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RELAY PROTECTION FOR LINES BEING
SLEET-MELTED BY THE SHORT-CIRCUIT METHOD

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Relay Protection for Lines Being Sleet-Melted by the Short-Circuit Method

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SLEET formation on transmission lines was recognized as a serious operating problem as early as 1916 and shortly thereafter methods were devised to melt sleet.¹ In recent years various ways have been presented²⁻⁵ for connecting lines and power sources to obtain the current necessary for sleet melting. Forced loading, phase shifting, and short circuiting are utilized extensively for this purpose.

Problems of relay protection during sleet melting were not specifically presented in former papers. The purpose of

this paper is to present the particular problem of protection under such conditions and to propose a means of detecting faults on lines being sleet-melted by the short-circuit method.

The short-circuiting method which is used in many instances presents a difficult relaying problem. This means of sleet melting consists of applying a 3-phase-to-ground short circuit at one end of the line so that the resultant line current will be large enough to melt sleet. The source of power may be an isolated

generator with step-up transformer which may be adjusted to supply the proper current. Some lines because of their particular length may lend themselves to sleet melting by direct connection to a station bus. Under these conditions the normal line relays cannot generally be set to give adequate fault protection.

Unique Problem of Line Relaying

The normal protective relaying equipment is usually located at the power source end of the line when the short-

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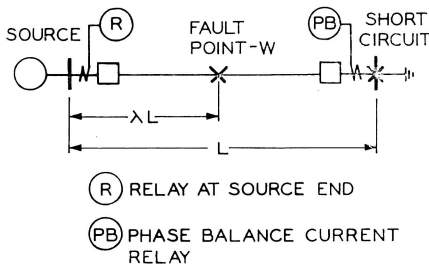


Fig. 1. Schematic diagram of faulted sleet-melted line and system

circuit method of sleet melting is employed. This protective equipment may consist of distance relays, pilot-wire relays, carrier current relays based on the directional- or phase-comparison principle, or overcurrent relays. Since the line already has a 3-phase-to-ground short circuit at its far end, the normal phase relays at the source end must either be removed from service and be replaced by other relays or their settings must be changed to make them less sensitive. Ground relays can normally be left in service.

In the case of distance relays the second- and third-zone elements must be blocked from tripping and the first zone must be set short of the end of the line. In some instances of extremely low voltage zone 1 may also have to be removed from service. If the normal line protection consists of pilot-wire relays they may be left in service when the intentional short circuit is applied outside of their zone of protection.

Directional-comparison carrier relays must be removed from service even though the intentional short circuit falls outside of their zone of protection because the line would automatically trip by second- and third-zone elements upon time delay if these elements were set to cover the entire length of line short-circuited for sleet melting. Phase-comparison carrier relays may be left in service if the intentional short circuit is outside of their zone of protection. This, however, would be objectionable since the transmitter nearest the intentionally faulted end would be keyed continuously.

Overcurrent relays, if utilized, must be set a safe margin above the sleet-melting current. In every case a certain portion of the line is unprotected. It will be shown that the percentage of the line upon which faults can be detected by overcurrent relays is dependent upon the type of fault, system impedance, and the relays applied.

During sleet-melting operations the lines and equipment are usually operating at or near their thermal capacities so that

the sleet will be melted and the line returned to normal service in the shortest possible time. Hence any increase in line currents due to additional faults on the line may damage the line or source equipment. For example, if an isolated generator is used as the power source, there is a certain amount of negative-sequence current during sleet melting because of the unbalanced impedances of the line conductors. Thus small amounts of additional negative-sequence currents due to faults not detected by source end relays may damage the machine. Substantial amounts of negative-sequence currents may be produced by single phasing resulting from conductor burndown because of poor splices or previous fault damage and by phase-to-phase faults incurred by bouncing conductors accompanying ice unloading. It is imperative to remove any unintentional faults as soon as possible.

