INFLUENCE OF PARALLEL LINE MUTUAL COUPLING ON DISTANCE RELAY OPERATION

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ABSTRACT

When two or more lines are running parallel to each other, mutual impedances between the lines influence the voltage and current profile measured by protective relays installed on each line. In this article the behavior of a distance relay on a double circuit transmission line is analyzed and simulated using Matlab/Simulink software. This article discusses about the influence of mutual impedance on impedance measured by distance protection and shows possibility of compensation these adverse effects using different compensation factors. Double-circuit 400 kV overhead lines supplied from two sides were used for this purpose. Phase-to-earth faults in different configurations of parallel lines in power systems were simulated on this network.

Keywords: *distance relay, Matlab, mutual impedance, parallel line, zero sequence factor*

1. INTRODUCTION

The principle of distance relaying is well-known: the impedance measured by a relay is proportional to the distance of that relay to the fault. Hence, by measuring the impedance it can be determined whether the line-to-be-protected is faulted or not [1].

Distance protection uses voltage and current to determine the zone of the fault. A distance protection scheme generally includes three phase distance elements (21) and three ground distance elements (21N), with three or more protection zones each. Source impedance changes have almost no effect on the high-speed zone reach of distance protection [2].

In transmission systems throughout the world, it is very common to find double-circuit towers transmitting power in narrow physical corridors. In many cases, two or more lines share the same right of way, or two or more circuits use the same transmission towers. Constructing a multiple-circuit line is less expensive than building separate transmission lines [2], [3].

Magnetic mutual induction occurs in multiple-circuit lines and also in single-circuit lines that run in close proximity to each other using the same right of way. Modeling mutually coupled lines for short-circuit analysis requires considering multiple factors, including line geometry and the multiple couplings that can take place in the right-of way corridors.

Magnetic mutual coupling affects mainly the zero sequence networks. Ground distance elements, which respond to zero sequence quantities, can be affected by mutual coupling. The user must either set these elements considering mutual coupling or apply compensation methods [2].

Fig. 1(a) is typical in double-circuit towers. This arrangement is generally the one that has received most consideration in literature. Fig. 1(b) illustrates the partial parallel trajectory of the two lines for a distance “d.” The two lines originate in a common bus and end in separate buses. Fig. 1(c) and Fig. 1(d) illustrate independent lines running in parallel for a distance “d” [3].

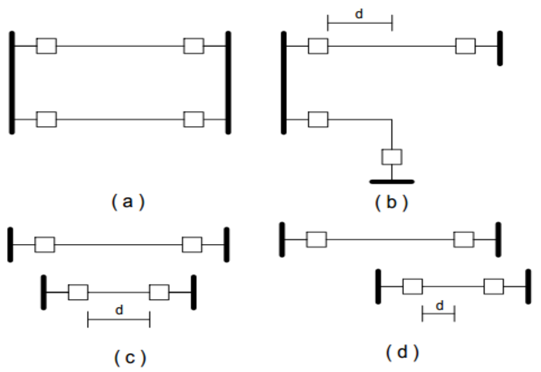

Fig. 1 Configuration of parallel lines in power systems

2. SETTINGS OF DISTANCE RELAY AT GROUND FAULTS IN POWER SYSTEM

Since the impedance seen by the distance relay is only based on the voltages and currents at the relay-installed point, its characteristic inherently varies. If the magnitude of load current varies or if there exists any ground resistance at a fault, the impedance seen by the distance relay will be significantly different from the actual impedance [4].

2.1. Measured impedance by ground distance elements

For a phase-to-ground fault, the input signals to the ground distance element are the current $I = I_a + k_0.I_r$ and the voltage $V = V_a$.

