Journal of Applied Science and Engineering Innovation, Vol.5, No.3, 2018, pp. 73-79
ISSN (Print): 2331-9062
ISSN (Online): 2331-9070

Research on Fault Location Algorithm with Traveling Wave Based on Determinant of Matrix A

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Abstract*:* In view of the dead judgment on the fault branch in the location with traveling wave based on the existing T circuit, a fault location algorithm with traveling wave based on determinant of matrix A is proposed. This algorithm does not need to judge the fault branch separately, the matrix A is constructed by the arrival time of traveling wave and wave beam, line length obtained by three ports on T circuit after faulting, the fault branch and fault location can be obtained directly by comparing the size of the determinant of matrix A. Through simulation analysis using MATLAB, the algorithm with clear analysis and high precision meets the requirements of fault location.

Keywords T circuit; Matrix A; Traveling wave; Fault location

INTRODUCTION

Along with the structure distribution of the power grid, the growth of regional power load and the increase of the density of the power grid, T circuits have been more and more used in high voltage and extra high voltage power system. The power system is connected to large power plants and substations, once the fault occurs, it is need to find the fault location as soon as possible and recover the power supply. The fault location of the T circuit consists of two parts: one is the judgment of the fault branch; the other is the judgment of the fault location. At present, the location algorithms with traveling wave for T circuit are single ended and double ended fault location methods. For single ended method, the literature [YU et al., 2007] injected the signal at one end of the line when the fault occurs. By recording the start time of the injection and collecting the time when the signal reached the fault point, the location can be fixed using distance measurement formula. Thus the method has many problems, such as great difficulties in the data processing; signal attenuation to traveling wave in transmission process; inaccurate back time captured; how to identified fault branch in the multi branch network and so on.

For double ended method, three endpoints in T circuit are proposed as the reference point in the literature [Li et al., 2013], select a fixed reference point, and then convert the branch into two separate lines with double end location method respectively. The method can only be used for different power lines, otherwise it will cause the fault. Literature [Li et al., 2014] combining the single ended and double ended traveling wave method for fault location, but the traveling wave attenuation can not be avoided in the single end positioning, which causes the traveling wave head difficult to be identified. In the literature [LU et al., 2011], three branches of the T circuit are transformed into two lines for fault location with double ended location method, but when the fault occurs in the vicinity of the branch node, there may be a fault dead zone which leads to the wrong point.

The new algorithm constructs the matrix A with the arrival time of traveling wave and wave beam、line length obtained by three ports on T circuit after faulting, the fault branch and fault location can be get directly by comparing the determinant of matrix A.

ALGORITHM BASED ON THE DETERMINANT OF MATRIX

The schematics of T circuit

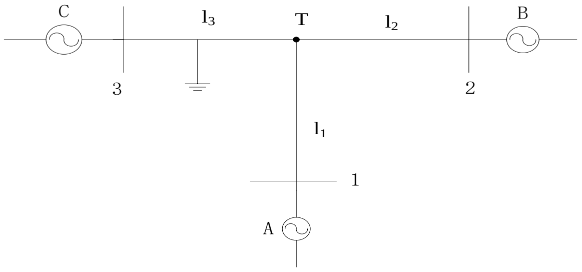

Figure 1 T circuit simulation diagram

As shown in Figure 1, A、B、C are the three ports in T circuit, 1, 2, 3 are the measurement points, T is the connection point, with the corresponding line length l_1、l_2、l_3. When the fault occurs in one point, the traveling wave will spread at A、B、C ports. The corresponding arrival time t_1、t_2、t_3 can be measured at 1、2、3 points respectively.

Algorithm principle

Consider the three branches in T circuit with $l_1=l_2=l_3$、$l_1<l_2=l_3$、$l_1>l_2=l_3$、$l_1<l_2<l_3$. When a fault occurs at any time, the time series

$t=(t_1、t_2、t_3)$ of traveling waves propagating to the three ends are obtained. The observation point 1 is the reference point.

