A New Method for Identifying the Fault Location on Series Compensated Lines Based on Transient Fault Information

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***Abstract*—Based on the transient circuit model of series compensated line, a new method for identifying the fault location relative to series capacitor (SC) is proposed. Comparing the transient model of series compensated line when fault occurs before the SC and the one when fault occurs after the SC, it is found that the only difference is the value of a model-parameter: it respectively equals 0 and a large value under the two circumstances. This method using transient data at several sample points after fault occurs calculates the model-parameter to identify the fault location. Since only the transient information before MOV operation is used, MOV's nonlinear characteristic needn't to be considered. The method is applicable to both single phase to earth fault and phase to phase fault. Moreover, communication channels can be saved for only locally derived information is used. The validity of the method is proved by simulating results.**

***Keywords*—series compensated lines, fault location, MOV, transient information, model-parameter identification.**

I. INTRODUCTION

Series capacitor compensation technique has been widely used in long distance EHV transmission systems to improve transient stability, increase power transfer capability, and reduce voltages drop along the lines[1~6]. However, the employment of series compensation creates certain problems for protective relays of transmission lines using conventional techniques. The most important singularity lays in the fact that the positive sequence impedance measured by traditional distance relays is no longer an indicator of the distance to a fault[7]. Additionally, the nonlinearity of MOV (Metal Oxide Varistor) which provides over-voltage protection for SC complicates the problems greatly[8~9].

The main problem when applying the traditional distance protection on series compensated lines is overreach for external faults. Currently the solutions can be divided into three types[2][10~11]: (a). Setting the protection range according to Z_{zd}-j$|Z_C|$, where Z_{zd} is 0.8~0.9 times the impedance of the line and Z_c is the impedance of SC. This solution avoids protection misoperation for external faults at the cost of sensitivity. But when Z_c is very large the protection sensitivity is very low, even equals zero. (b). Voltage-detected program, assuming the voltage across the SC always equals its protective level, however, when faults occur before the SC or faults occur after SC meanwhile the SC is bypassed, the protection sensitivity is still low. (c). Fault location indentifying program, firstly identify the fault is located before SC or after it according to the different characteristics between the two circumstances, only when the fault is located after SC the voltage-detected program in (b) is adopted. [12] employs this program and presents a fault location identifying method based on different fault models, but it only apply to the single phase to earth faults.

Nowadays, transient-based protection is one of hot topics in protection research area[13~15]. Based on transient fault information a new method for identifying the fault location relative to SC is presented in this paper. This method only uses the transient data at several sample points after faults occur, so it is unaffected by MOV's nonlinear characteristic for it must take a while to operate for MOV after faults occur. Both single phase to earth faults and phase to phase faults are considered in the method. Moreover, communication channels can be saved for only locally derived information is used. The simulation results in PSCAD/EMTDC verify its correctness and effectiveness.

II. MODEL OF SERIES COMPENSATED SYSTEM AND ANALYSIS OF MOV CHARACTERISTIC

Fig.1 shows the model of a typical series compensated system which concludes the protection scheme.

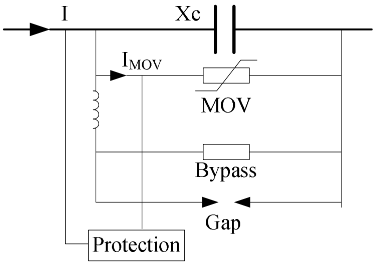

Figure 1. Model of a series compensated system

MOV is a nonlinear element which provides over-voltage protection for SC. When the transmission lines operate normally, the voltage across SC is low, and the resistance of MOV appears very large. When the fault occurs, the large short-circuit current leads high voltage across SC. Once the

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voltage rises to a certain setting value, MOV switches into conduction and limits the voltage. After MOV operates, it is very difficult to obtain the voltage across SC due to MOV's nonlinearity[15].

The short-circuit faults on transmission lines are often through transition resistance, thus the fault current is to some extent limited. Meanwhile, the voltage across a capacitor cannot change instantaneously according to circuit theorem. For the reasons outlined above, there must be a process for voltage across SC rising to the value that can conduct MOV. Research results of [12] show that even under the most serious fault condition the process lasts for several milliseconds. During this shot time, the affection of MOV's nonlinearity needn't be considered. Ideally, only using the data at several sample points after fault occurs, the method proposed in this paper can identify the fault location. However, considering various actual factors, the data in several milliseconds is still sufficient to ensure the correctness of identification.