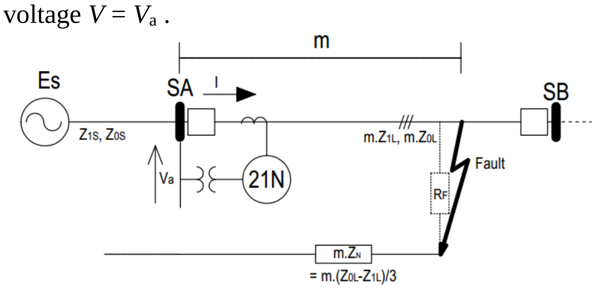

Fig. 2 Single Phase to Ground Fault

Calculation of impedance loop using residual compensation factor without influence of arc presented in Fig. 2 is given by:

$$Z_a = \frac{V_a}{I_a + k_0 I_r} \tag{1}$$

where:

k_0 – residual compensation factor,

Z_a, I_a, V_a – impedance, current, and voltage in phase A at the point where relay is installed,

I_r – residual (neutral) current ($I_r = I_a + I_b + I_c = 3.I_0$).

$$k_0 = \frac{Z_{0L} - Z_{1L}}{3Z_{1L}} \tag{2}$$

where:

Z_{0L} and Z_{1L} – zero and positive sequence impedances of the transmission line protected by the relay.

Impedance reach of zone must be set for all types of faults that may occur in the protected system. For this reason, it is important to find out which parameters of power line are necessary for this purpose.

Tripping characteristic for distance protection is set to positive sequence of impedance with different resistance range for phase-to-phase and phase-to-earth faults, due to the influence of the arc [5].

2.2. Impact of Mutual Coupling on Ground Distance Elements

Fig. 3 shows two parallel, mutually coupled lines. For a phase-to-ground fault on Line 1, the input signals to the ground distance element are the current $I = I_a + k_0.I_r$ and the voltage $V = V_a$ given by (3).

$$V_a = m.Z_{1L}.(I_a + k_0.I_r) + m.Z_{0M}.I_{0M} \tag{3}$$

where:

I_{0M} – is the zero-sequence current in the coupled line.

Z_{0M} – is the zero-sequence mutual coupling impedance between both lines.

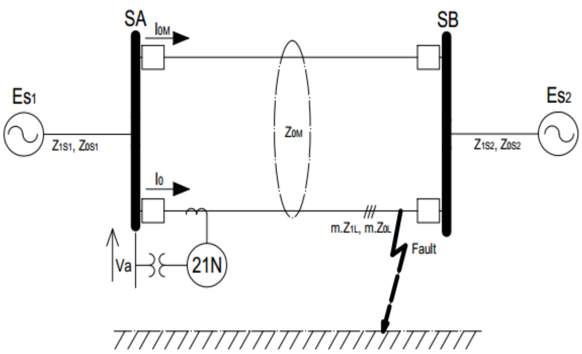

Fig. 3 Influence of mutual impedance on ground distance elements (In service)

Equation (4) gives the impedance Z_{APP} measured by the AG ground distance element on Line 1 [2].

$$Z_{APP} = \frac{V_a}{I_a + k_0 I_r} = m.Z_{1L} + m.Z_{0M} \frac{I_{0M}}{I_a + k_0 I_r} \tag{4}$$

The measured or apparent impedance Z_{APP} includes an error term, which is positive when currents I_{0M} and I_0 flow in the same direction (underreach) and negative when these currents flow in opposite directions (overreach). A distance element overreaches when the measured impedance is smaller than the actual impedance to the fault location. The element underreaches when the measured impedance is greater than the actual impedance to the fault location.

For the fault condition shown in Fig. 3, Z_{APP} is greater than m.Z_{1L} (the ground distance element underreaches). Fig. 4 is not an uncommon condition in a power system. For maintenance purposes, the parallel line is grounded at both ends, and the other line is in service. A ground fault in the operating line will produce a zero-sequence current in the parallel line. In this case currents I_{0M} and I_0 flow in opposite directions. Error term in (4) is negative and ground distance elements overreach [2].

