

# Identification of Permanent Faults for Three-phase Autoreclosing Using Inductance Parameter on Transmission Lines with Shunt Reactors

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## Abstract

*A novel method using mode component inductance parameter of shunt reactors is presented in order to identify temporary faults and permanent faults for three-phase adaptive reclosure on transmission lines with shunt reactors at both ends. The method uses  $\pi$ -type equivalent model as the prototype to build parameter identification formula. When some single phase-to-ground fault occurs, the parameter identification formula of zero-mode component is built; when some phase-to-phase fault occurs, the parameter identification formula of line-mode component is built. The current of the shunt reactor is given and the inductance of the shunt reactor is taken as the unknown parameter to evaluate the difference between the calculated inductance and the actual one so as to distinguish permanent fault from transient fault. The inductance difference of the temporary fault is minute because the actual fault model is consistent with the prototype. But the inductance difference of the permanent fault is distinct because the actual fault model is inconsistent with the prototype. Results of EMTP simulation show that the proposed method is reliable and effective, and can be applied to the three-phase adaptive reclosure on transmission lines with shunt reactors.*

**Keywords:** *transmission line; fault identification; three-phase adaptive reclosure; shunt reactors; fault criterion*

## 1. Introduction

Over the past decade, the research on identification of permanent fault is mainly directed at single-phase adaptive reclosure on transmission lines, but the research directed at three-phase adaptive is less. Compared with the traditional reclosing, three-phase adaptive reclosure technology possesses many advantages to ensure the safety and stable operation of power system, which can avoid the damage of equipment, reduce transmission capacity and even destabilize the power system.[1-3].

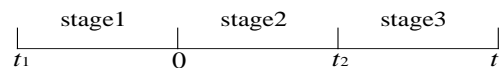
Generally, identification methods can be classified into three broad categories, including the method based on restore voltage in the instantaneous faults[4-6], the method based on arc characteristic in the instantaneous faults[7] and the method based on fault phase current characters of shunt reactors[8-10]. These methods have their own characteristics, and their scopes of application are also different. The method based on attenuation of high frequency signals is proposed to realize three-phase adaptive reclosure, but it is often affected by the line length, weather *etc* [11]. The method based on inductance parameter of shunt reactors distinguishes permanent fault from temporary fault, with  $\pi$ -prototype model of three-phase transmission line as reference model when some transient fault occurs, and with no decoupling between the reference models of three-phase. However, this method has complex identification formulas and large

computation, with insufficient sensitivity when a permanent fault occurs between two phase lines [12].

A novel method using mode component inductance parameter of shunt reactors is presented in this paper, which can distinguish permanent fault from temporary fault. Using Karrenbauer transform, three-phase system can be translated into modulus system which has no coupling relationship between two phase lines, and the parameter identification formulas of zero or line-mode component can be built. The current of shunt reactor is given and the inductance of shunt reactor is taken as the unknown parameter to evaluate the difference between the calculated inductance and the actual one. Results of EMTP simulation has demonstrated the accuracy and feasibility of this method.

## 2. Principle of Identifying Permanent Fault

The sequence of three-phase reclosure can be divided into 3 stages which are shown on Figure 1, and point “0” is the starting moment of fault. When some fault occurs, in  $0 \sim t_2$  period time, fault type and fault location are discriminated with relay protection device. At the moment of “ $t_2$ ”, circuit breaker trips out, and the fault is eliminated. So the permanent faults can be identified by using all kinds of data collected in  $0 \sim t_3$  period time.