III. PRINCIPLE OF IDENTIFYING FAULT LOCATION BASE ON TRANSIENT INFORMATION

Fig.2 shows the transient circuit model of series compensated lines.

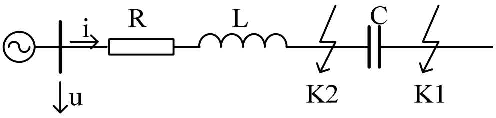


Figure 2. Transient circuit model of series compensated lines

When the fault occurs at K1,

$$u = \mathrm{R}i + \mathrm{L}\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{1}{\mathrm{C}}\int_{-\infty}^{t} i\mathrm{d}t \tag{1}$$

Calculating the derivative,

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \mathrm{R}\frac{\mathrm{d}i}{\mathrm{d}t} + \mathrm{L}\frac{\mathrm{d}^2 i}{\mathrm{d}t^2} + \frac{1}{\mathrm{C}}i = \mathrm{L}(\mathrm{K}\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\mathrm{d}^2 i}{\mathrm{d}t^2}) + \frac{1}{\mathrm{C}}i \tag{2}$$

K=R/L=r/l (r , l respectively represent resistance and inductance of transmission lines per unit length), K is a constant which can be determined beforehand.

Similarly, when the fault occurs at K2,

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \mathrm{R}\frac{\mathrm{d}i}{\mathrm{d}t} + \mathrm{L}\frac{\mathrm{d}^2 i}{\mathrm{d}t^2} = \mathrm{L}(\mathrm{K}\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\mathrm{d}^2 i}{\mathrm{d}t^2}) \tag{3}$$

(3) can be regarded as the special case of (2) in which $\frac{1}{\mathrm{C}}=0$. Therefore, (2) is always valid under the both circumstances. The following part only handles (2).

In (2), i is sample data, $\frac{\mathrm{d}i}{\mathrm{d}t}$, $\frac{\mathrm{d}^2 i}{\mathrm{d}t^2}$, $\frac{\mathrm{d}u}{\mathrm{d}t}$ can be calculated using sampled data as following:

$$\begin{cases} \dfrac{\mathrm{d}i(n)}{\mathrm{d}t} = \dfrac{i(n+1) - i(n-1)}{2T_s} \\ \dfrac{\mathrm{d}u(n)}{\mathrm{d}t} = \dfrac{u(n+1) - u(n-1)}{2T_s} \\ \dfrac{\mathrm{d}^2 i(n)}{\mathrm{d}t^2} = \dfrac{i(n+1) + i(n-1) - 2i(n)}{{T_s}^2} \end{cases} \tag{4}$$

Only L, $\frac{1}{\mathrm{C}}$ are unknown. L is the inductance of line in the fault loop. $\frac{1}{\mathrm{C}}$ is an indicator of the fault location relative to SC, if it equals zero the fault point is before SC, else it is after SC. Thus, the objective is to work out the value of $\frac{1}{\mathrm{C}}$.

Each sample point after the fault occurs can form an equation by substituting the sample data into (2). Since there are only two unknowns, $\frac{1}{\mathrm{C}}$ can be work out by solving equations at two sample points.

The following analysis discusses whether the solutions exist by considering the linear independence between equations at different sample points. When the system runs in the steady state, the current is simple harmonic. Assuming $i = I_m \sin(\omega t + \theta)$, the determinant of equations set is:

$$\begin{aligned} \Delta &= \\ &\begin{vmatrix} \mathrm{K}\omega I_m \cos(\omega t_1 + \theta) - \omega^2 I_m \sin(\omega t_1 + \theta) & I_m \sin(\omega t_1 + \theta) \\ \mathrm{K}\omega I_m \cos(\omega t_2 + \theta) - \omega^2 I_m \sin(\omega t_2 + \theta) & I_m \sin(\omega t_2 + \theta) \end{vmatrix} \\ &= \mathrm{K}\omega {I_m}^2 \sin[\omega(t_2 - t_1)] \neq 0 \end{aligned} \tag{5}$$

Hence the solutions exist. During the transient state after faults, the fault current includes abundant no-periodic component and harmonic component besides steady component. These components increase the linear independence of equations consequently assure the existence of solutions.