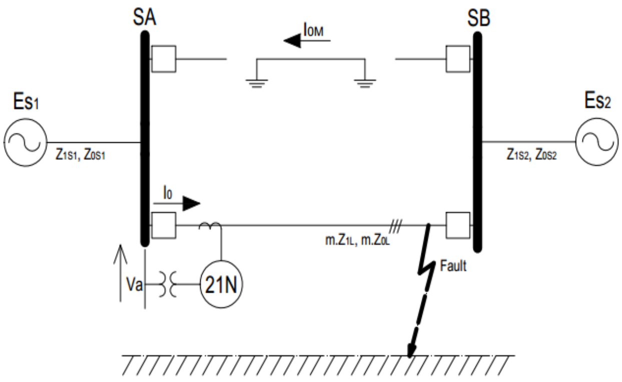

Fig. 4 Influence of mutual impedance on ground distance elements (One line grounded)

These impedance measurement errors affect ground distance elements of both lines and also affect impedance based single-ended fault locating algorithms using zero sequence quantities.

3. METHODS OF MUTUAL COUPLING COMPESATION USED FOR GROUND DISTANCE RELAYS

This subsection describes two methods to mitigate ground distance element errors either using reach settings or applying residual compensation factor.

3.1. Using fixed reach settings that consider impact of mutual impedance

This method consists of carefully determining ground distance element reach settings by calculating the apparent impedance considering mutual coupling for all practical system configurations and fault locations. Settings calculations require many contingency evaluations and extensive study of the power system under faulted conditions [2].

The measured impedances were derived from (4) with the following assumptions:

- The phase current and the residual current of the protected line are equal ($I_a = I_r$)

- The coupled line residual current is equal to the residual current of the protected line ($I_r = 3I_{0M}$).

In power system we can have three different switching states of the coupled line, namely [2]:

In service, where impedance is given:

$$Z_{APP} = Z_{1L} + \frac{Z_{0M}}{3(1+k_0)} \quad (5)$$

Out of service and grounded at one point only or not grounded, where impedance is given:

$$Z_{APP} = Z_{1L} \quad (6)$$

Out of service and grounded at both line ends, where impedance is given:

$$Z_{APP} = Z_{1L} - \frac{Z_{0M}^2}{3Z_{0L}(1+k_0)} \quad (7)$$

The formula (5) is a underreaching condition, the second formula (6) represents a correct measured impedance, and the last formula (7) is an overreaching condition. One alternative to deal with these scenarios is for the user to select reach settings values that accommodate all three scenarios. Another alternative is to use different settings groups.

In the fixed settings alternative, Zone 1 reach should be set smaller than the measured impedance for the third scenario (Out of service and grounded at both line ends). Zone 2 reach should be set greater than the measured impedance for the first scenario (in service), with a safety multiplier of at least 120 percent. Of course, the user must also evaluate other possible fault locations.

Another alternative to deal with the previous scenarios is to assign and adapt individual settings groups to different operating conditions (parallel line in service, out of service, or out of service and grounded) by considering the effective mutual coupling of the different operating conditions [2].

3.2. Using residual compensation factor for different configurations of parallel lines in power systems

Fig. 3 shows phase-to-ground fault in the system, m = 1 in (3). Assuming that the coupled line residual current is equal to the residual current of the protected line ($I_r = 3I_{0M}$), takes the form [2]:

$$V_a = Z_{1L}\left(I_a + \left(k_0 + \frac{Z_{0M}}{3Z_{1L}}\right)I_r\right) \quad (8)$$

The term in parentheses preceding I_r in (8) is the modified k_0 (2) value (k_0') required to eliminate the impedance measurement error when both lines are in service.

$$k_0' = k_0 + \frac{Z_{0M}}{3Z_{1L}} = \frac{Z_{0L} - Z_{1L} + Z_{0M}}{3Z_{1L}} \quad (9)$$

For a phase-to-ground fault in the Fig. 4 system, the coupled line residual current is:

$$I_{0M} = -\frac{Z_{0M}I_r}{3Z_{0L}} \quad (10)$$

Substituting (10) into (3) and making m = 1:

$$V_a = Z_{1L}\left(I_a + \left(k_0 - \frac{Z_{0M}^2}{3Z_{1L}Z_{0L}}\right)I_r\right) \quad (11)$$

The term in parentheses preceding I_r in (11) is the modified k_0 value (k_0'') required to eliminate the impedance measurement error when the coupled line is out of service and grounded at both ends.

$$k_0'' = k_0 - \frac{Z_{0M}^2}{3Z_{1L}Z_{0L}} = \frac{Z_{0L} - Z_{1L} - \frac{Z_{0M}^2}{Z_{0L}}}{3Z_{1L}} \quad (12)$$

For scenario that coupled line is out of service and grounded at one point only or not grounded, k_0 value remains unchanged (2).

