Advanced Line Current Differential Relay with Distance Protection and Adaptive Fault Locator

- Adaptive fault locator using line current differential telecommunication data and distance protection one-terminal data

Hideyuki Takani, Yasutaka Sonobe, Hidenari Amo

TOSHIBA Corporation, Japan

Abstract

A line current differential relay with integrated distance protection can provide an adaptive fault locator which implements both a one-terminal fault location method and a multi-terminal fault location method. The fault locator selects the most suitable fault location method automatically depending on telecommunication conditions and on the fault point. Usually, in case of no telecommunication failure, multi-terminal fault location is selected. The multi-terminal fault location principle is based on a fault-point-voltage determining algorithm using sequence components. Sequence components have the advantage that faulted phase selection is unnecessary, and there is little mutual coupling between parallel lines. In case of a telecommunication failure and a close-up point fault where the one-terminal fault location accuracy is better than that of the multi-terminal method, the one-terminal fault location method is selected adaptively. This paper presents an evaluation of advanced multi-terminal fault location methods and a new fault location algorithm applying adaptive fault location methods.

1. Introduction

Impedance-based fault location functions have generally been integrated into protective relays where voltage and current data from only one terminal are used. At the same time, the line current differential relay has proved to be one of the most successful types of transmission line protection system, providing high-speed and phase-segregated protection for use with telecommunication systems. More recently, using novel relaying and communication technologies, the line current differential relay has incorporated charging current compensation, GPS synchronization, back-up distance protection, and also IEC 61850 communication functions.

A line current differential relay with integrated distance protection can provide an adaptive fault locator which implements both a one-terminal fault location method and a multi-terminal fault location method. The fault locator selects the most suitable fault location method automatically depending on telecommunication conditions and on the fault point. Usually, in case of no telecommunication failure, multi-terminal fault location is selected. The multi-terminal fault location principle is based on a fault-point-voltage determining algorithm using sequence components made from two phase to phase electrical quantities. Sequence components have the advantage that faulted phase selection is unnecessary, and there is little mutual coupling between parallel lines. In case of a telecommunication failure and a close-up point fault where the one-terminal fault location accuracy is better than that of the multi-terminal type, the one-terminal fault location method is selected adaptively.

This paper introduces the method and accuracy of a fault locator based on the data of a line current differential relay. The fault locator employs a locating system which uses the positive sequence component at both terminals of the transmission line and is capable of locating fault points in any modes. It accomplishes a high accuracy fault location without being adversely affected by the resistance at the fault point.

This fault locator has the following functions:

- Acquisition of three-phase current data and positive sequence voltage data in both line current differential relay terminals.
- Conversion of the voltage drop component of the line to positive sequence quantities.
- Calculation of the fault location using positive sequence quantities and line parameters.

High accuracy fault location is required as the locator plays and important role in the support of inspection and routine maintenance of transmission lines. In relation to the location accuracy, we have successfully attained sufficient accuracy for practical purposes using only the electric quantities of the protected line in the case of parallel transmission lines. In this paper, the authors explain the locating system using positive sequence quantities at both terminals of the transmission line and the results of a study conducted with the emphasis placed on:

i) Location accuracy, and

ii) Simplification of system configuration,

in relation to the method of compensation of the mutual inductive component from the adjacent line when it is applied to parallel transmission lines, based upon the results of verification by simulation.

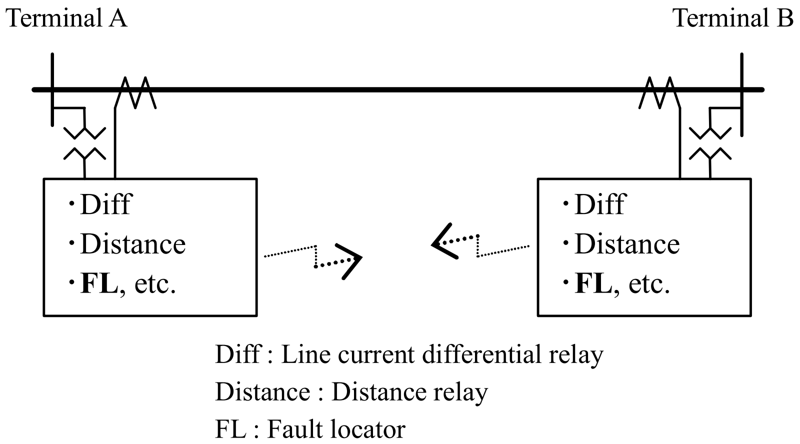

Figure 1. Fault locator based on the data of line current differential relay and distance relay

