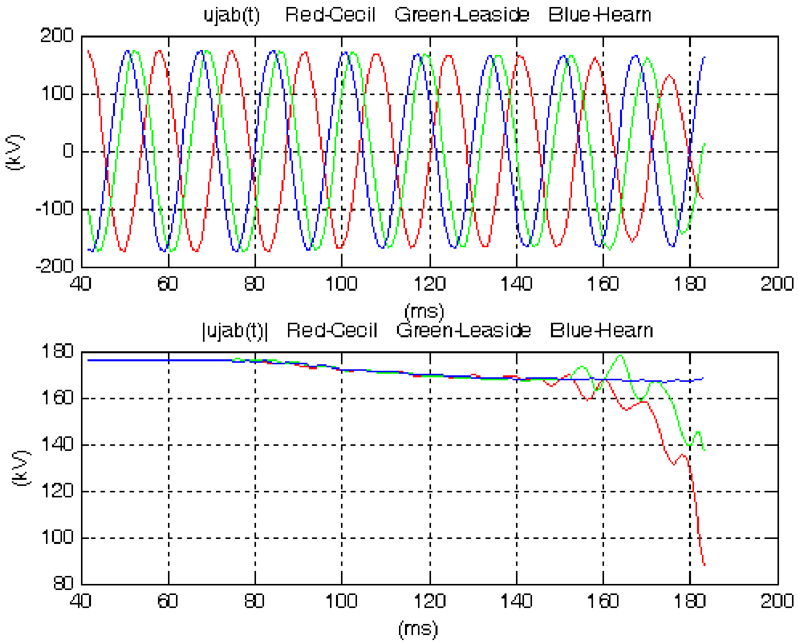

Figure 5 Joint Point Voltage Calculated from Each Terminal

From the waveforms, it is very clear that the calculated voltages have same magnitude but with different phase angles. It is necessary to align them according to (20) and (21) for next step of fault calculation.

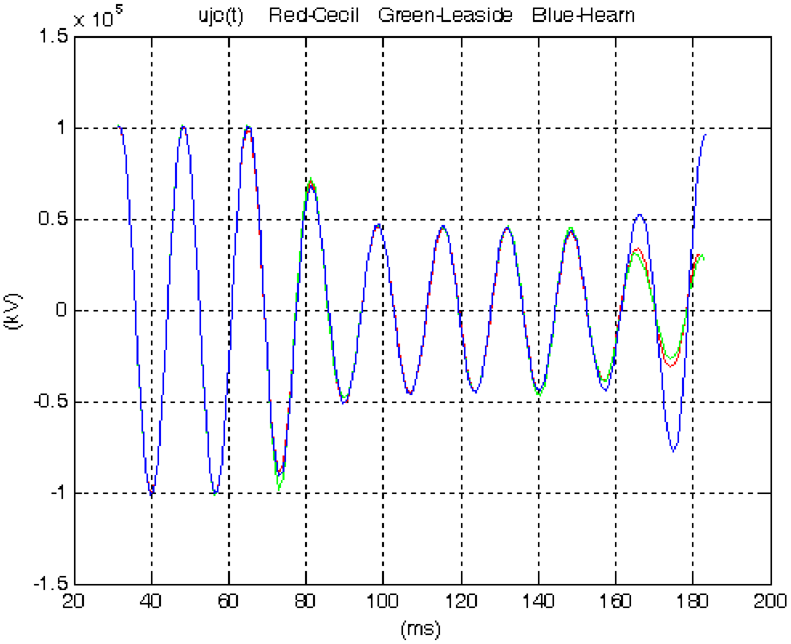

Figure 6 Aligned Currents and Voltages of Joint Point

Faulted phase voltages at Joint Point Figure 6 have been compensated with sampling synchronization angles according to (20) and (21). The three voltages almost completely overlap. According to (16), the fault should falls around Joint point.