Modern digital line protection relays allow the assigning of different k_0 values to different zones of the ground distance elements. One alternative is for the user to select k_0 values that accommodate all three receding scenarios. Another alternative is to use different settings groups.

In the fixed settings alternative, the user can apply the k_0'' value to Zone 1 to avoid overreaching and the k_0' value to Zone 2 to avoid underreaching. The user must also evaluate other possible fault locations.

In the settings group alternative, the user can apply the k_0 value to Zone 1 and the k_0' value to Zone 2 when the coupled line is in service. When the coupled line is out of service and grounded at both ends, the user can apply the k_0'' value to Zone 1 and the k_0' value to Zone 2. Alternatively, the user can apply the k_0 value to Zone 1 and Zone 2 if the coupled line is out of service and grounded at only one point [2].

4. CASE STUDY

In this paper distance relay setting on a double circuit transmission line including overreach and underreach problems are considered. The impedance estimated by the relay in steady state condition is calculated and it is compared with the protective zone of the relay.

The first step is to set the relay for a single circuit transmission line. For this purpose primitive simulations are conducted on a 400 kV single circuit transmission line with two equivalent networks connected to the ends of the line. Other system characteristics are specified in Table 1.

Table 1 Transmission line parameters

Parameters of transmission line	Values
Positive-sequence resistance R_{L1} [Ω/km]	0.0309
Zero-sequence resistance R_{L0} [Ω /km]	0.1681
Zero-sequence mutual resistance R_{LM0} [Ω /km]	0.1177
Positive-sequence inductance L_{L1} [H/km]	1.0517x10^{-3}
Zero-sequence inductance L_{L0} [H/km]	3.9368x10^{-3}
Zero-sequence mutual inductance L_{LM0} [H/km]	2.7557x10^{-3}
Positive-sequence capacitance C_{L1} [F/km]	11.28x10^{-9}
Zero-sequence capacitance C_{L0} [F/km]	7.2813x^{-9}
Zero-sequence mutual capacitance C_{LM0} [F/km]	-5.097x10^{-9}
Line voltage [kV]	400
Line length [km]	200

4.1. Simulation of double circuit line without using zero sequence compensation factors k_0' or k_0''

Zone 1 was set to Z_1 = 4.96+j52.83 Ω which is equal to 80 percent of the positive sequence impedance of the protected line. Phase to ground units of the distance relay use voltage and current of the related phase as well as zero sequence current to estimate the impedance according to equation (1) and (2). For the simulated line in this paper k_0 is equal to 0.92 e $^{j3.26°}$.

Fault was modeled at the end of the first transmission overhead line with different configuration of the parallel line in power systems, namely:

- Parallel line in service (Fig. 5)
- Parallel line is out of service and grounded at one point (Fig. 6)
- Parallel line is out of service and grounded at both ends (Fig. 7)

One phase-to-earth fault was simulated at distance 200 km (100% impedance of the line) from the substation SA using program Matlab/Simulink. Distance protection was installed in the substation SA at the beginning of the first line. Distance relay recorded this fault for different switching states of the coupled line in the different protective zone. This model of distance relay includes the whole internal logic composed of several parts which are necessary for calculation of impedance loop.