2. Advanced Multi-terminal Fault Location Method

2.1 Basic principle of multi-terminal fault location method

Present communications technology allows for use of data from all terminals of the transmission line. Multi-terminal fault location techniques are based on the following two-terminal approach. This technique uses the voltage from two terminals and the current data from all terminals of the transmission line. Eliminating the fault point voltage, the distance to the fault point x is given by the equation (1) or (2).

$$x = \frac{[V_A]_S - [V_B]_S + l \cdot \left[R \cdot \Sigma I_B + L \cdot \frac{d\Sigma I_B}{dt} \right]_S}{\left[R \cdot (\Sigma I_A + \Sigma I_B) + L \cdot \frac{d(\Sigma I_A + \Sigma I_B)}{dt} \right]_S} \quad (1)$$

or

$$x = \frac{\Delta[V_A]_S - \Delta[V_B]_S + l \cdot \Delta\left[R \cdot \Sigma I_B + L \cdot \frac{d\Sigma I_B}{dt} \right]_S}{\Delta\left[R \cdot (\Sigma I_A + \Sigma I_B) + L \cdot \frac{d(\Sigma I_A + \Sigma I_B)}{dt} \right]_S} \quad (2)$$

where, x : distance to the fault point
V_A : voltage at terminal A
V_B : voltage at terminal B
I_A : current at terminal A
I_B : current at terminal B
$[\ ]_S$: symmetrical transfer component
Δ : transverse difference component of double circuit lines
L : line length
Σ : total component
R,L : line parameter per unit length

The differential components of equations (1) and (2) are calculated by an improved differential algorithm. The multi-terminal algorithm shown in equation (1) is applied for simple faults on single lines or multiple faults on double circuit lines. The multi-terminal algorithm shown in equation (2) is applied to simple faults on double circuit lines.

2.2 Location systems

Location systems are generally divided into two groups according to the electric quantity used: Systems which use the electric quantities of only one terminal and systems which use the electric quantities of both terminals of the transmission line.

Systems that use the electric quantities of only one terminal perform the location function using the electric quantities of each phase separately. Discrimination of the fault mode is essential and high accuracy location requires to remove the effects of load current and resistance at the fault point. In particular, the effect of "remaining voltage at the fault point due to the resistance at the fault point" is significant as a cause of error. Very large errors may result from multiple faults at different points on parallel lines, where the effect of the mutual inductive component from the adjacent line is significant.

Systems that use the electric quantities of both terminals of a transmission line, as compared with the above, use the fact that the voltage at the fault point as viewed from each terminals is identical, based upon Kirchhoff's law, and are in principle capable of completely removing the effect of remaining voltage at the fault point.

Whereas the system based on the electric quantities of only one terminal is realizable by intake of the electric quantity from the local terminal only, the system using the electric quantities at all terminals requires a means to acquire data of electric quantities from the remote terminals. This requirement is met by simply employing the line current differential relay as shown in the present paper.