**Figure 1. Time Sequence of Three-phase Reclosure**

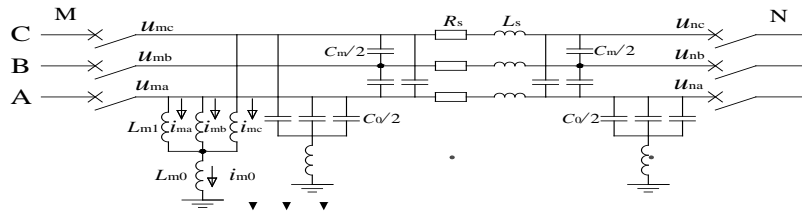
Karrenbauer transform is applied to analyze the transient process [13]. Using Karrenbauer transform, three-phase system can be translated into modulus system which contains zero-mode component and line-mode component. Based on fault type (earth faults or phase-to-phase faults) judged in  $0 \sim t_2$  period time, the current of shunt reactor is given and the inductance of shunt reactor is taken as the unknown parameter to evaluate. Using  $\pi$ -type equivalent model as the prototype, some parameter identification formulas are built. When some single phase-to-ground fault occurs, the parameter identification formula of zero-mode component is built; when some phase-to-phase fault occurs, the parameter identification formula of line-mode component is built. After inductances of shunt reactor calculated, permanent faults and temporary faults can be distinguished by using the difference between the calculated inductance and the actual inductance. The inductance difference of the temporary fault is minute because the actual fault model is consistent with the prototype. But the inductance difference of the permanent fault is distinct because the actual fault model is inconsistent with the prototype.

## 3. Formula of Parameter Identification for Transmission Lines with One-terminal Shunt Reactors

### 3.1. Equivalent Model for Temporary Fault of Three-phase Transmission System

In transmission system with three-phase reclosures, when some fault occurs, three-phase circuit breaker trips out at “ $t_2$ ” moment in Figure 1, then transmission lines lose “external excitation” and become “zero-input circuit”. So, the energy, which is stored in the elements of capacitances and inductances on transmission lines with shunt reactors, will continue to be discharged. When circuit breakers at both ends trip out, an oscillating circuit is formed between the capacitances of transmission lines and shunt reactors, and it presents free oscillation state.

When some temporary fault occurs, the model of three-phase transmission line with one-terminal shunt reactors is shown on Figure 2.



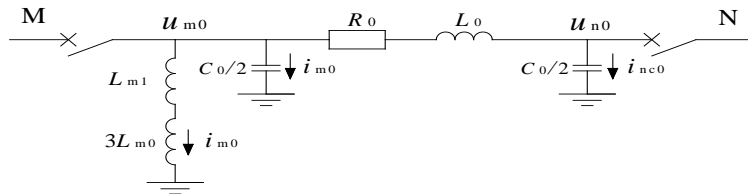
**Figure 2. Equivalent Model of π-type for the Transmission Line with One-terminal Shunt Reactors**

where  $C_0$  is the shunt capacitance of transmission lines;  $C_m$  is the capacitance between two phase lines;  $L_{m1}$  is the inductance of shunt reactors;  $L_{m0}$  is the inductance of small reactors installed on the neutral point;  $L_s$  is the reactance of transmission lines;  $R_s$  is the resistance of transmission lines;  $i_{ma}$ ,  $i_{mb}$ ,  $i_{mc}$  are current of shunt reactors for phase A, phase B and phase C at M-end respectively;  $i_{m0}$  is the current of small reactors installed on the neutral point at M-end;  $u_{ma}$ ,  $u_{mb}$ ,  $u_{mc}$  are the phase voltage for phase A, phase B and phase C at M-side respectively;  $u_{na}$ ,  $u_{nb}$ ,  $u_{nc}$  are the phase voltage for phase A, phase B and phase C at N-end respectively.

Normally, the influence of three-phase coupling is considered when the model of parameter identification formula is established. To simplify the parameter identification formula, some formula using zero-mode component is established based on Figure 2.

### 3.2. Identification Formula based on Zero-mode Parameter

Based on Figure 2, when some earth fault occurs, the parameter identification formula of zero-mode is established, and it is shown on Figure 3.



**Figure 3. Temporary Fault Zero Model for the Transmission Line with One-Terminal Shunt Reactors**

where  $R_0$  is the zero-sequence resistance;  $L_0$  is the zero-sequence reactance;  $u_{m0}$  and  $u_{n0}$  are the zero-mode voltage for M-end and N-end of transmission line respectively.

Based on Figure 3, zero-mode current formula is presented as:

$$i_{m0} + i_{mc0} + i_{nc0} = 0 \quad (1)$$

where:  $i_{mc0} = \frac{C_0}{2} \cdot \frac{du_{m0}}{dt}$ ,  $i_{nc0} = \frac{C_0}{2} \cdot \frac{du_{n0}}{dt}$ .