Proposed Method of Solution

Since relays at the source end cannot detect faults over the entire length of line, the proposed method of relaying which follows provides optimum protection for unsymmetrical faults. This method utilizes relays at the short-circuited end of the line which, together with the source end relays, provides complete protection for unsymmetrical line faults. The source end protection may consist of phase overcurrent relays, ground relay, and a negative-sequence overcurrent relay. In addition to the circuit breaker at the source end another circuit breaker is required between the line terminal and the 3-phase-to-ground short circuit at the far end of the line. The normal line breaker can serve this function. This breaker is equipped with a phase balance relay. Unsymmetrical faults which cannot be detected by the source end relays cause unbalanced line currents at the short-circuited end of the line. This unbalance is sufficient to initiate operation of a phase balance relay located at the short-circuited end. Operation of this relay opens the short-circuited end circuit breaker, thus removing the intentional 3-phase-to-ground short circuit. Since the fault is no longer obscured by the 3-phase-to-ground short circuit, the source end relays will operate to clear the fault. The arrangement used is shown in Fig. 1. It is to be noted, however, that unintentional 3-phase faults on the lines will not be seen by the far end relays and clearing for these faults must be initiated by the source end relays. Since the source end relays must be set a safe mar-

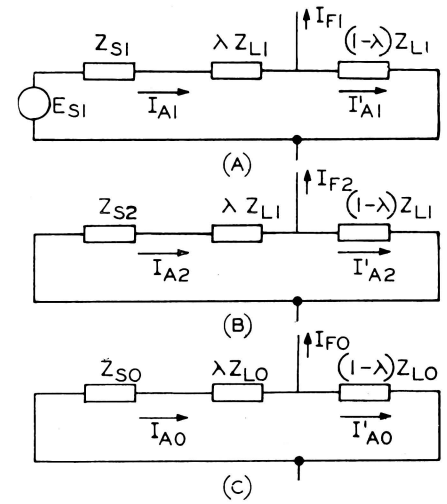


Fig. 2. Sequence network of system during fault:

- A—Positive
- B—Negative
- C—Zero

gin above the sleet-melting current, 3-phase faults can be detected over all but a small percentage of the line as shown later.

It is proposed that, in the instance where several lines are connected in series for sleet melting, the relays at the sectionalizing points between extreme terminals be removed from service.

Faults on Lines During Sleet Melting

If a fault occurs during sleet melting on a line of length L at a distance l from the source, the symmetrical component networks⁶ are as shown in Fig. 2. The circuit parameters are defined as follows:

- Z_{S1}, Z_{S2}, Z_{S0} = sequence impedances of the source
- $Z_{L1}, Z_{L2},$ and Z_{L0} = sequence impedances of the complete line of length L
- $\lambda = l/L$ = ratio of line length from source to fault compared to total line length L
- $I_{A1'}, I_{A2'},$ and I_{A0}' = sequence currents at the source end of line. The prefault sleet-melting current is taken as the base per-unit (pu) current

The positive- and negative-sequence impedances of the line are assumed to be equal ($Z_{L1} = Z_{L2}$). If instantaneous relaying is to be applied, calculations of currents are based on subtransient reactances of any machines involved; however, if slow-speed relaying is used, calculations are based on synchronous reactances of the machines. When an isolated generator is used as the source with slow-speed relaying, the positive- and negative-sequence source impedances are not equal. However, if a large system is used as a source of power, it will be composed of lines and transformers with equal positive-

and negative-sequence impedances in addition to the generators. Thus the generator sequence impedances will be only a part of the sequence networks involved and the system equivalent positive-sequence impedance will be approximately the same as its negative-sequence impedance. In the discussion to follow synchronous reactances will be used for positive-sequence reactances of any machines involved.

Faults as Seen From the Source

Considering first the case of a 3-phase fault at location W , in addition to the 3-phase-to-ground short circuit at the end of the line, the line currents will be symmetrical. Since the prefault sleet-melting current is equal to 1 pu the generated voltage of the equivalent source is given by

$$E_{S1} = Z_{S1} + Z_{L1} \text{ pu} \quad (1)$$

Since the parameter Z_{S1} is made up of subtransient reactances for applications involving instantaneous relays, a correction factor must be applied to equation 1 and all other expressions for voltage or current used in this paper when instantaneous relaying is used. This correction factor is the ratio of $Z_{S1} + Z_{L1}$ (using synchronous reactances) to $Z_{S1} + Z_{L1}$ (using subtransient reactances). Thus, returning to the case of slow-speed relaying, the expression for the line current becomes