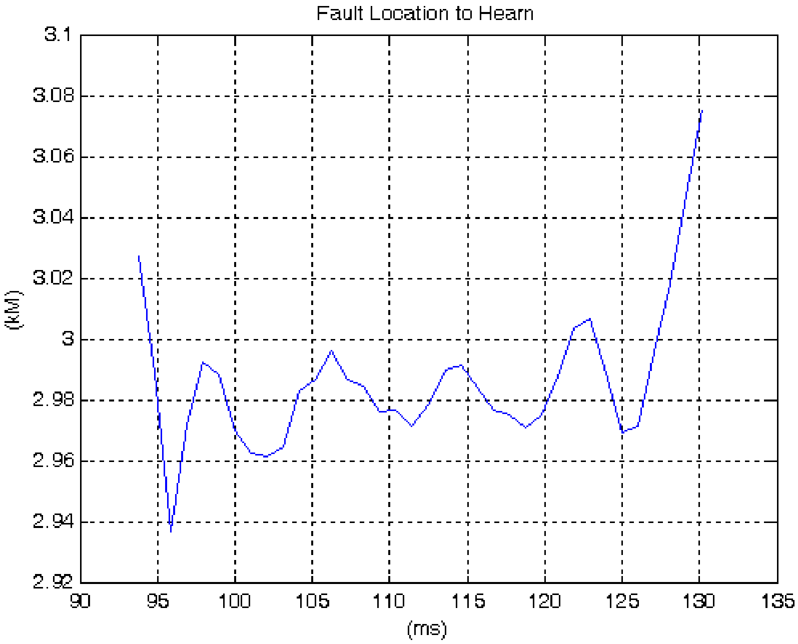

Figure 7 Fault Location to Hearn

In order to verify how far the fault is to the Joint, Hearn section is chosen to calculate the fault location according to (13)-(15), the final result is shown in Figure 7. The distance between the Joint to the calculated fault location is about 50 meters. Accuracy of calculation is 1.7%. The fault was finally found according to new calculation result at the Joint.

4.2 115 kV Two-Terminal parallel Line with Tapped Load Transformers

On September 3, 2007, line Q5B experienced 4 trips due to faults by lightning. Line configuration is shown in Figure 8. Fault locations reported by digital line protections are in Table 1.

Table 1 Fault Location Results By Line Protection

Fault #	Birch TS (km & %)	Thunder Bay SS (km & %)
1	10.24(75.3%)	10.89(80.1%)
2	10.08(74.1%)	10.62(78.1%)
3	10.00(73.5%)	10.58(77.8%)
4	9.98(73.4%)	10.60(77.9%)

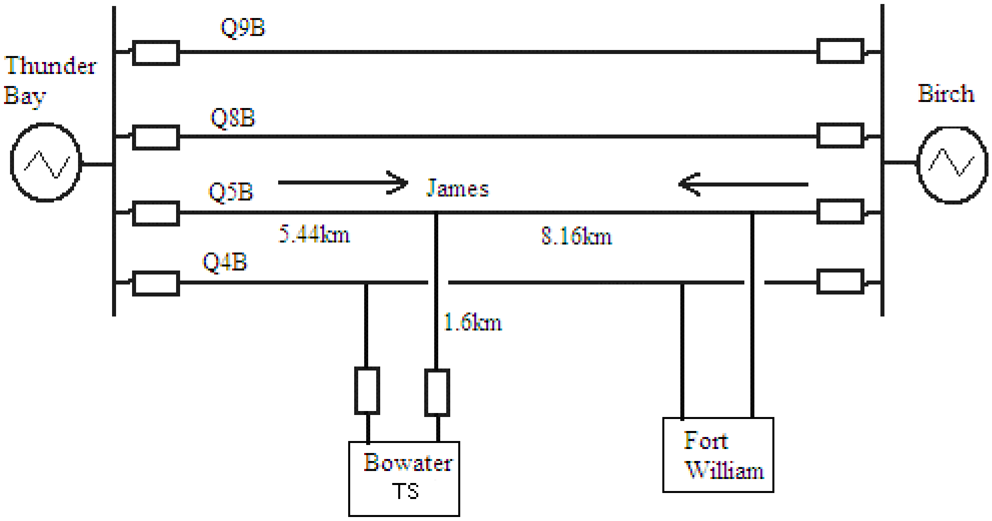

Figure 8 Parallel Lines Q5B with Tapped Load Stations

From Figure 8, it is very clear that results in Table 1 is not acceptable for fault patrolling because sum of distance from fault point to two ends is much larger than line length.