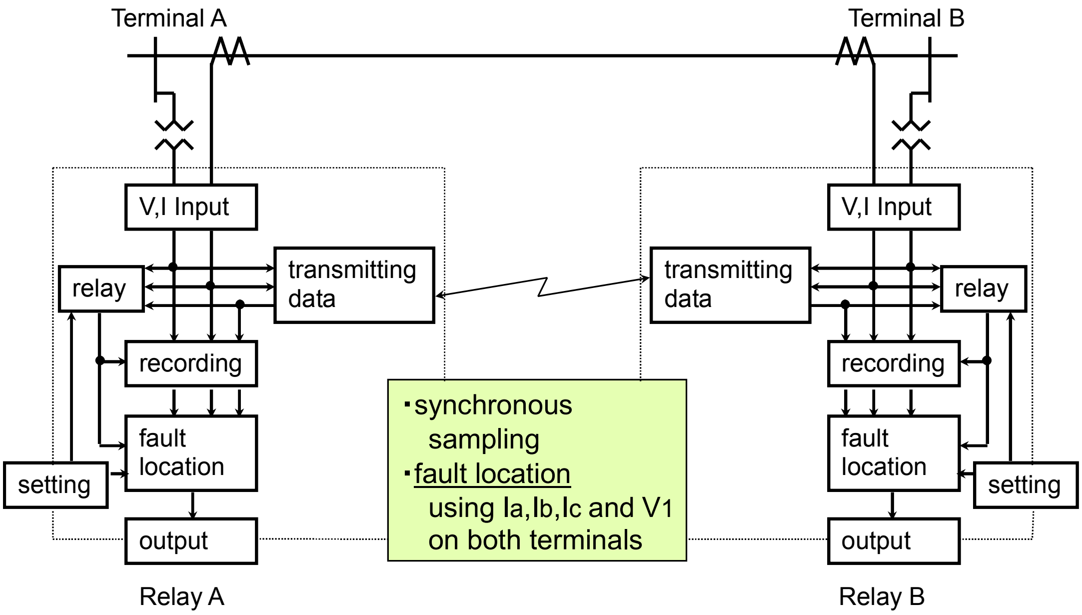

Figure 2. System configuration

Frame header	I_a	I_b	I_c	V_1	I_0	Control data	CRC

Figure 3. Data transmission format

2.3 Advanced location principle using positive sequence quantities at both terminals

The largest factor contributing to error, "remaining voltage at fault point" is completely removed by the method which uses the electric quantities of both terminals of a transmission line. Further, several advantages are attained by use of the positive sequence quantity as follows:

i) Functions to discriminate the mode and phase of fault are not required,
ii) Effects of the mutual inductive component from the adjacent circuit are small. Therefore, the location error is small even when using the positive sequence quantity on asymmetric parallel transmission lines, provided that the degree of asymmetry is small.
iii) Error in location of fault point is small in the case of multiple faults on double-circuit parallel lines. In particular, no error is caused in the case of symmetric transmission lines, theoretically.

Although use of the negative sequence quantity or the zero sequence quantity is conceivable in these cases, it is impossible to extract the negative sequence quantity in the case of a three-phase balanced fault or the zero sequence in a short-circuit fault. The positive sequence quantity can be extracted in all modes of fault.

The method estimates fault location "d" on a transmission line. Voltage and current from both terminals of the protected line are required. In case of the simplest single circuit two-terminal transmission line, the voltage at the fault point [VF] can be determined by using voltages and currents of local end A and remote end B, as follows:

$$[VF] = [VA] - \quad d\,[Z][IA] \tag{(3)-1}$$

$$[VF] = [VB] - (L - d)[Z][IB] \tag{(3)-2}$$

where, d :Distance from local end to fault point

L :Total span length of the transmission line

[VF] :Voltage of each phase at the fault point

[VA] :Voltage of each phase on fault of local end

[VB] :Voltage of each phase on fault of remote end

[IA] :Current of each phase on fault of local end

[IB] :Current of each phase on fault of remote end

[Z] :Impedance per unit length of transmission line on each phase

By subtracting (3)-2 from (3)-1 and converting to positive sequence quantity, the equation of fault location is given by (4).

$$d = \frac{[VA]_1 - [VB]_1 + L([Z][IB])_1}{\{[Z]([IA]+[IB])\}_1} \tag{4}$$

where, $[VA]_1$:Positive sequence voltage on fault of local end

$[VB]_1$:Positive sequence voltage on fault of remote end

$(\ )_1$:Positive sequence conversion quantity

Impedance settings on each phase of a transmission line as shown by (5) are required for location of Equation (4):

$$[Z] = \begin{bmatrix} Zaa & Zab & Zac \\ Zba & Zbb & Zbc \\ Zca & Zbc & Zcc \end{bmatrix} \tag{5}$$

Faults are located, however, without error by setting only the positive sequence impedance in case of a symmetric transmission line using Equation (6) as follows:

$$d = \frac{[VA]_1 - [VB]_1 + L \cdot Z_1 [IB]_1}{Z_1([IA]_1 + [IB]_1)} \tag{6}$$

$$Z_1 = (Zs - Zm)$$

$$Zs = Zaa = Zbb = Zcc$$

$$Zm = Zab = Zba = Zac = Zca = Zbc = Zcb$$

where, $[IA]_1$:Positive sequence current on fault of local end

$[IB]_1$:Positive sequence current on fault of remote end

In principle, for location of a fault without error on asymmetric parallel transmission lines, current in the adjacent line at local [IA'] and remote terminal [IB'] should be taken into consideration for Equation (4) as shown by Equation (7) as follows:

$$d = \frac{[VA]_1 - [VB]_1 + L([Z][IB] + [Z'][IB'])}{[Z]([IA] + [IB]) + [Z']([IA'] + [[IB'])} \tag{7}$$

$$[Z'] = \begin{bmatrix} Zaa' & Zab' & Zac' \\ Zba' & Zbb' & Zbc' \\ Zca' & Zbc' & Zcc' \end{bmatrix}$$

where, [IA'] :adjacent current of each phase on fault of local end
[IB'] :adjacent current of each phase on fault of remote end
[Z'] :Mutual impedance per unit length of transmission line on each phase

We have conducted a study of these location systems, (4), (6) and other systems which do not use the adjacent circuit current of the remote terminal, while taking simplification of the system, cost reduction and assurance of location accuracy into consideration.
Results of the evaluation by the simulation and actual machine are explained below.