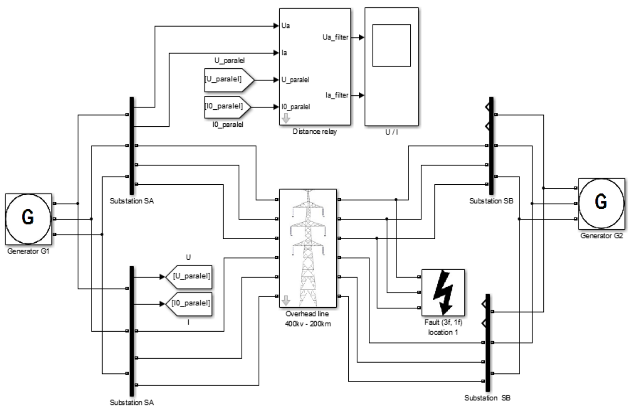

Fig. 5 Parallel line in service

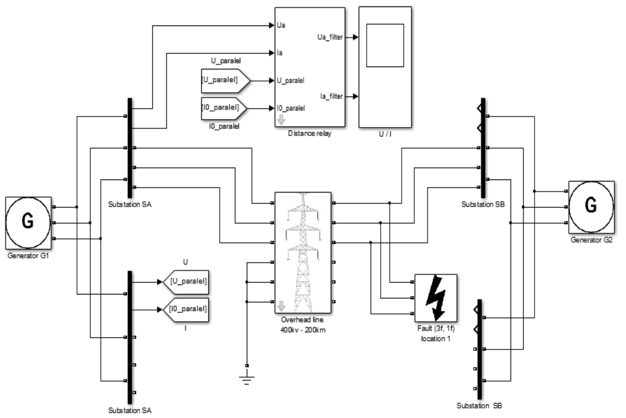

Fig. 6 Parallel line is out of service and grounded at one point

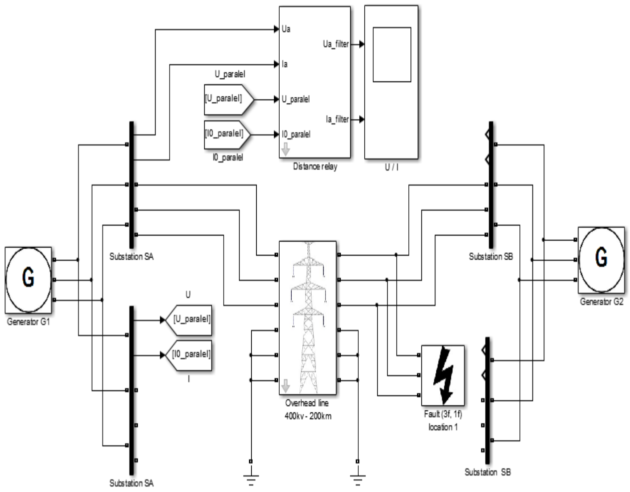

Fig. 7 Parallel line is out of service and grounded at both ends

In the first case when parallel line was in service (Fig. 5), measured impedance was greater (Fig. 8) than actual impedance (the ground distance element underreaches). In the second case when parallel line was out of service and grounded at one point (Fig. 6) measured impedance was correct (Fig. 8). For the last scenario when parallel line is out of service and grounded at both ends (Fig. 7) measured impedance was smaller (Fig. 8) than actual impedance (the ground distance element overreachs).

Waveforms of short-circuit impedance we can see at Fig. 8. The simulation did not include the impact of the arc. Therefore, waveforms of impedance were stabilized at Z_L (impedance of line).

Fig.9 shows waveforms of three-phase voltage (V_a) and current (I_a) in instantaneous values measured in substation SA on the first line when coupled line was in service. The individual RMS waveforms of voltages and currents values for the same case as was mentioned above are shown at Fig. 10. Fig. 11 shows state of coupled line out of service and grounded at one point for comparison with Fig.9. We can see difference in size of the short-circuit current in the first phase for coupled line in service and coupled line out of service and grounded at one point.

This difference of current (or reduction of the current I_a for couple line in service) caused that distance relay element underreaches (measured impedance is greater than the actual impedance to the fault location).

All values of the simulation are also shown in Tab. 2.

Table 2 Result of simulations for uncompensated double circuit line

	In service	Out of service (grounded at both ends)	Out of service (grounded at one point)
Measured Z [Ω]	10.26+91.08j	3.91+46.05j	7.157+66.14j
Actual Z [Ω]	6.1967+j66.046		
Fault position [km]	200		