Based on the principle of double end distance measurement, the distance between fault point on line AB and AC and observation point 1 is calculated respectively. Assume the distance is *x*, and the distance to the node T is x', as shown in Figure 2:

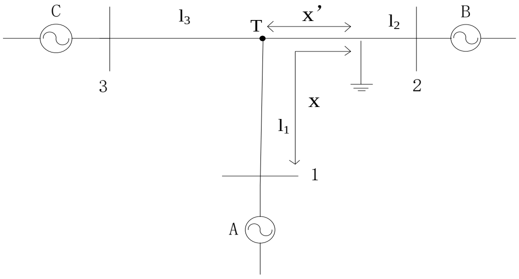

Figure 2 Simulation diagram after the fault occurs

According to the same principle of traveling wave velocity, the formula (1) can be obtained:

$$t_1-t_2=\frac{x}{v}-\frac{l_1+l_2-x}{v} \qquad (1)$$

so:

$$x=\frac{l_1+l_2+v(t_1-t_2)}{2} \qquad (2)$$

$$t_1-t_3=\frac{x'+l_1}{v}-\frac{x'+l_3}{v} \qquad (3)$$

then

$$l_1=\frac{l_1+l_3+v(t_1-t_3)}{2} \qquad (4)$$

and

$$x'=x-l_1=\frac{l_1+l_2+v(t_1-t_2)}{2}-\frac{l_1+l_3+v(t_1-t_3)}{2} \qquad (5)$$

thus

$$2x'=(l_2-vt_2)-(l_3-vt_3) \qquad (6)$$

Consider matrix $A_n=\begin{bmatrix} l_n & t_n \\ v & 1 \end{bmatrix}$, where l_n is the length of the branch in circuit T, *v* is the velocity of traveling wave, t_n is the arrival time.

So $|A_2|=\begin{vmatrix} l_2 & t_2 \\ v & 1 \end{vmatrix}$, $|A_3|=\begin{vmatrix} l_3 & t_3 \\ v & 1 \end{vmatrix}$, then

$$2x'=|A_2|-|A_3| \qquad (7)$$

When $\begin{cases} 2x'=|A_2|-|A_3|=0 \\ 2x'=|A_2|-|A_3|=\lambda<\varepsilon, \quad \varepsilon\approx 0.1 \end{cases}$, fault occurs at branch AT.

$2x'=|A_2|-|A_3|>0$, fault occurs at branch BT.

$2x'=|A_2|-|A_3|<0$, fault occurs at branch CT.

For the different situations on the branches, the determinant of matrix A can be used to identify the fault. x' is the distance between the fault and T node in equation(7), the corresponding fault points can be obtained when getting the fault branches.

The fault occurred at branch AT, as shown in Figure 3:

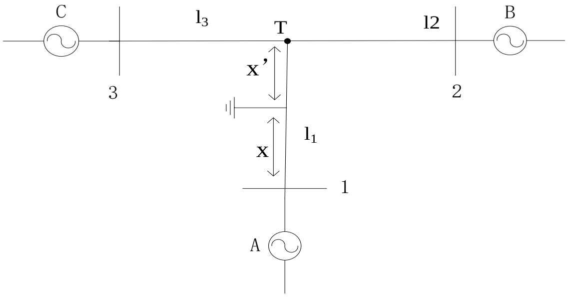

Figure 3 The fault occurred at branch AT

In this case the value of $x'=\lambda<\varepsilon\approx 0.1$ can be calculated. Thus we can only get the fault branch without the location of the fault, at this point it is need to change the reference point. Assume the conversion reference point is 3, calculate $2x'=|A_1|-|A_2|$, where x' is still the distance between the fault and T node, and the fault location can be obtained by the conversion.

Flow chart of the algorithm

In the actual power system, the length of power line has been determined. Figure 4 is the flow chart of fault location algorithm based on determinant of matrix A.