2.4 Study of Location System by Simulation

A study was conducted on three cases with parallel transmission lines taken as the subject for Equations (4) and (6) as follows.

i) Impedance matrix on transmission lines of #1L and #2L, both of which are approximately symmetrical.
ii) #1L asymmetric, #2L symmetric approximation.
iii) Both #1L and #2L are asymmetric.

Evaluation was made on the difference in location error for i), ii) and iii) depending upon the compensation methods of the mutual inductive component ((I)～(IV), below).

(I) IA_1,IB_1 ···(above-mentioned Equation(6))
(II)IA_1,IA_2,IA_0,IB_1,IB_2,IB_0 ···(above-mentioned Equation(4))
(III)IA_1,IA_2,IA_0,IB_1,IB_2,IB_0 and IA_0 of adjacent line
(IV)IA_1,IA_2,IA_0,IB_1,IB_2,IB_0 and IA_1,IA_2,IA_0 of adjacent line

The evaluation was conducted by modification of Equation (4) to its equivalent Equation (8) and changing the method of compensation.

$$d = \frac{[VA]_1 - [VB]_1 + L(Z_{11}[IB]_1 + Z_{12}[IB]_2 + Z_{10}[IB]_0}{Z_{11}([IA]_1 + [IB]_1) + Z_{12}([IA]_2 + [IB]_2) + Z_{10}([IA]_0 + [IB]_0)} \tag{8}$$

$$Z_{11} = \frac{1}{3}(Zaa + \partial Zab + \partial^2 Zac + \partial^2 Zba + Zbb + \partial Zbc + \partial Zca + \partial^2 Zcb + Zcc)$$

$$Z_{12} = \frac{1}{3}(Zaa + \partial Zab + \partial^2 Zac + \partial Zba + \partial^2 Zbb + Zbc + \partial^2 Zca + Zcb + \partial Zcc)$$

$$Z_{10} = \frac{1}{3}(Zaa + \partial Zab + \partial^2 Zac + Zba + \partial Zbb + \partial^2 Zbc + Zca + \partial Zcb + \partial^2 Zcc)$$

$$\partial = e^{j\frac{3\pi}{2}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \qquad \partial^2 = e^{-j\frac{3\pi}{2}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

where, $[IA]_2$:Negative sequence current on fault of local end
$[IA]_0$:Zero sequence current on fault of local end
$[IB]_2$:Negative sequence current on fault of remote end
$[IB]_0$:Zero sequence current on fault of remote end

In parallel transmission lines, the current of the adjacent circuit is required and it is generally based upon Equation (7). The requirement for current of the adjacent circuit at the remote end may be eliminated, however, by using Equations (9) and (10), provided that there are not faults on two circuits of a double-circuit parallel line.
The equation for the location is given by (9) for (III).

$$d = L - \frac{[VB]_1 - [VA]_1 + L(Z_1[IA]_1 + Z_{12}[IA]_2 + Z_{10}[IA]_0 + Z'_{10}[IA']_0}{Z_1([IA]_1 + [IB]_1) + Z_{12}([IA]_2 + [IB]_2) + Z_{10}([IA]_0 + [IB]_0)} \qquad (9)$$

$$Z'_{10} = \frac{1}{3}(Zaa' + \partial Zab' + \partial^2 Zac' + Zba' + \partial Zbb' + \partial^2 Zbc' + Zca' + \partial Zcb' + \partial^2 Zcc')$$

where, ' :quantity of adjacent line

The equation of location is given by (10) for (IV).

$$d = L - \frac{[VB]_1 - [VA]_1 + L([Z][IA] + [Z'][IA'])_1}{\{[Z]([IA] + [IB])\}_1} \qquad (10)$$

While it is difficult to incorporate current of the adjacent circuit at the remote terminal, for example, acquisition of data by connecting to a line current differential relay on the adjacent circuit, it is easier to incorporate the current of the adjacent circuit directly to the present line current differential relay provided that only the current of the adjacent circuit at the local terminal is needed. For evaluation of the system, we have applied a method which does not use the adjacent circuit current of the remote terminal (Equations (9), (10)) to (III), (IV).

The performance of fault location was evaluated using Electromagnetic Transients Program (EMTP) generated data. An actual 500kV power system was modeled using EMTP and was taken as a test system for various fault event simulations. Test system parameters used for EMTP modeling are given in the Appendix.

- Line length : 100km
- Types of fault : simple fault, multiple(simultaneous) faults
- Fault resistance : 15ohm

Table 1 shows results of simulation of simple faults.