$u_{m0}$  and  $u_{n0}$  can be calculated by the equation (2) and (3).

$$u_{m0} = (3L_{m0} + L_{m1}) \frac{di_{m0}}{dt} \quad (2)$$

$$u_{n0} = u_{m0} + R_0(i_{m0} + i_{mc0}) + L_0 \left( \frac{di_{m0}}{dt} + \frac{di_{mc0}}{dt} \right) \quad (3)$$

In order to reduce the differential order and the calculation of equation, if setting  $L_{m1}$  as the model parameter to be solved, and if substituting parameters of equation (2) and (3) into formula (1), then formula (4) as follows can be obtained.

$$A_0 L_{m1} = -B_0 \quad (4)$$

where:

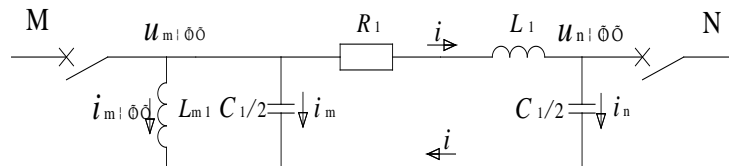
$$A_0 = C_0 \frac{d^2 i_{m0}}{dt^2} + k_1 R_0 \frac{d^3 i_{m0}}{dt^3} + k_1 L_0 \frac{d^4 i_{m0}}{dt^4},$$

$$B_0 = i_{m0} + k_2 \frac{di_{m0}}{dt} + k_3 \frac{d^2 i_{m0}}{dt^2} + k_1 k_4 R_0 \frac{d^3 i_{m0}}{dt^3} + k_1 k_4 L_0 \frac{d^4 i_{m0}}{dt^4},$$

and  $k_1 = \frac{C_0^2}{4}$ ,  $k_2 = \frac{R_0 C_0}{2}$ ,  $k_3 = C_0 \left( 3L_{m0} + \frac{L_0}{2} \right)$ ,  $k_4 = 3L_{m0}$ .

### 3.3. Analysis of Temporary Fault Line Model

Based on Figure 2, when some phase-to-phase fault occurs, the parameter identification formula of line-mode is established, and it is shown on Figure 4.



**Figure 4. Temporary Fault Line Model for the Transmission Line with One-terminal Shunt Reactors**

where  $R_1$  is the positive sequence impedance;  $L_1$  is the positive sequence reactance;  $C_1$  is the positive sequence capacitance;  $u_{m\varphi\varphi}$  and  $u_{n\varphi\varphi}$  are the line-mode voltage for M-end and N-end of transmission line respectively.

Based on Figure 4, line-mode current formula is presented as:

$$i_{m\varphi\varphi} + i_m + i_n = 0 \quad (5)$$

where:  $i_m = \frac{C_1}{2} \frac{du_{m\varphi\varphi}}{dt}$ ,  $i_n = \frac{C_1}{2} \frac{du_{n\varphi\varphi}}{dt}$ , and “ $\varphi\varphi$ ” represents phase line  $ab, bc$ , or  $ca$  respectively.

$u_{m\varphi\varphi}$  and  $u_{n\varphi\varphi}$  can be calculated by the equation (6) and (7).

$$u_{m\varphi\varphi} = L_{m1} \frac{di_{m\varphi\varphi}}{dt} \quad (6)$$

$$u_{n\varphi\varphi} = u_{m\varphi\varphi} + R_1 i + L_1 \frac{di}{dt} \quad (7)$$

where:  $i = i_m + i_{m\varphi\varphi}$ .

Similarly, in order to reduce the differential order and the calculation of equation, if setting  $L_{m1}$  as the model parameter to be solved, and if substituting parameters of equation (6) and (7) into formula (5), then formula (8) as follows can be obtained.

$$A_1 L_{m1} = -B_1 \quad (8)$$

where:

$$A_1 = C_1 \frac{d^2 i_{m\varphi\varphi}}{dt^2} + k_5 R_1 \frac{d^3 i_{m\varphi\varphi}}{dt^3} + k_5 L_1 \frac{d^4 i_{m\varphi\varphi}}{dt^4}, \quad k_5 = \frac{C_1^2}{4},$$

$$B_1 = i_{m\varphi\varphi} + \frac{R_1 C_1}{2} \frac{di_{m0}}{dt} + \frac{L_1 C_1}{2} \frac{d^2 i_{m\varphi\varphi}}{dt^2}.$$

And instantaneous value of  $i_{m\varphi\varphi}$  at the moment of “k” can be obtained with the protection device of M-end of transmission line.