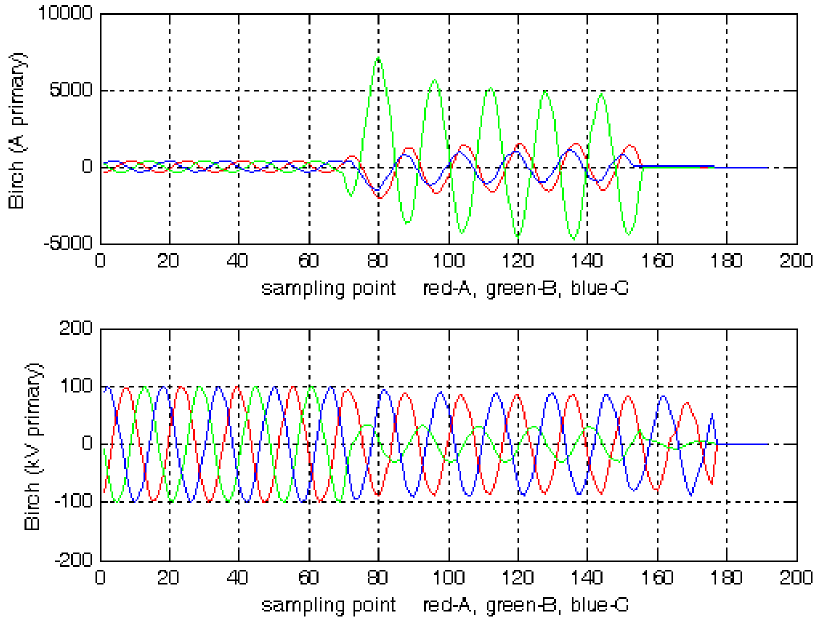

Figure 9 Fault currents and voltages at Birch

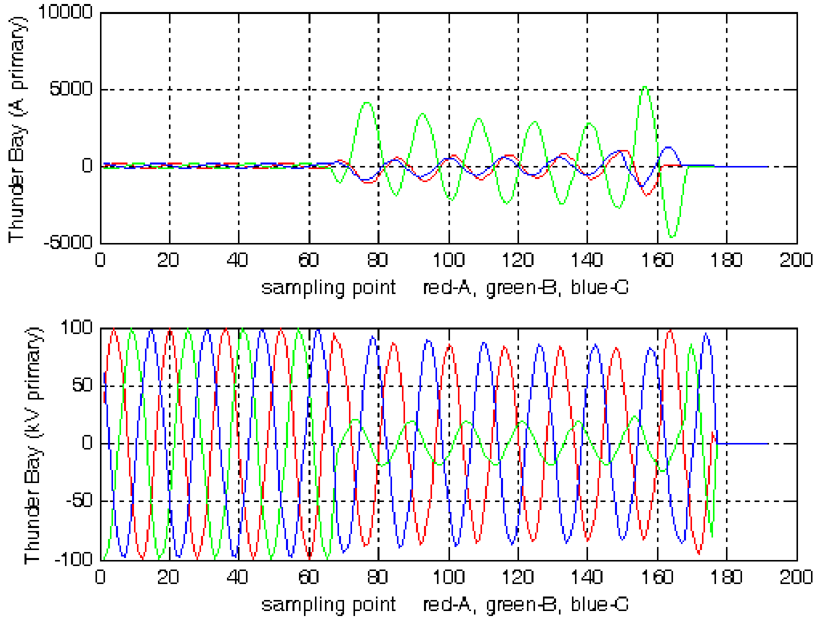

Figure 10 Fault Currents and voltage at Thunder Bay

Because there is no fault data from tapped stations, we recalculated the fault location according to two-ended algorithm (8). New result shown in Figure 11 indicates that the fault should fall around James Joint or the short section of line from the James Joint to Bowater TS.