To decrease the disturbance and improve the accuracy, the least square optimal method is adopted. Assuming:

$$\begin{cases} a_1 = \mathrm{L} \\ a_2 = \dfrac{1}{\mathrm{C}} \end{cases}, \begin{cases} g_1(n) = \mathrm{K}\dfrac{\mathrm{d}i(n)}{\mathrm{d}t} + \dfrac{\mathrm{d}^2 i(n)}{\mathrm{d}t^2} \\ g_2(n) = i(n) \end{cases}, y(n) = \frac{\mathrm{d}u(n)}{\mathrm{d}t} \tag{6}$$

Substituting them to (2):

$$g_1 a_1 + g_2 a_2 = y \tag{7}$$

($g_1(n)$, $g_2(n)$, $y(n)$)($n = 1,2,\cdots,m$) is sample data at m sample points. The objective of optimization is to find a_1, a_2 which minimize E^2, that is:

$$E^2 = \sum_{n=1}^{m}\left[\sum_{k=1}^{2} a_k g_k(n) - y(n)\right]^2 = \min \tag{8}$$

The necessary condition of (8) is:

$$\frac{\partial E^2}{\partial a_k} = 0, \quad k = 1,2 \tag{9}$$

(9) can be changed into:

$$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}=\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tag{10}$$

Where,

$$\begin{cases} h_{ij} = \sum\limits_{n=1}^{m} g_i(n)g_j(n), \quad i,j=1,2 \\ b_i = \sum\limits_{n=1}^{m} g_i(n)y(n), \quad i=1,2 \end{cases} \tag{11}$$

a_2 (i.e. $\frac{1}{C}$) can be obtained by solving (10). On the basis of above analysis, if the fault occurs at K1 $\frac{1}{C}$ should be the inverse of SC's capacity and its value is very large, and if the fault occurs at K2 $\frac{1}{C}$ should equal zero. Therefore the fault location can be identified according to the solved value of $\frac{1}{C}$ by the following criterion:

$$\begin{cases} \left|\frac{1}{C}\right| < \left(\frac{1}{C}\right)_{set} & \text{fault located before SC} \\ \left|\frac{1}{C}\right| > \left(\frac{1}{C}\right)_{set} & \text{fault located after SC} \end{cases} \tag{12}$$

To improve the reliability of identification, $\left(\frac{1}{C}\right)_{set}$ can be set by $\left(\frac{1}{C}\right)_{set} = 0.5\times\frac{1}{C_{SC}}$ where C_{SC} is the value of SC's capacity.

IV. APPLICATION IN THREE-PHASE TRANSMISSION LINES

A. *Clark transform*

In order to simplification the above principle analysis is based on single phase system, but the practical three-phase system have complicated electromagnetic coupling. To realize decoupling Clark transform is adopted considering the method proposed is based on time domain where sequence component method is no longer suitable. The transform matrix is expressed as[6]:

$$\begin{bmatrix} F_0 \\ F_1 \\ F_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \times \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} \tag{13}$$

The three phase system can be transformed into three mode network, 1-mode, 2-mode and 0-mode. To symmetrical three phase transmission lines, the 1-mode resistance and inductance, 2-mode resistance and inductance, 0-mode resistance and inductance respectively equal positive-sequence resistance and inductance, negative-sequence resistance and inductance, zero-sequence resistance and inductance.

B. *Single phase to earth faults*

Fig. 3 shows a three phase system with single phase to earth fault. Applying Clark transform the voltage of a-phase at M side in time domain is:

$$u_{ma} = \mathrm{R}_1(i_{ma} + \mathrm{K}_r \times 3i_{m0}) + \mathrm{L}_1\frac{\mathrm{d}(i_{ma} + \mathrm{K}_l \times 3i_{m0})}{\mathrm{d}t} + \frac{1}{\mathrm{C}}\int_{-\infty}^{t} i_{ma}\mathrm{d}t + i_{fa}\mathrm{R}_f \tag{14}$$