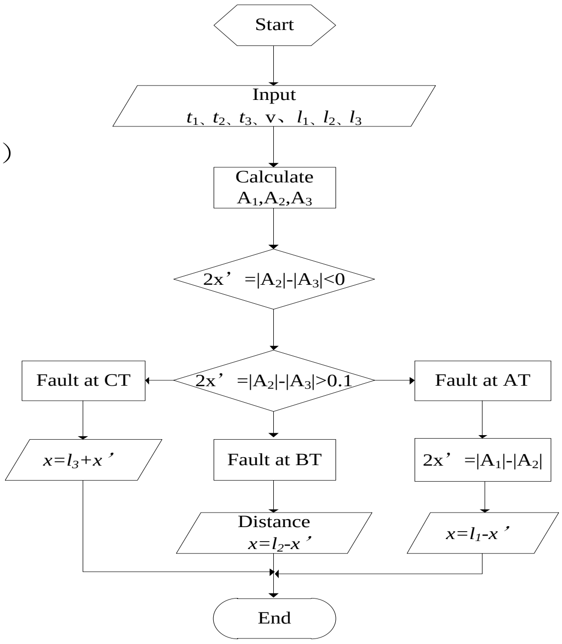

Figure 4 The flow chart of fault location algorithm based on determinant of matrix A

SIMULATIONS AND FAULT ANALYSIS

In order to verify the proposed algorithm, three end power system model with 220KV voltage is established using MATLAB/Simulink as shown in Figure 1. In the simulation, wavelet transform is used to find the corresponding time after the modulus maximum of the fault current extracted by the linear model transform. Consider the simulation time is 0.03S, the sampling frequency is 1MHZ, the start time of the fault is 0.01S, the line parameters are: R_1=0.01273Ω/*km*; R_0=0.3864Ω/*km*; L_1=0.9337 $\times 10^{-3}$ H / *km*; L_0=4.1264 $\times 10^{-3}$ H / *km*; C_1=12.74 $\times 10^{-9}$ F/*km*; C_0=7.751 $\times 10^{-9}$ F/*km*; the velocity probability value of traveling wave is $V = 1/\sqrt{L_1 C_1} = 289942 km/s$, simulation results [Silvio et al., 2015] showed as follows:

1. Consider branch AT, BT and CT with length of 220km, 220km, 220km, the simulation results of fault current extracting the modulus maxima after linear model transform and wavelet transform are shown in Figure 5.

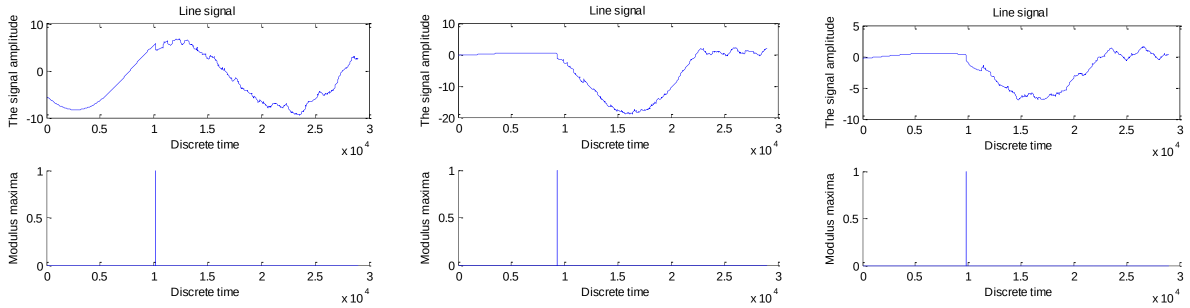

Figure 5 Results with fault at AT、BT、CT

Table 1~3 show the time series, matrix A_1、A_2 and A_3 with the different fault types when the fault occurs at AT, BT, CT respectively. Table 4~6 give the solutions of $2x'$ to determine the fault branch, and the location and the absolute error of the fault point.