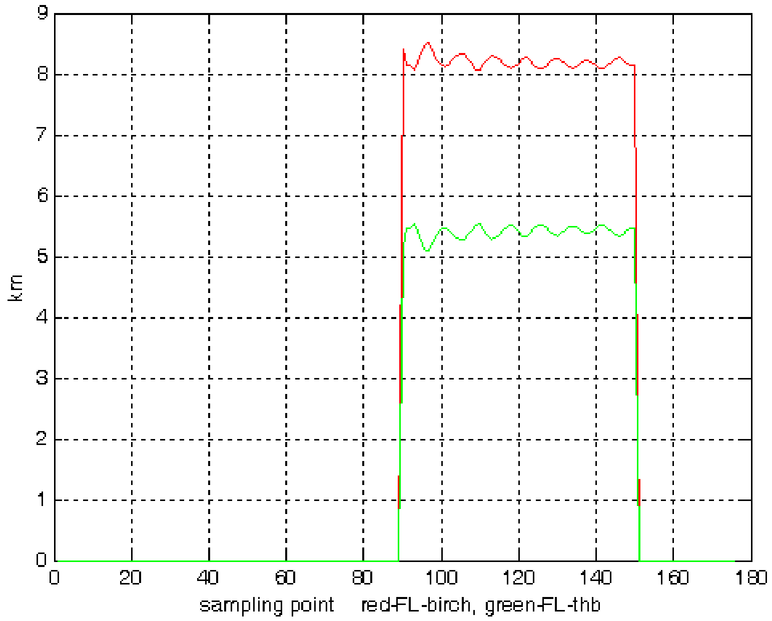

Figure 11 New Calculation Results of Fault Location

If the fault occurs on section between James and Bowater TS, further calculation will be required. Because there was no information from Bowater TS, we will use single-ended Takigi method [1]. The method needs voltage and current at James. We calculate them as below.

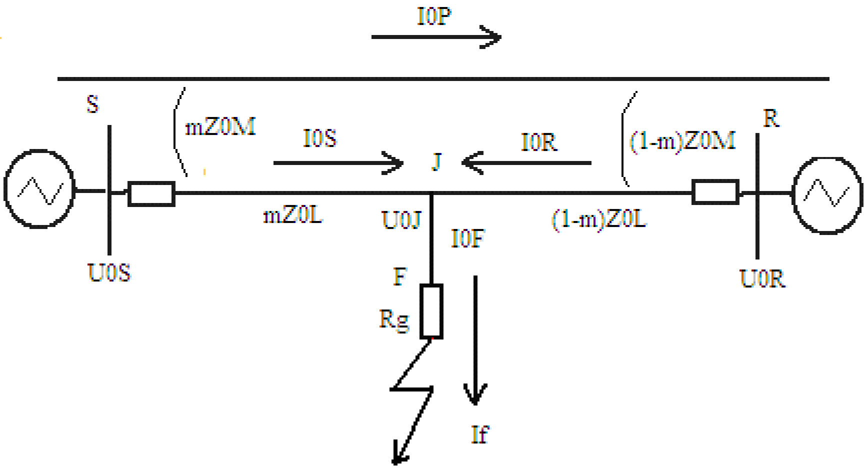

Figure 12 Parallel Line with Tapped Load

In Figure 12, I0P and Z0M represent total equivalent mutual coupling effect from other parallel lines.

For left side of the junction J,

$$U_{0J} = U_{0S} - mI_{0S} \cdot Z_{0L} - mI_{0P} \cdot Z_{0M} \qquad (26)$$

For right side of the junction J,

$$U_{0J} = U_{0R} - (1-m)I_{0R} \cdot Z_{0L} + (1-m)I_{0P} \cdot Z_{0M} \qquad (27)$$

Here, m is ratio of distance between J and S to whole line length. m is a known constant. For convenience on writing, all voltages and currents have been compensated by sampling synchronism angle.

Because both I_{0P} and Z_{0M} are mysterious to us, they should be eliminated. From (26) and (27), we have,

$$U_{0J} = (1-m)U_{0S} + mU_{0R} - m(1-m)(I_{0S} + I_{0R}) \cdot Z_{0L} \qquad (28)$$

Therefore, voltage and current to fault point at the junction J are

$$\begin{aligned} U_J &= (U_J - U_{0J}) + U_{0J} \\ &= \frac{(U_{\varphi S} - U_{0S}) - (I_{\varphi S} - I_{0S}) \cdot mZ_{1L} + (U_{\varphi R} - U_{0R}) - (I_{\varphi R} - I_{0R}) \cdot (1-m)Z_{1L}}{2} + U_{0J} \\ I_{J12} &= I_{1J} + I_{2J} = I_{\varphi S} - I_{0S} + I_{\varphi R} - I_{0R} \\ I_f &= I_{0J} = I_{0S} + I_{0R} \end{aligned} \qquad (29)$$

Fault location from the junction J can be found according to Takigi method [1],

$$\mathrm{Im}\left(\frac{U_J}{I_f}\right) = n \cdot \mathrm{Im}\left(\frac{I_{J12}}{I_f} \cdot Z_{1J} + Z_{0J}\right) \qquad (30)$$

That is,

$$n = \frac{\mathrm{Im}\left(\frac{U_J}{I_f}\right)}{\mathrm{Im}\left(\frac{I_{J12}}{I_f} \cdot Z_{1J} + Z_{0J}\right)} \qquad (31)$$

Here, Z_{1J} and Z_{0J} are total positive and zero sequence impedances from J to the transformer terminal at the tapped load station. Im in (30) and (31) stands for imaginary part of a complex number.

n is percentage distance from the junction J to fault point.