#### 4. Formula of Parameter Identification for Transmission Lines with Two-terminal Shunt Reactors

For the transmission lines with two-terminal shunt reactors, when some transient fault occurs, zero-mode component model and line-mode component model are shown as Figure 5.

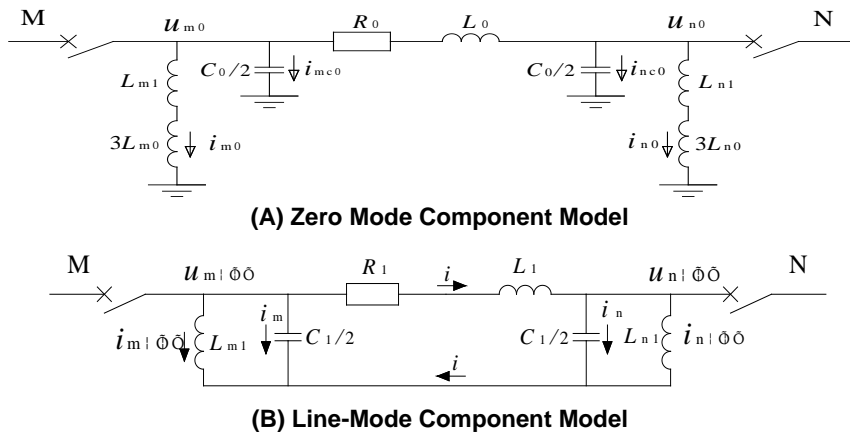


Figure 5. Temporary Fault Model for the Transmission Line with Two-terminal Shunt Reactors

Based on Figure 5.(a), when some earth fault occurs, the parameter identification formula of zero-mode is established and it is similar to the formula (4).

Where:

$$A_0 = \frac{C_0}{2} \frac{d^2 i_{m0}}{dt^2}, \quad B_0 = i_{m0} + i_{n0} + \frac{3C_0 L_{m0}}{2} \frac{d^2 i_{m0}}{dt^2} + \frac{C_0}{2} (L_{n1} + 3L_{n0}) \frac{d^2 i_{n0}}{dt^2}$$

Similarly, based on Figure 5.(b), when some phase-to-phase fault occurs, the parameter identification formula of line-mode is established and it is similar to the formula (8).

Where:

$$A_1 = \frac{C_1}{2} \frac{d^2 i_{m\varphi\varphi}}{dt^2}, \quad B_1 = i_{m\varphi\varphi} + i_{n\varphi\varphi} + \frac{C_1 L_{n1}}{2} \frac{d^2 i_{n\varphi\varphi}}{dt^2}$$

### 5. Principle Analysis and Criterion

#### 5.1. Principle Analysis

The key idea of this method is that the inductance of shunt reactors is taken as the unknown parameter to evaluate the difference between the calculated inductance “ $L_{m1}$ ”

and the actual inductance “ $L_{m1r}$ ” so as to distinguish temporary fault from permanent fault.

In theory, when some temporary fault occurs, after circuit breakers on both ends of transmission line trip out and secondary arc extinguish, the evaluated inductance parameter is similar to actual inductance parameter and does not change with time. However, when some permanent fault occurs, the actual fault model is inconsistent with the reference model, and the difference between evaluated inductance and actual parameter is significant. So, permanent faults can be identified based on the difference between calculated inductance and actual inductance.

## 5.2. The Data Processing

Since reference model is the  $\pi$ -model, the high frequency components of shunt reactor current must be filtered before calculation. In this paper, a low-pass filter whose cutoff frequency is 100 Hz is adopted.