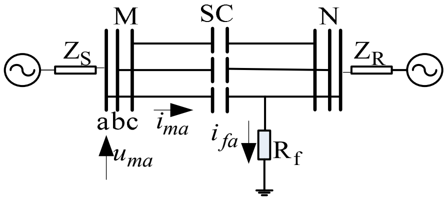


Figure 3. Three phase system with single-phase-to-earth fault

K_r , K_l are the 0-mode compensating factor of resistance and inductance respectively. Assuming r_0 , r_1 , l_0 , l_1 are 0-mode resistance,1-mode resistance, 0-mode inductance,1-mode inductance respectively, $\mathrm{K}_r = (r_0 - r_1)/3r_1$, $\mathrm{K}_l = (l_0 - l_1)/3l_1$. They are constants and can be computed forehand from line parameters; u_{ma} , i_{ma} , i_{m0} are instantaneous value of a-phase voltage at M side, a-phase current and 0-mode current respectively and can all be obtained by sample data; i_{fa} is fault current of a-phase and it has relationship with i_{f0} , the 0-mode current at fault point , as following:

$$i_{fa} = 3i_{f0} \tag{15}$$

i_{f0} can be detected directly at M side, but it has relationship with i_{m0} , the 0-mode current at M side, as following:

$$\mathrm{K}_{f0} = \frac{i_{m0}}{i_{f0}} \tag{16}$$

K_{f0} is the current distribution ratio in 0-mode network shown in Fig.4. [16] gives the conclusion that because of the existence of system impedance even in the series compensated lines the impedance angle difference between two sides of the fault point is less than 100 and it can be approximately assumed that the zero sequence current through relay-installed place and the one through fault point have the same phase angle. Based on this, K_{f0} is regarded as a constant here. Defining:

$$\mathrm{R}_f{'} = \frac{\mathrm{R}_f}{\mathrm{K}_{f0}} \tag{17}$$

$\mathrm{R}_f{'}$ is also a constant, substituting (15), (16) and (17) into (14),

$$u_{ma} = \mathrm{R}_1(i_{ma} + \mathrm{K}_r \times 3i_{m0}) + \mathrm{L}_1\frac{\mathrm{d}(i_{ma} + \mathrm{K}_l \times 3i_{m0})}{\mathrm{d}t} + \frac{1}{\mathrm{C}}\int_{-\infty}^{t} i_{ma}\mathrm{d}t + 3i_{m0}\mathrm{R}_f{'} \tag{18}$$

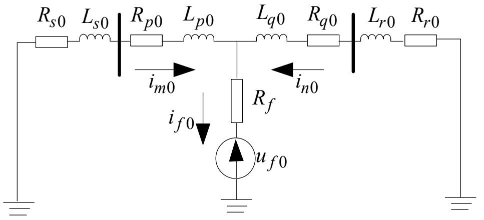


Figure 4. Zero modal network of the single-phase-to-earth fault

Compared with (2), (18) have one more unknowns, R_f', so at least three sample points are necessary to work out $\frac{1}{C}$. The least square optimal method using redundant data to some extent correct the error caused by assuming K_{f0} is a constant.

C. *Phase to phase faults*

For phase to phase faults, the transition resistance between two fault phases is mainly caused by arc. It is very low and can be ignored. Assuming short circuit occurs between A-phase and B-phase, then:

$$u_{ab} = R_1 i_{ab} + L_1 \frac{di_{ab}}{dt} + \frac{1}{C}\int_{-\infty}^{t} i_{ab} dt \tag{19}$$

u_{ab}, i_{ab} are respectively the voltage difference and current difference between two fault phases. (19) has the same form as (1), so it can be handled by the method mentioned above.

V. CASE STUDIES

To validate the proposed method, a practical series compensated line named Yi Feng is taken as a case. Its model is established in PSCAD/EMTDC and the simulation data is handled by a MATLAB program which realizes the method proposed.

Yi Feng series compensated system of 500kV is shown as Fig. 5. The SC is installed at the Fengtun side. The compensated degree is 25%, therefore the capacity of SC is $119\mu F$. According to the criterion mentioned above, $\left(\frac{1}{C}\right)_{set}$ should be 4200. The system parameters are given as following.