Table1 The measured time series under single phase earthing-short fault

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	100	(0.010346、0.011174、0.011174)	$\begin{bmatrix} 220 & 0.010346 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.011174 \\ 289942 & 1 \end{bmatrix}$
BT	85	(0.011226、0.010295、0.011226)	$\begin{bmatrix} 220 & 0.010295 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.011226 \\ 289942 & 1 \end{bmatrix}$
CT	205	(0.010812、0.010812、0.010709)	$\begin{bmatrix} 220 & 0.010812 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.010709 \\ 289942 & 1 \end{bmatrix}$

Table2 The measured time series under single short circuit between two phases

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	185	(0.010640、0.010881、0.010881)	$\begin{bmatrix} 220 & 0.010640 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.010881 \\ 289942 & 1 \end{bmatrix}$
BT	215	(0.010778、0.010743、0.010778)	$\begin{bmatrix} 220 & 0.010743 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.010778 \\ 289942 & 1 \end{bmatrix}$
CT	15	(0.011468、0.011468、0.010053)	$\begin{bmatrix} 220 & 0.011468 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.010053 \\ 289942 & 1 \end{bmatrix}$

Table3 The measured time series under phase-to-phase grounding short-circuit fault

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	203	(0.010702、0.010819、0.010819)	$\begin{bmatrix} 220 & 0.010702 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.010819 \\ 289942 & 1 \end{bmatrix}$
BT	35	(0.011399、0.010122、0.011399)	$\begin{bmatrix} 220 & 0.010122 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.011399 \\ 289942 & 1 \end{bmatrix}$

CT	115	(0.011123、 0.011123、0.010398)	$\begin{bmatrix} 220 & 0.011123 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 220 & 0.010398 \\ 289942 & 1 \end{bmatrix}$

Table4 The judgement of single phase earthing-short fault

Solution of $2x'$	Solution of $\lvert x' \rvert$	Fault branch	Fault distance(km)	Error(m)
240.07	120.04	AT	99.96	-40
269.94	134.97	BT	85.03	30
-29.87	14.94	CT	205.06	60

Table5 The judgement of single short circuit beteen two phases

Solution of $2x'$	Solution of $\lvert x' \rvert$	Fault branch	Fault distance(km)	Error(m)
69.88	34.94	AT	185.06	60
10.15	5.075	BT	214.93	-70
-410. 27	205.14	CT	14.86	-140

Table6 The judgement of phase-to-phase grounding short-circuit fault

Solution of $2x'$	Solution of $\lvert x' \rvert$	Fault branch	Fault distance(km)	Error(m)
33.92	16.96	AT	203.04	40
370.26	185.13	BT	34.87	130
-210.21	105.11	CT	114.89	110

2. Consider branch AT, BT and CT with length of 160km, 200km, 200km, the simulation results of fault current extracting the modulus maxima after linear model transform and wavelet transform are shown in Figure 6.

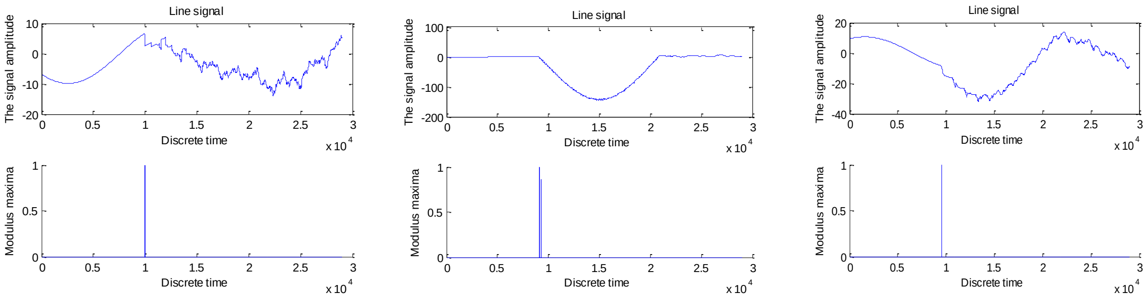

Figure 6 Results with fault at AT、BT、CT

Table 7~9 show the time series, matrix A_1、A_2 and A_3 with the different fault types when the fault occurs at AT, BT, CT respectively. Table 10~12 give the solutions of $2x'$ to determine the fault branch, and the location and the absolute error of the fault point.