In formula (4) and (8), because the difference of shunt reactor current cannot be solved directly, this process can only be replaced by numerical difference approximately.

On account of the influence of various errors, when some transient fault occurs,  $L_{m1}$  always fluctuates. To improve the reliability of identification, the least squares parameter estimation is adopted in this paper. That is, the value of inductance parameter is estimated by using sampling sequence values over a period of time, and then the identification parameter sequence can be obtained with the sampling time moving forward.

## 5.3. Criterion for Permanent Fault

Setting  $K(k) = \left| \frac{\sum_{i=1}^n L_{m1}(k+i) / n - L_{m1r}}{L_{m1r}} \right|$ , where  $L_{m1}(k)$  is the sequence of parameters estimated by adopting the least square method, and  $n=10$  is set so as to improve the identification reliability, the criterion for permanent fault is shown as:

$$K(k) > \lambda \quad (9)$$

where  $\lambda$  is the margin coefficient. When some fault occurs, after circuit breakers at both ends of transmission line trip out, and if formula (9) stands repeatedly, the permanent fault can be confirmed. Otherwise the temporary fault can be confirmed.

## 6. Simulation and Verification

### 6.1 The simulation system and its parameters

Based on ATP-EMTP, some 500kv transmission system with one-terminal shunt reactors is proposed, and its equivalent system of double power supply is shown as Figure 6.

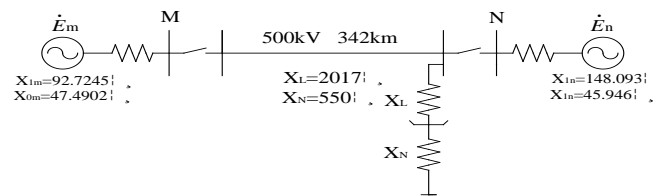
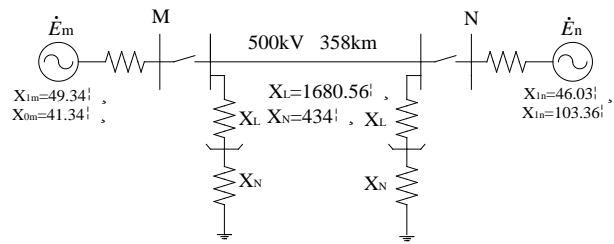


Figure 6. 500kV-transmission System with One Shunt Reactor

where:  $R_1 = 0.027 \quad \Omega/\text{km}$ ,  $R_0 = 0.1957 \quad \Omega/\text{km}$ ,  $L_1 = 0.9651 \quad \text{mH}/\text{km}$ ,  
 $L_0 = 2.211 \text{ mH}/\text{km}$ ,  $C_1 = 0.0136 \quad \mu\text{F}/\text{km}$ ,  $C_0 = 0.0092 \quad \mu\text{F}/\text{km}$ .

Similarly, based on ATP-EMTP, some 500kv transmission system with two-terminal shunt reactors is proposed, and its equivalent system of double power supply is shown as Figure 7.



