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Evaluating Accuracy of Fault Location Algorithms Based on Terminal Current and Voltage Data

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Abstract—**Accurate estimation of fault location is essential for reliability of power system. For this purpose, fault location algorithms are studied and compared in this paper. These algorithms are based on the measurements taken from either sending end of a transmission line or both sending and receiving ends of the line. The types of fault location algorithms are discussed first. The effectiveness of the algorithms are tested on a faulty transmission line simulated in DigSILENT. Algorithms developed in MATLAB use the voltage and current values obtained from the simulated system. The impact of the fault distance, fault types and the fault resistance are examined in detecting the fault location. The study results reveal that the symmetrical fault location algorithm accurately estimates the fault location in all cases.**

Index Terms—**one-end fault location, two-end fault location, fault location algorithms, fault resistance**

I. INTRODUCTION

When any kind of faults occur in a power system, the first action must be to clear the fault from the system. Once the protection action is taken, the most accurate distance of fault information should be provided to aid the user in locating the fault to remove the cause of the fault. Fault location can be estimated from current and voltages measured from one-end or two-end of the line.

Many studies are carried out on the fault location algorithms in transmission systems, including travelling wave algorithms [1]-[3], one-end fault location algorithms [4]-[6], two-end and multi-end fault location algorithms [7], [8]. Some parameters such as fault types, fault impedance and source impedance affect the performance of fault location algorithms.

Travelling wave algorithms have been used for fault location since 1931 for overhead lines and underground cables [9], [10]. These algorithms are improved to immune to fault type, fault resistance, fault inception angle and source parameters of a system [11]. However, high sampling rate, sampling window selection and problems of distinguishing between travelling waves reflected from a fault and the remote end of the line are drawbacks of travelling wave algorithms [12].

Drawbacks mentioned above yield to the development of one-end and two-end fault location algorithms. One-end fault location algorithms are simple, economic and use only measurements from one terminal. On the other hand, the feature of one-end measurement may cause estimation errors. Two-end and multiple-end fault location algorithms based on synchronized [13] and unsynchronized [14] measurements of two or more bus terminals are utilized for higher accuracy. These algorithms can be developed considering various situations in a power system, for example load oriented power systems [15], a power system including FACTS [16], a power system having untransposed lines [17]. Solution skills of artificial intelligence can be an alternative method for fault location applications [18], [19].

In this paper, selected one-end and two-end fault location algorithms are described. The effects of the fault types, fault resistance and fault distance on the accuracy of these algorithms are demonstrated followed by comparison and discussion of the results.

II. ONE-END FAULT LOCATION ALGORITHMS

One-end fault location algorithms usually use variables from the sending end. Fig. 1 is a basic circuit for fault location. Sending end voltage can be defined as;

$$V_S = I_S(mZ_L) + I_f R_f \qquad (1)$$

where, m: distance to fault location, R_f: fault resistance, I_f: fault current, Z_L: line impedance, V_S and I_S: voltage and current at the sending end bus respectively.

As given in Fig. 1, V_R and I_R are voltage and current at the receiving end bus respectively and V_f is the fault voltage.

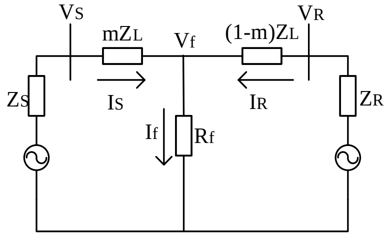

Figure 1. Circuit representation of line fault.

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A. *Simple Reactance Method*

This method compares the measured line impedance (Z_L) and calculated impedance (V_S/I_S) to find the fault location. Accuracy of this method depends on the angle of I_S being equal to the angle of I_f.

The simple form of the distance to the fault can be obtained as given in Eq. (2) where the fault resistance is ignored in Eq. (1), dividing this equation by I_S and saving the imaginary part;

$$m = Im(V_S/I_S)/Im(Z_L) \tag{2}$$

B. *Takagi Method*

The Takagi method requires additionally pre-fault current values. This method improves simple reactance method by reducing the effect of load flow and minimizing the effect of fault resistance.

Superposition current (Isup) can be described as follows;

$$Isup = I - Ipre = If/d \tag{3}$$

where, *I*: fault current and *Ipre*: pre-fault current.

If the source and line have the same impedance, d becomes a real number. Accuracy of this method depends on this assumption.