Because we already consider the effect of other parallel circuits in (26) and (27), result of fault location from (31) should be accurate.

Maximum zero sequence current will flow on this faulted section. Mutual coupling from other circuit to the short faulted line shall be ignorable. The calculation result is shown in Figure 13. It is very close to 1.6 km. The fault was finally located at end of the circuit at Bowater. The calculated location is exactly same as real fault point.

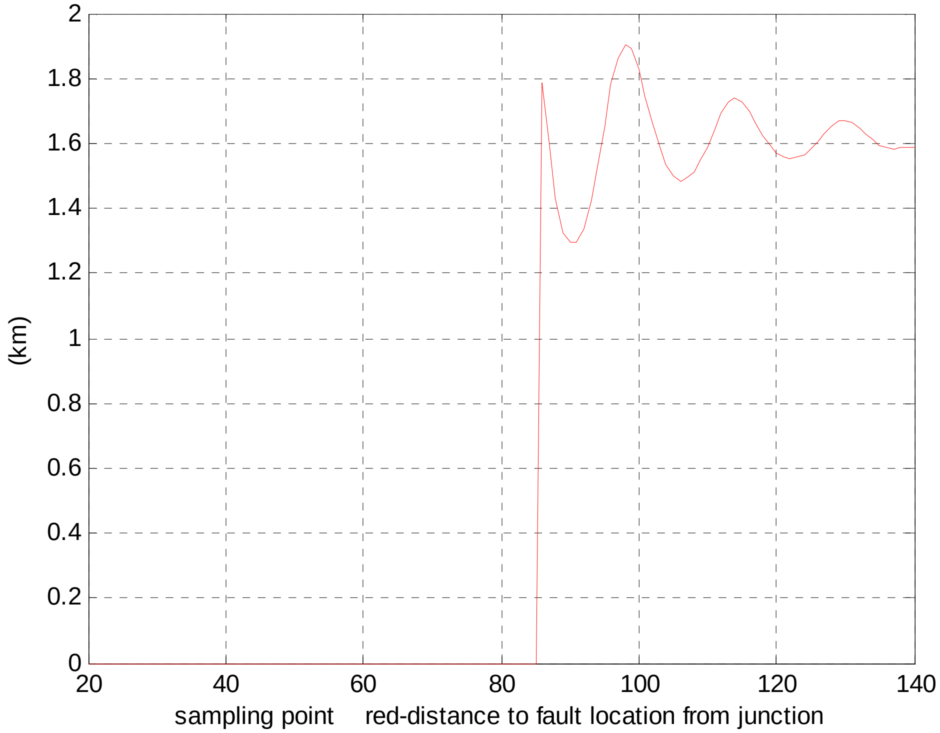

Figure 13 Final Calculation Result of Fault Location

5.0 Conclusions

A new algorithm of fault location is developed for two- or three-terminal circuits. It has following advantages:

1. It uses samplings of phase voltages and currents from each terminal of the line. Synchronization of sampling is not required. Therefore, it is not necessary to install additional synchronization devices.
2. An Alignment algorithm of the samplings is proposed to compensate sampling synchronization angle. The algorithm uses non-faulted phase current and voltage so that the higher compensation accuracy can be guaranteed because non-faulted phase voltage has higher value.
3. The algorithm does not need source impedances behind the relays. Positive sequence impedance of line is only requirement for fault location calculation.
4. The new algorithm is not influenced with fault resistance, mutual coupling from other lines.
5. The algorithm of fault location can be used to accurately measure fault location for two or three terminals circuit with or without parallel circuit.

The algorithm of fault location has been verified with numerous actual fault data and simulation with high accuracy. Therefore, it can be used as a tool for fault patrolling purpose.

6.0 Acknowledgement

The Authors would appreciate Dr. Lianxiang Tang and Dr. Marti Luis for reviewing earlier version of this paper.