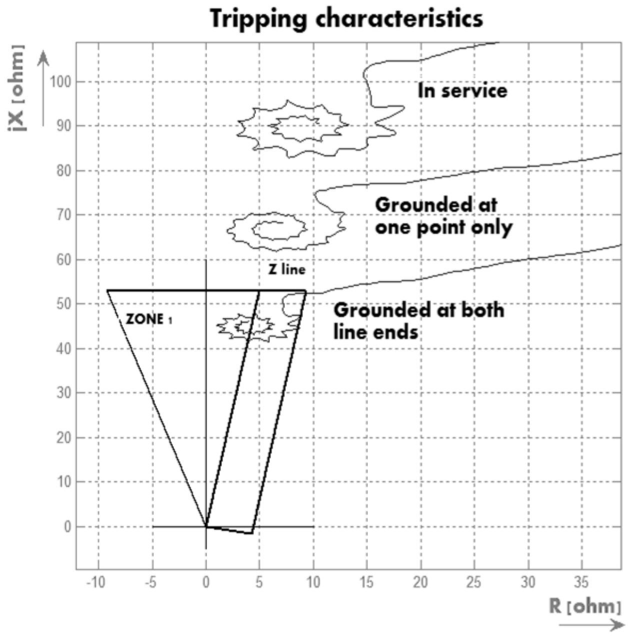

Fig. 8 Waveforms of impedances of phase-to earth faults for different switching states of the coupled line without using zero sequence compensation factors

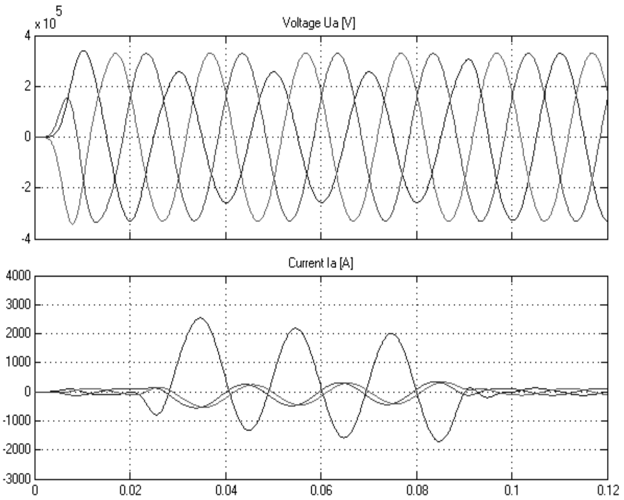

Fig. 9 Waveforms of current and voltage at phase-to-earth fault in instantaneous values for coupled line in service

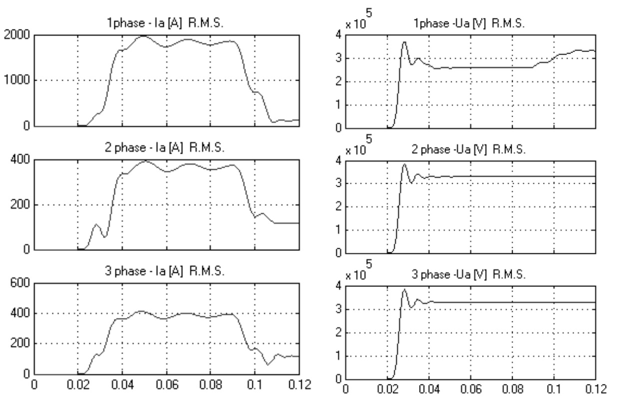

Fig. 10 Waveforms of current (left) and voltage (right) at phase-to-earth fault in RMS values for coupled line in service

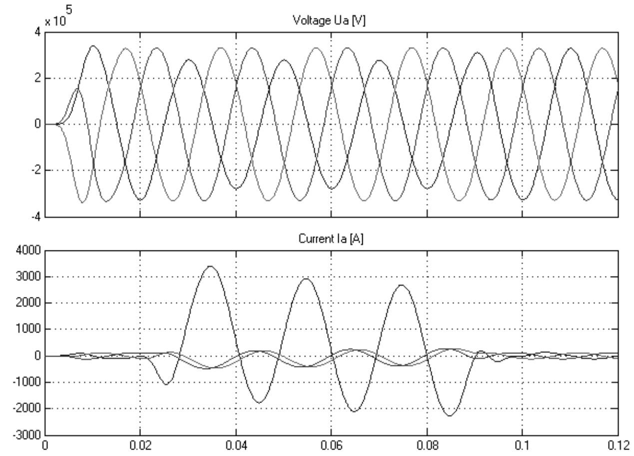

Fig. 11 Waveforms of current and voltage at phase-to-earth fault in instantaneous values for coupled line out of service and grounded at one point