Through Eq. (3) and Eq. (1);

$$V_S = I_S(mZ_L) + I_{sup}dR_f \tag{4}$$

$$V_{Sr} = mR_LI_{Sr} - mX_LI_{Si} + I_{supr}dR_f \tag{5}$$

$$V_{Si} = mX_LI_{Sr} + mR_LI_{Si} + I_{supi}dR_f \tag{6}$$

By multiplying Eq. (5) with I_{supi} and Eq. (6) with I_{supr} and subtract Eq. (6) from Eq. (5);

$$m = a/(b-c) \tag{7}$$

where;

$$a = V_{Sr}I_{supi} - V_{Si}I_{supr} \tag{8}$$

$$b = R(I_{Sr}I_{supi} - I_{Si}I_{supr}) \tag{9}$$

$$c = X(I_{Sr}I_{supr} + I_{Si}I_{supi}) \tag{10}$$

C. *Modified Takagi Method*

Modified Takagi method replaces superposition current with zero sequence current of sending end.

This method is limited with ground faults since zero sequence current exists for ground faults. Then, the fault distance is calculated as follows:

$$m = Im(3V_SI_0^*e^{-jT})/Im(3Z_LI_SI_0^*e^{-jT}) \tag{11}$$

where, I_{0S}: zero sequence current and *T*: angle between I_{0S} and I_f.

III. TWO-END FAULT LOCATION ALGORITHMS

Two-end fault location algorithms calculate fault location from the impedance seen from both end of the line. Because of accurately detecting fault location, these algorithms usually better than one-end fault location algorithms. Two-end fault location algorithms take V_f as a reference point.

A. *Basic Two-End Method*

This method is fundamental for the other two-end fault location methods.

$$V_f = V_S - I_SmZ_L \tag{12}$$

$$V_f = V_R - I_R(1-m)Z_L \tag{13}$$

Fault location can be calculated with Eq. (12) and Eq. (13);

$$m = (V_S - V_R + Z_LI_R)/(Z_L(I_S + I_R)) \tag{14}$$

B. *Symmetrical Fault Method*

This method calculates the fault resistance with high accuracy for symmetrical faults and doesn't require line parameters for detecting fault location. Accuracy of this method depends on the fault type.

Voltage equations of V_S, V_R and V_f can be derived from the circuitry given in Fig. 2 where D is the line length, l is the distance from the fault point and z is the line impedance.

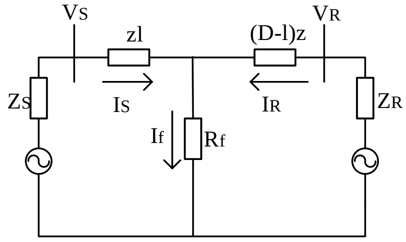

Figure 2. Circuit representation of line fault for symmetrical fault method.

$$V_S - zlI_S - V_F = 0 \tag{15}$$

$$V_R - z(D-l)I_R - V_F = 0 \tag{16}$$

$$V_f = R_f(I_R + I_S) \tag{17}$$

With Eq. (15), Eq. (16) and Eq. (17), line parameters can be obtained;

$$z(D-l) = (V_R/I_R) - ((I_S+I_R)/I_R)R_f \tag{18}$$

$$zl = (V_S/I_S) - ((I_S+I_R)/I_S)R_f \tag{19}$$

$$zl = (a_1+b_1R_f) + j((a_2+b_2R_f) \tag{20}$$

$$z(D-l) = (c_1+d_1R_f) + j((c_2+d_2R_f) \tag{21}$$

where;

$$a_1 = Re(V_S/I_S) \tag{22}$$

$$a_2 = Im(V_S/I_S) \tag{23}$$

$$b_1 = Re(-((I_S+I_R)/I_S)) \tag{24}$$

$$b_2 = Im(-((I_S+I_R)/I_S)) \tag{25}$$

$$c_1= Re(V_R/I_R) \tag{26}$$

$$c_2= Im(V_R/I_R) \tag{27}$$

$$d_1= Re(-((I_S+I_R)/I_R)) \tag{28}$$

$$d_2= Im(-((I_S+I_R)/I_R)) \tag{29}$$

Z impedance is in first quadrant;

$$a_1+b_1R_f >0 \tag{30}$$

$$a_2+b_2R_f >0 \tag{31}$$

$$c_1+d_1R_f >0 \tag{32}$$

$$c_2+d_2R_f >0 \tag{33}$$

Both equations are part of the same line. Because of that, their angles must be equal;

$$\tan(\theta) = (a_2+b_2R_f)/(a_1+b_1R_f) \tag{34}$$

$$\tan(\theta) = (c_2+d_2R_f)/(c_1+d_1R_f) \tag{35}$$

From Eq. (34) and Eq. (35), R_f can be derived;