Table7 The measured time series under single phase earthing-short fault

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	60	(0.010208、 0.011036、0.011036)	$\begin{bmatrix} 160 & 0.010208 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.011036 \\ 289942 & 1 \end{bmatrix}$
BT	10	(0.011209、 0.010036、0.011347)	$\begin{bmatrix} 200 & 0.010036 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.011347 \\ 289942 & 1 \end{bmatrix}$
CT	158	(0.010698、 0.010836、0.010546)	$\begin{bmatrix} 200 & 0.010836 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.010546 \\ 289942 & 1 \end{bmatrix}$

Table8 The measured time series under single short circuit between two phases

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	75	(0.010260、0.010985、0.010985)	$\begin{bmatrix} 160 & 0.010260 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.010985 \\ 289942 & 1 \end{bmatrix}$
BT	25	(0.011157、0.010088、0.011295)	$\begin{bmatrix} 200 & 0.010088 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.011295 \\ 289942 & 1 \end{bmatrix}$
CT	189	(0.010591、0.010729、0.010653)	$\begin{bmatrix} 200 & 0.010729 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.010653 \\ 289942 & 1 \end{bmatrix}$

Table9 The measured time series under phase-to-phase grounding short-circuit fault

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	123	(0.010426、0.010819、0.010819)	$\begin{bmatrix} 160 & 0.010426 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.010819 \\ 289942 & 1 \end{bmatrix}$
BT	72.3	(0.010994、0.010251、0.011132)	$\begin{bmatrix} 200 & 0.010251 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.011132 \\ 289942 & 1 \end{bmatrix}$
CT	5	(0.011226、0.011364、0.010019)	$\begin{bmatrix} 200 & 0.011364 \\ 289942 & 1 \end{bmatrix}$	$\begin{bmatrix} 200 & 0.010019 \\ 289942 & 1 \end{bmatrix}$

Table10 The judgement of single phase earthing-short fault

Solution of $2x'$	Solution of $\lvert x' \rvert$	Fault branch	Fault distance(km)	Absolute error(m)
200.07	100.04	AT	59.96	-40
380.11	190.07	BT	9.94	-60
-84.08	42.04	CT	157.96	-40

Table11 The judgement of phase-to-phase grounding short-circuit fault

Solution of $2x'$	Solution of $\lvert x' \rvert$	Fault branch	Fault distance(km)	Absolute error(m)
170.21	85.11	AT	74.89	-110
349.96	174.98	BT	25.02	20
-22.04	11.02	CT	188.98	-20

Table12 The judgement of phase-to-phase grounding short-circuit fault

Solution of $2x'$	Solution of $\lvert x' \rvert$	Fault branch	Fault distance(km)	Absolute error(m)
74.95	36.97	AT	123.03	30
255.44	127.72	BT	72.28	20
-389.97	194.98	CT	5.01	10

3. Consider branch AT, BT and CT with length of 180km, 225km, 253km, the simulation results of fault current extracting the modulus maxima after linear model transform and wavelet transform are shown in Figure 7.

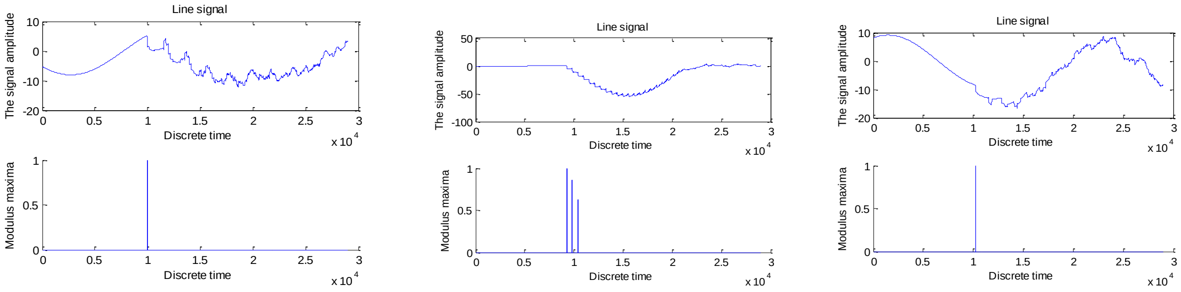

Figure 7 Results with fault at AT、BT、CT

Table 13~15 show the time series, matrix A_1、A_2 and A_3 with the different fault types when the fault occurs at AT, BT, CT respectively. Table 16~18 give the solutions of $2x'$ to determine the fault branch, and the location and the absolute error of the fault point.