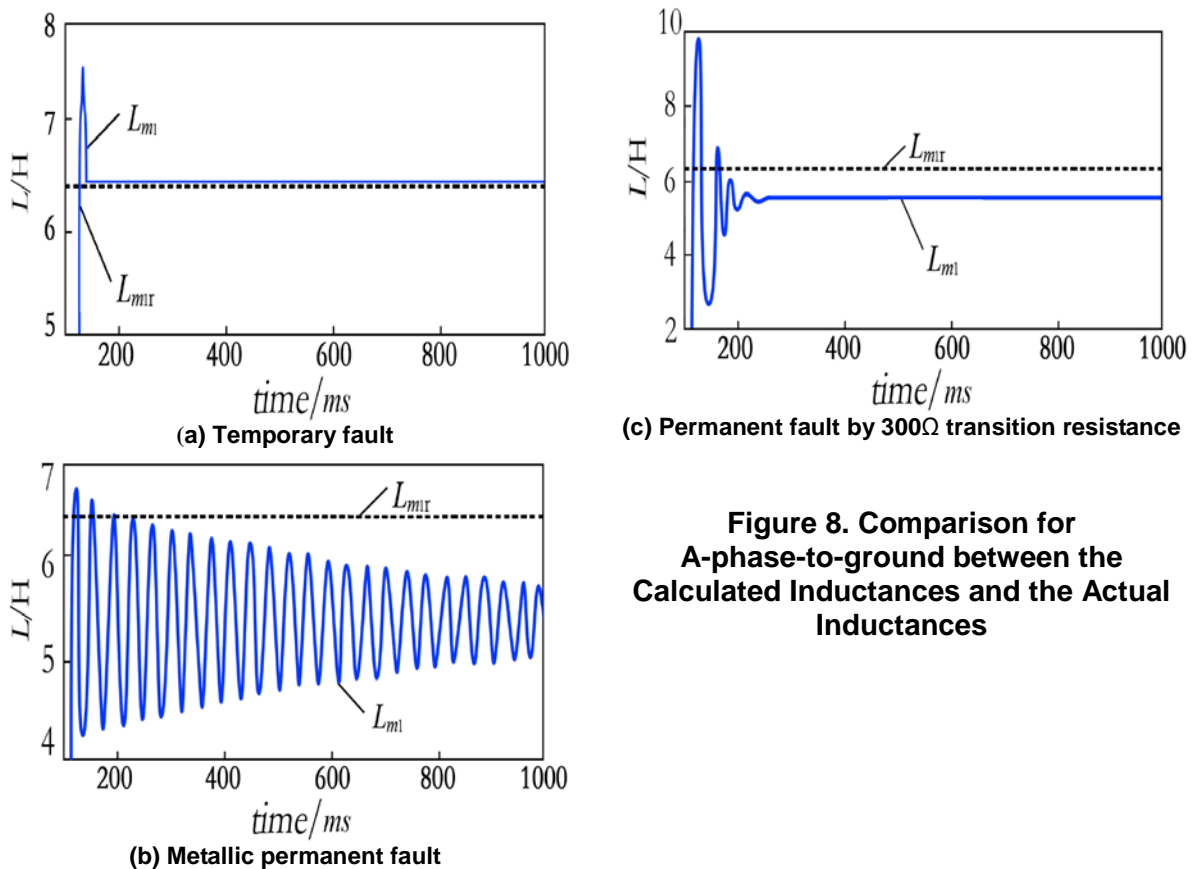
**Figure 7. 500kV-transmission SYSTEM with Two SHUNT Reactors**

where:  $R_1 = 0.0195 \Omega/\text{km}$ ,  $R_0 = 0.1675 \Omega/\text{km}$ ,  $L_1 = 0.9134 \text{ mH}/\text{km}$ ,  $L_0 = 2.719 \text{ mH}/\text{km}$ ,  
 $C_1 = 0.014 \mu\text{F}/\text{km}$ ,  $C_0 = 0.00834 \mu\text{F}/\text{km}$ .