$$R_f^2+pR_f +q= 0 \tag{36}$$

where;

$$p=(a_1d_1+b_1c_2-a_2d_1-b_2c_2)/(b_1d_2-b_2d_1) \tag{37}$$

$$q=(a_1c_2 - a_2c_1)/(b_1d_2-b_2d_1) \tag{38}$$

Eq. (36) has two roots;

$$(R_f)_1=(-p + \sqrt{(p^2-4q)})/2 \tag{39}$$

$$(R_f)_2=(-p - \sqrt{(p^2-4q)})/2 \tag{40}$$

Only one of roots gives the correct angle value;

$$\theta_1 = \arctan[(a_2+b_2R_{f1})/(a_1+b_1R_{f1})] \tag{41}$$

$$\theta_2 = \arctan[(a_2+b_2R_{f2})/(a_1+b_1R_{f2})] \tag{42}$$

Correct value of R_f should give an angle which is closer to typical values of the line characteristic and angle must be in the first quadrant.

Fault location can be given as;

$$l\%=100(zl)/((zl+z(D\text{-}l)) \tag{43}$$

By including Eq. (20), Eq. (21) and the correct fault resistance obtained from Eq. (41) or Eq. (42), the final form of the fault location is as follows;

$$l\%=100(e/f) \tag{44}$$

where;

$$e= (a_1+b_1R_f) + j(a_2+b_2R_f) \tag{45}$$

$$f= e+(c_1+d_1R_f) + j(c_2+d_2R_f) \tag{46}$$

IV. EVALUATION OF ALGORITHMS

The single line diagram of an 8 bus system that fault location algorithms are tested is shown in Fig. 3. The system consists of 3 synchronous generators, 2 external grids, 6 transformers and 2 asynchronous motors.

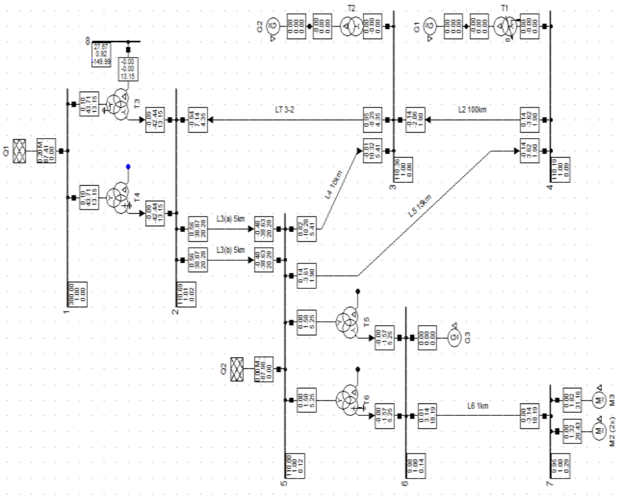

Figure 3. Test transmission system.

Fault location algorithms are tested at line L2 in Fig. 3, between bus 3 (sending end) and bus 4 (receiving end). Line parameters are given in Table I while bus parameters for bus 3 and 4 at load flow state are tabulated in Table II.

TABLE I. LINE PARAMETERS

	R	X	C
Positive sequence	0.03Ω/km	0.242Ω/km	14.86nF/km
Negative sequence	0.03Ω/km	0.242Ω/km	14.86nF/km
Zero sequence	0.131Ω/km	0.855Ω/km	6.44nF/km
The length of transmission line is 100km			

TABLE II. BUS PARAMETERS

	Bus 3	Bus 4
Voltage	110.36kV	110.19kV
Frequency	50Hz	50Hz

Firstly, the algorithms are implemented on the system for phase to ground fault at different locations (Table III). Test distances are selected to be 30km, 50km and 70km from the sending end of the line.

TABLE III. A-PHASE TO GROUND FAULT AT DIFFERENT LOCATIONS (R_F=0Ω)

	30 km	% error	50 km	% error	70 km	% error
Takagi Method	30.5 km	1.66	50.91 km	1.82	71.31 km	1.87
Modified Takagi Method	30.51 km	1.7	50.92 km	1.84	71.31 km	1.87
Simple Reactance Method	30.51 km	1.7	50.92 km	1.84	71.31 km	1.87
Basic Two-End Method	29.93 km	0.23	50.06 km	0.12	70.17 km	0.24
Symmetrical Fault Method	29.95 km	0.16	50.03 km	0.06	70.03 km	0.04

As expected, when distance between fault location and sending bus increases, accuracy of one-end fault location algorithms decreases. The accuracy of these algorithms seems to be nearly the same, however the Takagi method has a less estimation error among them by reducing the effect of load flow. Two-end fault location algorithms show better performance in estimating the fault location with an error less than 1%. The best fault location estimation is obtained with the symmetrical fault method.