Table 1. Results of typical cases on simple fault

Model	Fault point (km)	Fault type	Error (km)			
			(I)	(II)	(III)	(IV)
i)	50	1Lg	0	0	0	0
		2Ls	0	0	0	0
		3Lg	0	0	0	0
ii)	50	a-g	0.4	0	0	0
		b-g	0.9	0	0	0
		c-g	0.2	0	0	0
		a-b	0.4	0	0	0
		b-c	0.6	0	0	0
		c-a	0.7	0	0	0
		a-b-c-g	0.1	0	0	0
iii)	50	a-g	1.3	0.8	0.8	0
		b-g	0.6	0.3	0.3	0
		c-g	1.1	0.9	1.0	0
		a-b	0.0	0.5	0.5	0
		b-c	0.2	0.4	0.5	0
		c-a	1.7	0.9	0.9	0
		a-b-c-g	0.5	0.6	0.6	0

where,

(I) IA_1,IB_1 (Equation (6))

(II)$IA_1,IA_2,IA_0,IB_1,IB_2,IB_0$ (Equation (4))

(III)$IA_1,IA_2,IA_0,IB_1,IB_2,IB_0$ and IA_0 of adjacent line (Equation (9))

(IV)$IA_1,IA_2,IA_0,IB_1,IB_2,IB_0$ and IA_1,IA_2,IA_0 of adjacent line (Equation (10))

Result of simulation for multiple faults is summarized in Table 2.

Table 2. Results of typical cases on multiple faults

Model	Fault point (km)		Fault type		Error (km)			
					1L			
	1L	2L	1L	2L	(I)	(II)	(III)	(IV)
i)	50	50	a-g	b-g	0	0	0	0
		20	a-g	b-g	0	0	0	0
ii)	50	50	a-g	b-g	0.6	0	0	0
		20	a-g	b-g	0.6	0	0	0
iii)	50	50	a-g	b-g	0.6	1.0	1.0	2.8
		20	a-g	b-g	1.4	0.8	0.8	1.6

Findings can be drawn from the above Tables 1 and 2 as follows:

- Location is possible without error on symmetric transmission lines by (I) (Equation (6)) which uses impedance of each phase using the positive sequence current.

-In case of #1L asymmetric, #2L symmetric approximation, location is possible without error by (II) (Equation (4)) which uses impedance of each phase using the current of each phase.

- In case where both #1L. #2L are asymmetric, it is a little improved by introduction of the zero sequence current of adjacent circuit as shown in (III) (Equation (9)).

- Location is possible without error in case of multiple faults at different locations on symmetric transmission line.

Advantages are confirmed in use of the positive sequence quantities described in Section 2.3 by simulation:

i) Location is possible independently of the mode of the fault.

ii) Location is possible for a symmetric transmission line using the positive sequence quantity in (I). Even with an asymmetric two-circuit transmission line, there is little effect on the location result since the positive sequence quantity of the mutual inductive component between the protected circuit and the adjacent circuit is small.

iii) Little error is caused by multiple faults at different locations in case of a symmetric transmission line.

iv) The method of Equation (10) in (IV) is applicable for locating fault points in any mode of simple fault.

In case of multiple faults at different locations, the location method needs to be changed from Equation (10) in (IV) into Equation (9) in (III).

It was confirmed that high accuracy can practically be attained for parallel transmission lines by the location method of Equations (6) in (I) and (4) in (II) which use the electric quantities of the protected line alone.

According to the above, Equations (4) and (6) have been applied to realize the location system, using the electric quantities of the protected line in the fault locator, with the aim of achieving simplification of system.

In operation, two types of setting are established, setting of the positive sequence impedance only and setting of the impedance of each phase, and the system is designed such that selection is possible between the two types of setting.

By the above method, the system configuration is simplified and the cost is reduced since the necessity for incorporation of the electric quantities of the adjacent circuit is eliminated.

Table 3 shows typical cases of results for an actual machine with i) symmetric and iii) asymmetric transmission line taken as the subject. As with the simulation, 100 km symmetric and asymmetric transmission line models for a 500 kV system are used.

Table 3. Typical case of result for an actual machine

	Fault point (km)	Fault type	Maximum Error (km)	
			(I)(Eq.(6))	(II)(Eq.(4))
i)	50	a-g	0.5	0.5
		b-c	0.3	0.3
iii)	50	b-g	0.9	0.6
		c-a	1.7	0.9

As errors due to the asymmetric line are removed by the fault location method using each phase impedance of Equation 4, it is found that the measurement error becomes smaller than the fault location method using only positive sequence impedance of Equation 6.
The error is slightly larger than that of the simulation result due to the influence of VT and CT errors in the input conversion section.