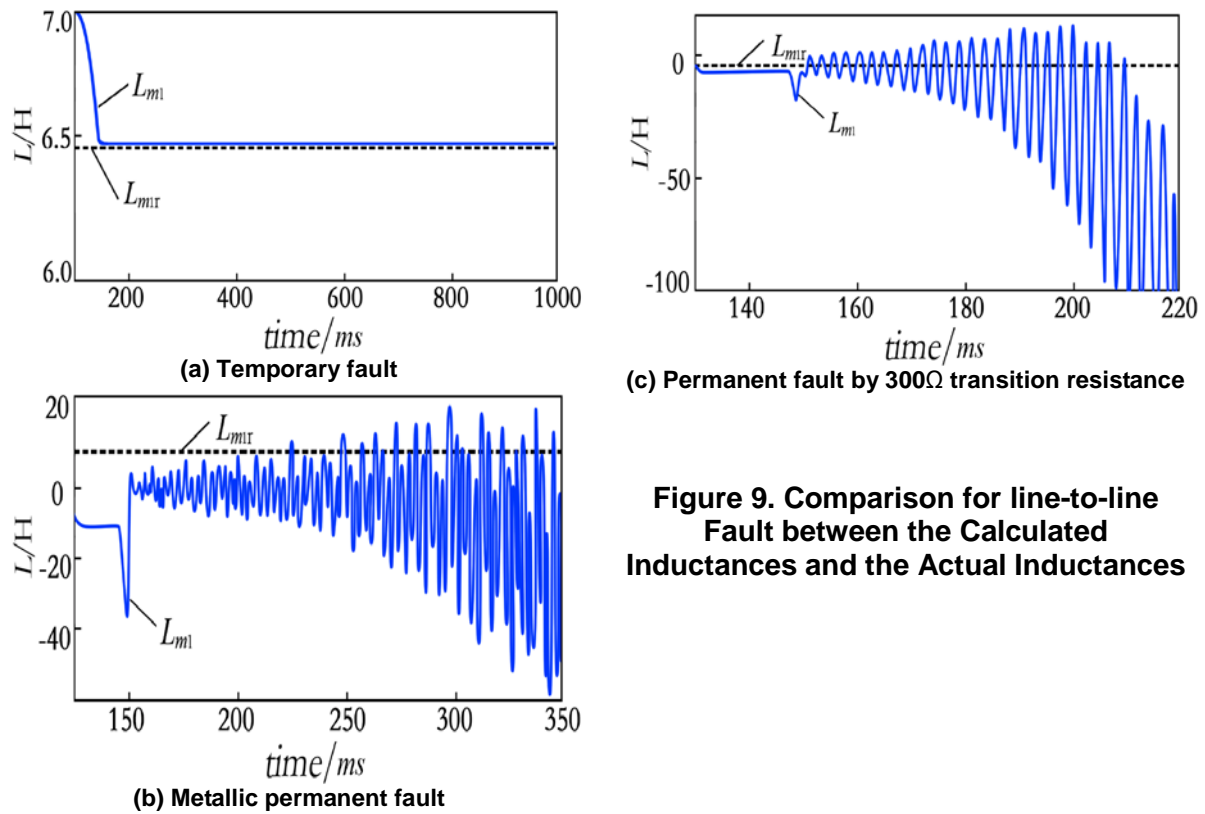
## 6.2. Simulation and Verification

In the process of simulation, the sampling frequency is set as 2kHz. When some transient fault occurs at the moment of 40ms, the circuit breaker trips out 100ms later, and the secondary arc of transient fault extinguishes.

Comparing fault types, the calculated inductances of “ $L_{m1}$ ” and the actual inductances of “ $L_{m1r}$ ” are shown on Figure 8 and Figure 9, where transient fault occurs at somewhere 200 km away from N-end of transmission line with one-terminal shunt reactors.



**Figure 8. Comparison for A-phase-to-ground between the Calculated Inductances and the Actual Inductances**



**Figure 9. Comparison for line-to-line Fault between the Calculated Inductances and the Actual Inductances**

Figure 8 and Figure 9 show: when some temporary fault occurs, after circuit breaker trips out and secondary arc extinguishes, the evaluated inductance parameter of “ $L_{m1}$ ” is similar to the actual inductance parameter of “ $L_{m1r}$ ”. However, when some permanent fault occurs, the actual fault model is inconsistent with the reference model, and “ $L_{m1}$ ” deviates from “ $L_{m1r}$ ” significantly. Figure 9 (a) and (b) also show: when some phase-to-phase permanent fault occurs, energy stored in the capacitors and inductors is released quickly, and the difference between “ $L_{m1}$ ” and “ $L_{m1r}$ ” increases dramatically after the circuit breaker trips out, and what's worse, short circuit by transition resistance occurs.

In order to verify the applicability of the criterion in different fault positions and transition resistance situations, simulation results are shown at the following tables corresponding to different transmission systems with shunt reactors, where the fault locations are presented by the percentage of the length of transmission line which starts from fault position to the N-end of transmission line, and  $L = \frac{1}{10} \sum_{k=601}^{610} |L_{m1}(k)|$ ,  $K = \left| \frac{L - L_{m1r}}{L_{m1r}} \right| \times 100\%$ . “ $K$ ” presents the value of “ $K(k=165ms)$ ” in criterion formula (9).