Secondly, the selected algorithms are tested for different faults at 50km (Table IV) fault distance from the sending end of the line.

TABLE IV. DIFFERENT FAULTS AT 50KM (R_F=0Ω)

	a-b	% error	b-c-t	% error	a-b-c	% error
Takagi Method	52.8 km	5.6	51 km	2	51 km	2
Modified Takagi Method	-	-	51 km	2	-	-
Simple Reactance Method	52.8 km	5.6	51 km	2	51 km	2
Basic Two-End Method	50.3 km	0.6	50.2 km	0.4	50.2 km	0.4
Symmetrical Fault Method	50.1 km	0.2	49.9 km	0.2	49.9 km	0.2

One-end fault location algorithms exceed 2% error rate. On the other hand, two-end algorithms have maximum 0.6% error rate. The symmetrical fault method has the best accuracy rating.

Thirdly, algorithms are tested for asymmetrical faults with the fault resistance of 0.5, 1 and 1.5 ohm at the 50km fault distance from the sending end of the line (Table V).

TABLE V. A-PHASE TO GROUND FAULT AT 50KM WITH DIFFERENT FAULT RESISTANCES

	0.5 Ω	% error	1 Ω	% error	1.5 Ω	% error
Takagi Method	51.1 km	2.2	51.3 km	2.6	55.2 km	10.44
Modified Takagi Method	51 km	2	51.1 km	2.2	55.2 km	10.44
Simple Reactance Method	51 km	2	51.1 km	2.2	55.2 km	10.44
Basic Two-End Method	50 km	0	50 km	0	49.8 km	0.4
Symmetrical Fault Method	49.8 km	0.4	49.8 km	0.4	49.4 km	1.2

The errors for one-end fault location algorithms are around 10%. Superposition current seems to have a negative effect on the Takagi method. Therefore, the accuracy of this method is worse than other methods. The estimation error obtained from the modified Takagi method and simple reactance method are the same. As expected the basic two-end method has better accuracy at an asymmetrical fault with the fault resistance.

Finally, algorithms are tested at symmetrical fault with the fault resistance as above at the 50km fault distance from the sending end of the line (Table VI).

TABLE VI. THREE PHASE FAULT AT 50KM WITH DIFFERENT FAULT RESISTANCES

	0.5 Ω	% error	1 Ω	% error	1.5 Ω	% error
Takagi Method	50.82 km	1.64	49.83 km	0.34	50.46 km	0.92
Modified Takagi Method	-	-	-	-	-	-
Simple Reactance Method	50.82 km	1.64	49.83 km	0.34	50.46 km	0.92
Basic Two-End Method	50.18 km	0.36	49.88 km	0.24	50.03 km	0.06
Symmetrical Fault Method	50.09 km	0.18	49.88 km	0.24	49.99 km	0.02

The symmetrical fault method seems to be more accurate in this case because symmetrical fault has no zero sequence components affecting the calculation of the fault resistance.

In two cases, one-end location algorithms exceed 5% error rate causing more than 2km miscalculation. If the faults occur at a distance greater than 50km from the sending end, error rate will increase. This is an unwanted result for one-end fault location algorithms. Two-end fault location algorithms have maximum 0.6 km miscalculation in one case and other cases have less than 0.3km miscalculation. Two-end fault location algorithms generally have a better accuracy than one-end location algorithms and this test system proves that assumption.

V. CONCLUSION

This paper evaluates the effects of certain parameters on the accuracy of fault location algorithms. These algorithms use voltage and current data taken from one or two end of transmission lines. The developed algorithms are implemented on a test system.

One-end fault location methods give nearly identical results. The modified Takagi method does not use pre-fault values like the simple reactance method except this method is limited to only ground faults while the simple reactance method can be used at all fault types with the same accuracy. The Takagi method uses pre-fault current, which requires extra calculation and measurement values. Though these measurements and calculations do not improve its accuracy because of the source and line impedance difference. The simple reactance method could be a better choice since it has the same accuracy in handling the problem of impedance difference between the source and the line without requiring extra components.

The symmetrical fault method gives better results except for asymmetrical faults with a fault resistance in two-end fault location algorithms. Basic two-end method has the best results at asymmetrical fault with a fault resistance. Both of these methods have acceptable accuracy for any fault, but if the fault type is predetermined and the suitable two-end fault location method is chosen, then the fault location estimation error is minimized.

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