3. Adaptive Fault Location Method

The line current differential relay with distance protection can provide an adaptive fault locator which integrates a one-terminal fault location method and a multi-terminal fault location method. The fault locator selects the most suitable fault location method automatically depending on telecommunication conditions and on the fault point. Usually, in case of no telecommunication failure, multi-terminal fault location is selected.

3.1 Multi-terminal fault location method

The multi-terminal method is tested by using the typical 500kV, 100km symmetrical single transmission line in Figure 4.

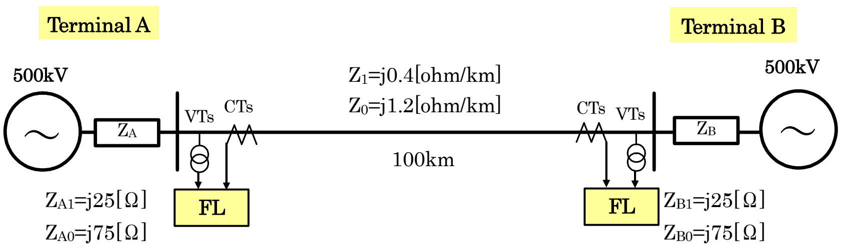

Figure 4. Typical 500kV, 100km symmetrical single line

Figure 5 shows the evaluation results of the measured error by the multi-terminal method in which the fault point is assumed to be a parameter under 0.5 digit input error condition. The measuring errors of the multi-terminal method increased towards both ends of the line.

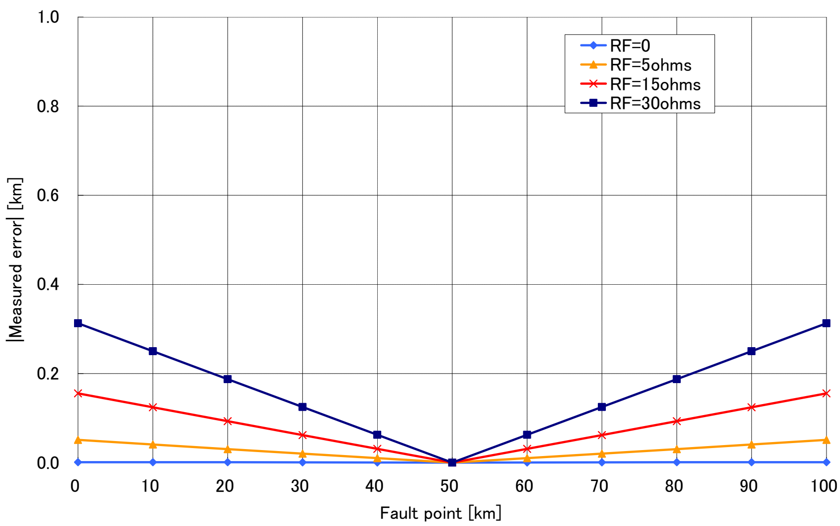

Figure 5. Measuring accuracy of multi-terminal method on typical single line

3.1 One-terminal fault location method

A general technique for accurate fault location using information from only one-terminal of the line has been suggested. This technique takes advantage of the additional information provided by the pre-fault currents seen by the relay. If the superposition current I" is assumed to be in phase with the current of the fault point, distance x from one terminal to the fault point can be multiplied by the conjugate of I" to obtain equation (11).

$$x = \frac{\mathrm{Im}(V \cdot I''^{*})}{\mathrm{Im}(Z \cdot I \cdot I''^{*})} \qquad (11)$$

where, x : distance to the fault point
V : fault phase voltage
I : current
I'' : superposition current
$*$: complex conjugate component
Z : line parameter per unit length
Im( ) : imaginary component

The one-terminal method is tested by using the typical 500kV, 100km symmetrical single transmission line in Figure 6, the same as that in Figure 4.

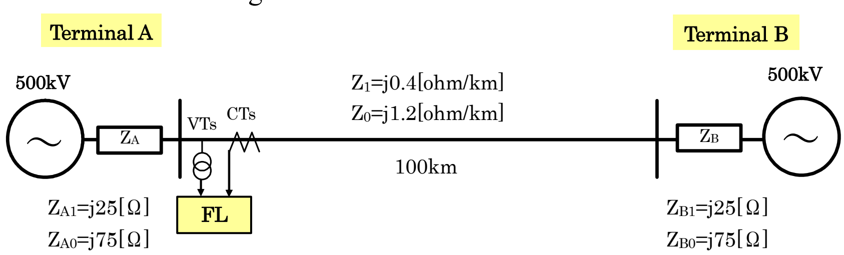

Figure 6. Typical 500kV, 100km symmetrical single line

Figure 7 shows the evaluation results of the measured error for the one-terminal method in which the fault point is assumed to be a parameter under 0.5 digit input error condition. The accuracy of the one-terminal method is good near to the measured end.