Impedance of sending end:

$$Z_{S1} = 1.82 + j189.3\Omega, Z_{S0} = 1.12 + j106.2951\Omega$$

Impedance of receiving end:

$$Z_{R1} = 1.731 + j180.98\Omega, Z_{R0} = 1.38 + j130.87\Omega$$

Parameters of line:

$$z_1 = 0.0242 + j0.295\Omega/\text{km}, c_1 = 0.016\mu\text{F/km}$$

$$z_0 = 0.299 + j1.33\Omega/\text{km}, c_0 = 0.00944\mu\text{F/km}$$

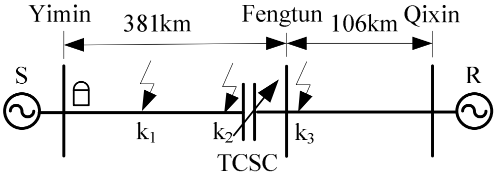
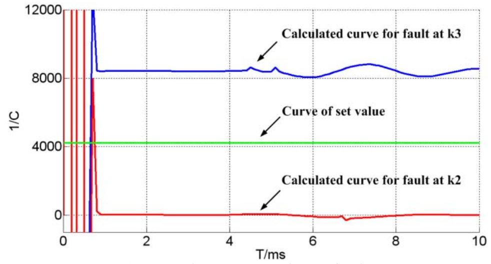


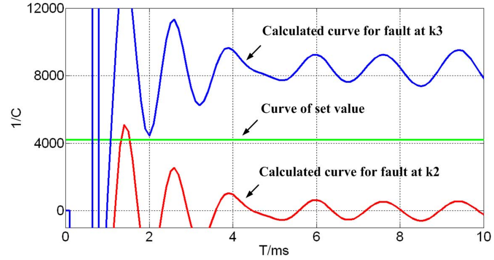
Figure 5. Yifeng series compensated system

Arranging three fault points along the series compensated line: k_1 (190 km far from Yimin), k_2 (381 km far from Yimin, before SC) and k_3 (381 km far from Yimin, after SC). At each point all types of faults are simulated and the faults occur at 0 s.

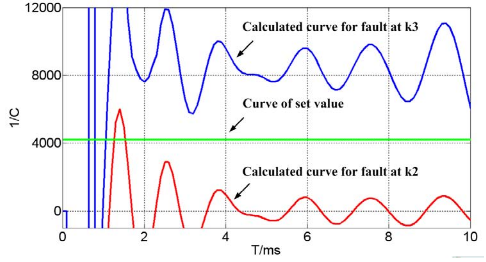
Fig.6 shows the calculated curve of $\frac{1}{C}$ when different faults occur. It can be seen from the figure that for faults at k_3 the value of calculated $\frac{1}{C}$ is much larger than the set value and for faults at k_2 it is much smaller than the set value. The more simulation results are listed in Table I. From the figure and table, it can be concluded that the proposed method can identify the fault location relative to SC to all types of short-circuit faults and it has little influence of transition resistance.



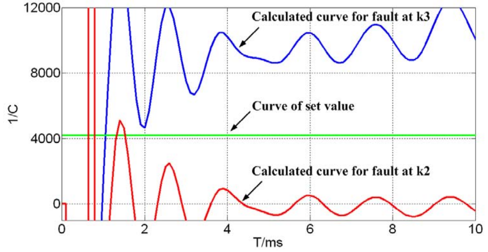
(a) A-phase to B-phase fault



(b) A-phase to earth fault



(c) A-phase to earth through 50Ω fault



(d) A-phase to earth through 200Ω fault

Figure 6. Calculated curve

TABLE I. SIMULATION RESULTS FOR FAULTS ALONG THE SERIES COMPENSATED LINE

Fault Point	**Identifying Rusults**						
	A-B	***A-B-G***	***A-B-C-G***	***A-G through transition resistance***			
				0 Ω	*50Ω*	*100Ω*	*200 Ω*
k_1	before	before	before	before	before	before	before
k_2	before	before	before	before	before	before	before
k_3	after	after	after	after	after	after	after

"A-B-G" represents A- B-phase earth fault, "before" represents the fault occurs before SC. The rest are same with this analogize

VI. CONCLUSION

Based on the analysis of transient model of series compensated line, a new method for identifying the fault location relative to SC has been presented in this paper. Its advantages can be concluded as following: (a) Only using the transient data before MOV's operation, it is not affected by MOV's nonlinearity. (b) It is applicable to all types of short-circuit faults. (c) Cooperated with this new method, traditional distance protection will avoid overreach for external faults and the sensitivity of Zone I can be greatly improved.

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