**Table 1. Results for A-phase-to-ground with One-terminal Shunt Reactors Line System**

Fault point/%	Resistance/Ω	Temporary fault		Permanent fault	
		L/H	K/%	L/H	K/%
0	0.1	6.3792	0.789	6.8055	5.97
	300	6.4702	0.681	5.3743	16.31
50	0.1	6.4697	0.782	5.9798	6.69
	300	6.3991	0.811	5.3913	15.89
100	0.1	6.4701	0.783	5.6008	15.01
	300	6.4698	0.819	5.3753	16.47



**Table 2. Results for Double Line-to-ground Fault w with One-terminal Shunt Reactors Line System**

Fault point/%	Resistance/ $\Omega$	Temporary fault		Permanent fault	
		L/H	K/%	L/H	K/%
0	0.1	6.3871	0.966	7.2991	13.82
	300	6.3897	1.117	4.6908	25.93
50	0.1	6.4912	0.824	4.8319	24.74
	300	6.4719	0.781	4.7103	26.02
100	0.1	6.4679	0.763	4.8183	25.15
	300	6.5127	0.832	4.7079	25.17

**Table 3. Results For Line-to-line Fault with One-terminal Shunt Reactors Line System**

Fault point/%	Resistance/ $\Omega$	Temporary fault		Permanent fault	
		L/H	K/%	L/H	K/%
0	0.1	6.3929	0.349	8792	128901
	50	6.3901	0.317	13142	200141
50	0.1	6.5121	0.338	821.9	113972
	50	6.5301	0.319	6409	110081
100	0.1	6.3996	0.321	0.7207	84.56
	50	6.3921	0.342	8359	129105

**Table 4. Results for Three-phase Fault with One-terminal Shunt Reactors Line System**

Fault point/%	Resistance/ $\Omega$	Temporary fault		Permanent fault	
		L/H	K/%	L/H	K/%
0	0.1	6.3902	0.297	13917	201699
	50	6.3817	0.289	4029	53967
50	0.1	6.4391	0.301	493.17	7627
	50	6.5013	0.321	849.18	12879
100	0.1	6.3978	0.271	0.9760	81.76
	50	6.4629	0.251	2692.1	42942

**Table 5. Results for Line-to-line Fault with Two-terminal Shunt Reactors Line System**

Fault point/%	Resistance/ $\Omega$	Temporary fault		Permanent fault	
		L/H	K/%	L/H	K/%
0	0.1	5.3713	1.491	5824	104927
	50	5.3913	1.523	8679	138849
50	0.1	5.3819	1.536	116.33	2301
	50	5.6129	1.572	2405	42991
100	0.1	5.5527	1.534	196.07	3418
	50	5.3927	1.528	3210	57688

**Table 6. Results for Three-Phase Fault with Two-terminal Shunt Reactors Line System**

Fault point/%	Resistance/ $\Omega$	Temporary fault		Permanent fault	
		L/H	K/%	L/H	K/%
0	0.1	5.3811	1.527	12481	238468
	50	5.2893	1.548	2478	42684
50	0.1	5.2904	1.519	286.47	5369
	50	5.3921	1.532	1201	21698
100	0.1	5.4287	1.566	269.89	5345
	50	5.3719	1.554	755.07	14014

From the tables above, it is obvious that whether it is the line with shunt reactors at one end, or the line with shunt reactors at both ends, when some temporary fault occurs, the value of “K” is

smaller, and the evaluated inductance parameter is similar to actual inductance parameter. However, when a permanent fault occurs, the value of “ $K$ ” is larger in most cases, the actual fault model is inconsistent with the reference model, and the difference between evaluated inductance and actual parameter is significant.

## 7. Conclusion

A novel permanent fault identification method suitable for three-phase adaptive reclosure is proposed in this paper. In the presented method, the inductance parameter of mode component on transmission line with shunt reactors is used. Two parameter identification formulas are built to evaluate the difference between the calculated inductance and the actual one so as to identify temporary faults and permanent faults. In this approach, the identification formula is characterized by simplification, less calculation, high velocity, high efficiency and etc. Results of EMTP simulation show that the proposed method can reliably and effectively distinguish permanent fault from transient fault, and is suitable for the three-phase adaptive reclosure in transmission lines with shunt reactors.

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