7.0 References

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8.0 Biographies

Fenghai Sui joined in Hydro One Networks Inc. in 2006. Before he came to Canada, Mr. Sui worked in Nanjing Automation Research Institute (NARI), China as a senior protection development engineer. He currently is a network management engineer in Hydro One Inc, Ontario, Canada. Mr. Sui is a registered professional engineer in Ontario. Mr. Sui is a senior IEEE member.

Aaron Cooperberg joined Ontario Hydro (predecessor of Hydro One Inc.) in 1977, working in the protection design group for 21 years. In 1998, he transferred to the newly created Asset Management department at Hydro One as a senior network management engineer. Mr. Cooperberg is currently manager of protection and control planning. He is registered with professional engineers Ontario with a license in protective relaying systems design.

Appendix: Prove Equation (5)

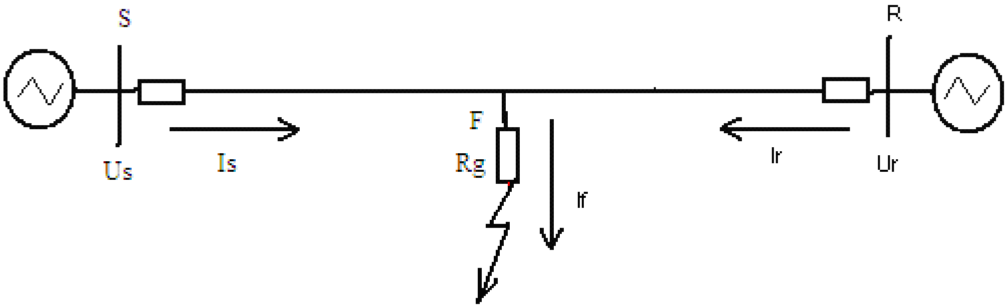

Figure A.1 Two-Terminal System Model

When phase A to ground fault occurs at point F,

$$\begin{aligned}
U_{AS} &= U_{1S} + U_{2S} + U_{0S} \\
U_{BS} &= a^2U_{1S} + aU_{2S} + U_{0S} \\
U_{CS} &= aU_{1S} + a^2U_{2S} + U_{0S} \\
U_{AR} &= U_{1R} + U_{2R} + U_{0R} \\
U_{BR} &= a^2U_{1R} + aU_{2R} + U_{0R} \\
U_{CR} &= aU_{1R} + a^2U_{2R} + U_{0R}
\end{aligned} \qquad \text{(A-01)}$$

$$\begin{aligned}
I_{AS} &= I_{1S} + I_{2S} + I_{0S} \\
I_{BS} &= a^2I_{1S} + aI_{2S} + I_{0S} \\
I_{CS} &= aI_{1S} + a^2I_{2S} + I_{0S} \\
I_{AR} &= I_{1R} + I_{2R} + I_{0R} \\
I_{BR} &= a^2I_{1R} + aI_{2R} + I_{0R} \\
I_{CR} &= aI_{1R} + a^2I_{2R} + I_{0R}
\end{aligned} \qquad \text{(A-02)}$$

For non-faulted phases B and C,

$$\begin{aligned}
I_{BS} + I_{BR} &= 0 \\
I_{CS} + I_{CR} &= 0
\end{aligned} \qquad \text{(A-03)}$$

Therefore,

$$\begin{aligned} U_{BCS} &= U_{BS} - U_{CS} = (a^2 - a)(U_{1S} - U_{2S}) \\ U_{BCR} &= U_{BR} - U_{CR} = (a^2 - a)(U_{1R} - U_{2R}) \\ I_{BCS} &= I_{BS} - I_{CS} = (a^2 - a)(I_{1S} - I_{2S}) \\ I_{BCR} &= I_{BR} - I_{CR} = (a^2 - a)(I_{1R} - I_{2R}) \end{aligned} \quad \text{(A-04)}$$

$$I_{BCS} + I_{BCR} = 0 \quad \text{(A-05)}$$

$$U_{BCS} - I_{BCS} \cdot mZ_{1L} + I_{BCR} \cdot (1-m)Z_{1L} = U_{BCR} \quad \text{(A-06)}$$

That is,

$$U_{BCS} - I_{BCS} \cdot Z_{1L} = U_{BCR} \quad \text{(A-07)}$$

After considering sampling synchronism compensation angle, we can obtain equation (5).

As difference values of two phase voltages and currents are used in (A-07), zero sequence current and voltage have fully been eliminated. Therefore, it is very obvious that equation (A-07) will not been affected with mutual coupling from paralleling and fault location on faulted line.