As the Fig. 12 shows the steady state values of resistance and reactance are 10 Ω and 91 Ω respectively for coupled line in service and for parallel line out of service and grounded at both ends the steady state values of resistance and reactance are 4 Ω and 46 Ω. They are considerably different from the actual values (Table 2 – actual *Z*) where resistance and reactance were 6.2 Ω and 66 Ω. It means that neglecting argument of k_0' or k_0'' may cause maloperations especially for faults close to the end of the protective zone.

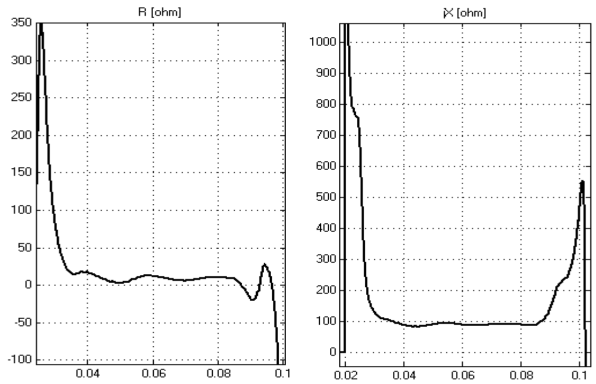

Fig. 12 R and X values for a fault at the end of the first line when coupled line was in service (underreach)

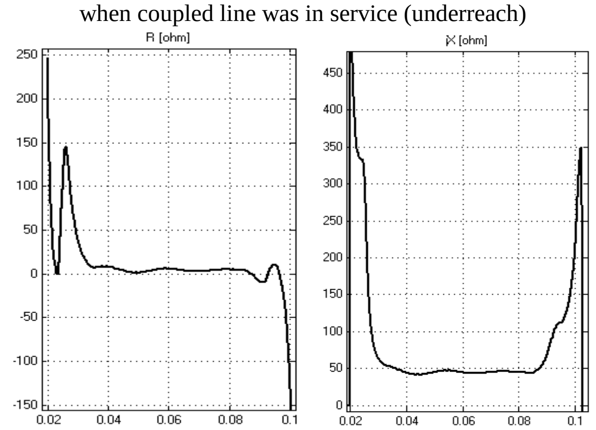

Fig. 13 R and X values for a fault at the end of the first line when parallel line was out of service and grounded at both ends (overreach)

4.2. Simulation of double circuit line using zero sequence compensation factors k_0' and k_0''

A suitable method to solve the problems associated with the reach of distance relay on a double circuit line is to consider the effect of zero sequence mutual coupling. To do this, the effect of zero sequence current of a circuit should be considered when estimating impedance of the other circuit [6].

Equation (13), derived from (3), shows a theoretical way to eliminate the impedance measurement error caused by mutual coupling.

$$V_{\mathrm{a}} = m.Z_{1\mathrm{L}}\left(I_{\mathrm{a}} + k_0 I_{\mathrm{r}} + \frac{Z_{0\mathrm{M}}}{Z_{1\mathrm{L}}}.I_{0\mathrm{M}} \right) \tag{13}$$

The term in parentheses in (13) is the current required to eliminate the impedance measurement error. This current includes an additional compensation term that contains $I_{0\mathrm{M}}$. Hence, the ground distance element requires zero-sequence current information from the coupled line

This method has the following problems:

- The method requires wiring between the protection panels of the mutually coupled lines. In many system configurations, current information from the coupled line is not locally available because the lines terminate at different substations
- It is not possible to obtain the zero-sequence current from the coupled line when the line is out of service for maintenance and is grounded at both ends.
- Protection engineers prefer not to mix currents from different line terminals into one relay panel because of the possibility of incorrect installation, for safety considerations, and to avoid testing mistakes and etc.

For all these reasons, it is not recommended to use the zero-sequence current from the coupled line for mutual coupling compensation [2].