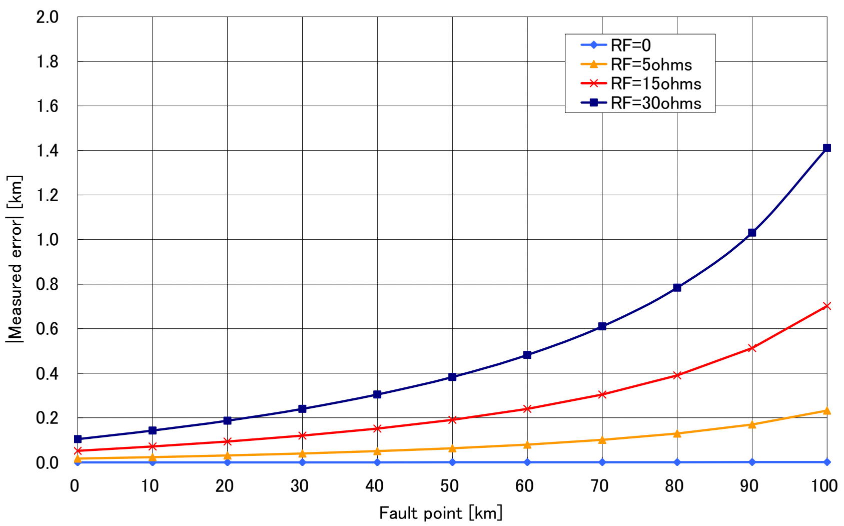

Figure 7. Measuring accuracy of one-terminal method at terminal A on typical single line

3.3 Adaptive fault location method

The accuracy of multi-terminal method tends to be best around the center of transmission line. On the other hand, in case of telecommunication failure and a close-up point fault, the one-terminal fault location accuracy is better than that of the multi-terminal method.

Therefore, it is possible by combining multi-terminal and one-terminal method to obtain high accuracy over a greater range. Figure 8 shows the evaluation of the adaptive method.

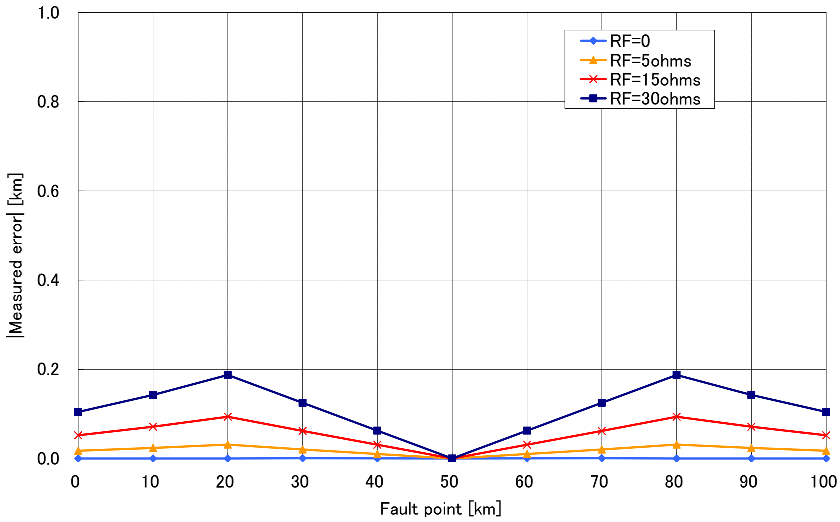

Figure 8. Measuring accuracy of adaptive method

4. Conclusion

The authors have developed a fault locator which is incorporated in a line current differential protection relay and uses the positive sequence quantities of both terminals on a transmission line.

This paper presented the evaluation of advanced multi-terminal fault location methods and a new fault location algorithm by applying adaptive fault location methods.

REFERENCES

[1] Takagi T., Yamakosi Y., Yamaura M., Kondow R. and Matsushima T., "Development of new type fault locator using the one-terminal voltage and current data", IEEE Transactions on Power Apparatus and Systems, Vol.PAS-101,No.8, August 1982,pp2892-2898.

[2] K. Suzuki, Y. Ohura, Y. Kurosawa, T. Takemura, S. Kumano, M. Yoshikawa, T. Funabashi, and F. Iwatani, “Existing condition and experiences of distance relays and fault locators using digital technology,” in Cigre Symposium, Boumemouth, 1989, pp.S34-89.

[3] Y. Ohura, T. Matsuda, M. Suzuki, M. Yamaura, Y. Kurosawa, and T. Yokoyama, "Digital Distance Relay with Improved Characteristics against Distorted Transient Waveforms," IEEE Trans. on Power System, Vol. 4, October 1989, pp.2025-2031.