Table13 The measured time series under single phase earthing-short fault

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	60	(0.010208、0.011191、0.011288)	$\begin{bmatrix}180 & 0.010208\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}225 & 0.011191\\289942 & 1\end{bmatrix}$
BT	100	(0.011054、0.010346、0.011306)	$\begin{bmatrix}225 & 0.010346\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}253 & 0.011306\\289942 & 1\end{bmatrix}$
CT	200	(0.010805、0.010960、0.010691)	$\begin{bmatrix}225 & 0.010960\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}253 & 0.010691\\289942 & 1\end{bmatrix}$

Table14 The measured time series under single short circuit between two phases

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	75	(0.010260、0.011140、0.011237)	$\begin{bmatrix}180 & 0.010260\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}225 & 0.011140\\289942 & 1\end{bmatrix}$
BT	150	(0.010881、0.010519、0.011133)	$\begin{bmatrix}225 & 0.010519\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}253 & 0.011133\\289942 & 1\end{bmatrix}$
CT	250	(0.010633、0.010788、0.010864)	$\begin{bmatrix}225 & 0.010788\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}253 & 0.010864\\289942 & 1\end{bmatrix}$

Table15 The measured time series under phase-to-phase grounding short-circuit fault

Actual fault branch	Actual fault distance(km)	Time serials（s）	Matrix A	Matrix A
AT	150	(0.010519、0.010881、0.010978)	$\begin{bmatrix}180 & 0.010519\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}225 & 0.010881\\289942 & 1\end{bmatrix}$
BT	80	(0.011123、0.010277、0.011375)	$\begin{bmatrix}225 & 0.010277\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}253 & 0.011375\\289942 & 1\end{bmatrix}$
CT	65	(0.011271、0.011426、0.010226)	$\begin{bmatrix}225 & 0.011426\\289942 & 1\end{bmatrix}$	$\begin{bmatrix}253 & 0.010226\\289942 & 1\end{bmatrix}$

Table16 The judgement of single phase earthing-short fault

Solution of $2x'$	Solution of $\lvert x'\rvert$	Fault branch	Fault distance(km)	Absolute error(m)
240.01	120.01	AT	59.99	-10
250.34	125.17	BT	99.83	170
-105.99	52.99	CT	200.01	10

Table17 The judgement of phase-to-phase grounding short-circuit fault

Solution of $2x'$	Solution of $\lvert x'\rvert$	Fault branch	Fault distance(km)	Absolute error(m)
210.15	105.07	AT	74.93	-70
150.02	75.01	BT	74.98	-20
-5.96	2.98	CT	250.02	20

Table18 The judgement of phase-to-phase grounding short-circuit fault

Solution of $2x'$	Solution of $\left\|x'\right\|$	Fault branch	Fault distance(km)	Absolute error(m)
59.96	29.98	AT	150.02	20
290.36	145.18	BT	79.82	180
-375.93	187.97	CT	65.03	30

The simulation results show that the fault location algorithm based on determinant of matrix A has high precision and feasibility. With the same two branches, the maximum absolute error is 110m; When the branches are not the same, the maximum absolute error is 180m; otherwise the error maintains within 100m, which satisfy the engineering application. In addition the algorithm does not need to know the time at which fault occurred, only to know the arrival time of the traveling wave for fault location.

CONCLUSIONS

In this paper, a fault location algorithm based on determinant of matrix A is proposed to avoid the judgment of the branches in T circuit. With the calculation of the two lines, we can directly determine the fault branch, thus reducing the actual calculations and the errors. In practical application, the wave velocity can be determined directly by the line parameters, and the arrival time accuracy of current traveling wave is improved by the wavelet transform. When the fault occurs the branch can be accurately judged by the arrival time of the traveling wave with no misjudgement, and the measurement errors meet the needs of practical engineering.

ACKNOWLEDGMENT

This work was supported by projects of Artificial Intelligence Key Laboratory of Sichuan Province (2014RYY05,2015RYY01), and projects of Sichuan University of Science & Engineering (2012PY18).

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