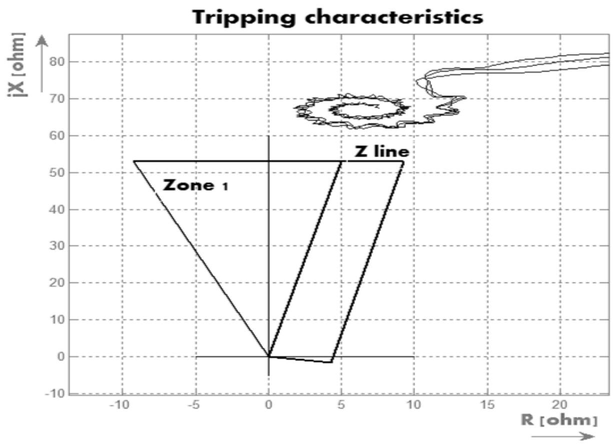

Fig. 14 Waveforms of impedances of phase-to earth faults for different switching states of the coupled line with using zero sequence compensation factors

Therefore, for the following simulation was chosen formula (8). According to the configuration of parallel lines were selected different zero sequence factors (term in parentheses preceding I_{r} in (8), k_0, k_0' or k_0"). Well as in section 4.1 were simulated three states of parallel lines with the same parameters but with using zero sequence compensation factors as mentioned above.

Results of simulations based on equation (8) are shown in Fig (14). Figure (14) shows that if equation (8) is used instead of equation (1), calculated impedances are very close to the actual values. Given that the short circuit was simulated at the end of the first line, all three measured impedances were stabilized at 100% line impedance, which is the correct value.

It is concluded from the simulations of this section that mutual zero sequence current compensation is a relatively suitable method to overcome the underreach and overreach problems of distance relays on double circuit transmission lines, so that the zero sequence effect and sensitivity to short circuit capacity of the networks connected to the protected line is largely reduced.

4.3. Simulation of fault at different locations

In the previous sections, impedance measurement was mainly performed for faults at the end of the line. In this section fault at different locations of a double circuit line is simulated and results for both uncompensated and compensated relays are evaluated. Simulation results for these two cases are stated in Table 3. From this table it is concluded that an uncompensated distance relay overreaches for faults next to the beginning of the line, and underreaches for faults next to the end of the line.

Table 3 Result of simulations on double circuit line

	Measured impedance without zero sequence compensation [Ω]			
Fault location [km]	In service	Out of service (grounded at one point)	Out of service (grounded at both ends)	Actual impedance [Ω]
20	0.4+9.6j	0.31+6.74j	0.13+4.6j	0.62+6.6j
60	3.17+27.9j	2.19+20.12j	1.4+13.7j	1.86+19.81j
100	5.3+45.7j	3.55+33.69j	2.4+22.7j	3.09+33.02j
140	7.4+63.7j	4.95+47.32j	3.2+32.3j	4.34+46.23j
180	8.9+82.4j	5.58+61.32j	3.4+41.1j	5.58+59.43j
	Measured impedance with zero sequence compensation [Ω]			
20	0.4+6.7j	0.31+6.7j	0.3+6.7j	0.62+6.6j
60	2.3+20j	2.2+20.2j	2.01+20.1j	1.86+19.81j
100	3.7+33.3j	3.55+33.7j	3.6+33.6j	3.09+33.02j
140	5.3+46.79j	4.9+47.3j	4.6+47.3j	4.34+46.23j
180	6.2+61.1j	5.6+61.3j	5.1+60.47j	5.58+59.43j

5. CONCLUSIONS

In this paper a double circuit transmission line is modeled and the measured impedance by distance relay in various conditions is studied. We can conclude the following:

- Zero sequence mutual coupling may cause the distance relay to overreach or underreach.
- To get accurate distance relay setting it is suggested to take the zero sequence current factor k_0, k_0' or k_0''.
- Zero sequence coupling compensation can overcome many of the distance relay problems on double circuit lines.

It is concluded that the described method is a relatively suitable method to solve many of the problems, associated with double circuit line protection.

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BIOGRAPHIES

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