[4] K.Igarashi, Y.Sukegawa, I.Shuto, H.Amoh, M.Saga: "Development of High-Speed Numerical Line Differential Relay," ICEE '99 Power System Protection & Fault Locator Session, 1999-8

[5] K.Zimmerman, D.J.Novosel:"Fault Location Techniques," IEEE Tutorial course - Advancements In Microprocessor based Protection and Communication, 1997 IEEE - 97TP120 - 0

[6] H.Ito et al, "Development of an improved multifunction high speed operating current differential relay for transmission line protection", Proc. IEE DPSP 2001

[7] S. Imai, K. Kihara, T. Inoue, M. Inukai, H. Takani, and T. Kagami, "A Newly Developed Web-based Fault Locating Technology for Transmission Lines and Its Experience in the Field." IEEE/PES Transmission and Distribution Conference Proceedings Vol.1, October 2002, pp.136-141.

[8] T. Maekawa, Y. Obata, M. Yamaura, Y. Kurosawa, and H. Takani, "Fault Location for Series Compensated Parallel Lines" IEEE/PES Transmission and Distribution Conference Proceedings Vol.2, October 2002, pp.824-829.

[9] I.Hall et al, "New Line Current Differential Relay using GPS Synchronization", IEEE Bologna Power Tech 2003

[10] D. Itagaki, K. Ohashi, M. Saga, I. Shuto, "Development of High Resolution and High Reliability Time Synchronizing Signal Distribution Technique for Substation Systems," IEE DPSP2004 Conference Proceedings Vol.2, 2004, pp.714-717.

[11] H. Takani, Y. Kurosawa, S. Imai, M. Inukai, "Analysis and Evaluation of Multi-terminal Fault Location using Actual Fault Data," IEE DPSP2004 Conference Proceedings Vol.1, 2004, pp.208-211.

[12] T. Kagami, H. Takani, K. Sekiguchi, "Web-based Wide Area Measurement System - System Architecture and Experiences," Georgia Tech Fault and Disturbance Analysis Conference, 2005.

[13] IEEE std C37.114 IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines, IEEE Power Engineering Society, 2005

[14] H. Takani, Y. Kurosawa, F. Kawano, "High Accuracy Fault Location Algorithm with Distributed Parameters and Evaluation Using Actual Fault Data," Georgia Tech Fault and Disturbance Analysis Conference, 2007.

Appendix

Table A-1. Impedance of model i) in case of #1L, #2L symmetric

	Real value (ohm/km)		
	Za	Zb	Zc
a	0.0427+j0.4113		
b	0.0313+j0.1453	0.0427+j0.4113	
c	0.0313+j0.1453	0.0313+j0.1453	0.0427+j0.4113
a'	0	0	0
b'	0	0	0
c'	0	0	0

Table A-2. Impedance of model ii) in case of #1L asymmetric, #2L symmetric

	Real value (ohm/km)		
	Za	Zb	Zc
a	0.0421+j0.4356		
b	0.0311+j0.1725	0.0424+j0.4173	
c	0.0310+j0.1163	0.0318+j0.1485	0.0442+j0.3857
A'	0	0	0
B'	0	0	0
C'	0	0	0

Table A-3. Impedance of model iii) in case of #1L, #2L asymmetric

	Real value (ohm/km)		
	Za	Zb	Zc
a	0.0421+j0.4356		
b	0.0311+j0.1725	0.0424+j0.4173	
c	0.0310+j0.1163	0.0318+j0.1485	0.0442+j0.3857
A'	0.0309+j0.1626	0.0310+j0.1412	0.0308+j0.1060
B'	0.0310+j0.1412	0.0311+j0.1476	0.0314+j0.1199
C'	0.0308+j0.1060	0.0314+j0.1199	0.0322+0.1215

Biographies

Hideyuki Takani received the B.E. and M.E. degrees in electrical engineering from Gunma University, Japan, in 1990 and 1992, respectively. In 1992, he joined Toshiba Corporation. He has been engaged in the research and development of protective relays, fault location systems, and wide area measurement systems. He is a member of IEEE and IEEJ.

Yasutaka Sonobe received the B.E. degree in electrical engineering from Kougakuin University, Japan, in 1991. He joined Toshiba Corporation in 1991. He has been engaged in the research and development of protective relays and relay apparatus.

Hidenari Amo received the B.S. degree in electrical engineering from Kougakuin University, Japan, in 1987. He joined Toshiba Corporation in 1998. He has been engaged in the development of the protective relay and relay apparatus. He is a member of IEEE.