$$I_a = I_{a1} = \frac{Z_{S1} + Z_{L1}}{Z_{S1} + \lambda Z_{L1}} \quad (2)$$

The total line current is thus a function of the location of point W at which the fault occurs. Since only positive-sequence currents are involved, the fault is best detected by overcurrent or impedance relays. These must be set for a safe margin higher than the sleet-melting current. Suppose, e.g., the overcurrent relays are set for a pickup of 1.2 times sleet-melting current. For this condition equation 2 becomes

$$I_a = 1.2 = \frac{Z_{S1} + Z_{L1}}{Z_{S1} + \lambda Z_{L1}} \text{ pu} \quad (3)$$

or

$$\lambda = \frac{Z_{L1} - 0.2Z_{S1}}{1.2Z_{L1}} \quad (4)$$

Thus the overcurrent relay will protect for faults out to a point given by λ in equation 4. For values of λ greater than this value the overcurrent relays provide no protection. This zone of protection is dependent on the relative values of Z_{S1} and Z_{L1} . Thus the smaller the ratio of

Table I. Sequence Currents at Source End and at Short-Circuited End of Line

Double-Line-to-Ground Fault	Line-to-Line Fault	Line-to-Ground Fault
$I_{a1} \dots \frac{Z_{S1} + Z_{L1}}{Z_{S1} + \lambda Z_{L1} + \frac{(1-\lambda)Z_{L1}}{\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)}} \dots$	$\frac{Z_{S1} + Z_{L1}}{Z_{S1} + \lambda Z_{L1} + \frac{(1-\lambda)Z_{L1}}{\left(1 + \frac{1}{\gamma_2}\right)}} \dots$	$\frac{\left(1 + \gamma_3 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}{\left(\gamma_1 + \gamma_2 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}$
$I_{a2} \dots -\frac{(1-\lambda)Z_{L1}}{(Z_{S2} + \lambda Z_{L1})\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)} I_{a1} \dots$	$-\frac{(1-\lambda)Z_{L1}}{(Z_{S2} + \lambda Z_{L1})\left(1 + \frac{1}{\gamma_2}\right)} I_{a1} \dots$	$\frac{(1-\lambda)Z_{L1}}{Z_{S2} + Z_{L1}} \frac{I_{a1}}{\left(\gamma_1 + \gamma_2 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}$
$I_{a0} \dots -\frac{(1-\lambda)Z_{L1}}{(Z_{S0} + \lambda Z_{L1})\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)} I_{a1} \dots$	$0 \dots$	$\frac{(1-\lambda)Z_{L0}}{(Z_{S0} + Z_{L1})} \frac{I_{a1}}{\left(\gamma_1 + \gamma_2 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}$
$I_{a1'} \dots \frac{1}{\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)} I_{a1} \dots$	$\frac{1}{\left(1 + \frac{1}{\gamma_2}\right)} I_{a1} \dots$	$\frac{\gamma_3 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}}{\left(\gamma_1 + \gamma_2 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}$
$I_{a2'} \dots I_{a1'} \dots$	$I_{a1'} \dots$	$-\frac{\gamma_3}{\left(\gamma_1 + \gamma_2 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}$
$I_{a0'} \dots \frac{(Z_{L1})}{(Z_{L0})} I_{a1'} \dots$	$0 \dots$	$-\frac{\gamma_0}{\left(\gamma_1 + \gamma_2 + \frac{(Z_{L0})\gamma_0}{(Z_{L1})}\right)}$

Note: γ_1 , γ_2 , and γ_0 are as given in equations 6, 7, and 8 respectively.

Z_{L1} to Z_{S1} becomes, faults occurring on a greater percentage of the line will go undetected. For the foregoing relay setting of 20 per cent above sleet-melting current and Z_{L1} approximately equal to Z_{S1} , the relays will detect faults on the 67 per cent of the line nearest the source. Faults occurring beyond that point will not be detected.

In a similar manner the sequence currents can be determined for unsymmetrical faults and the response of relays sensitive to negative-sequence currents, ground currents, and unbalanced phase currents can be predicted; see Appendix I. The sequence currents at the source end and at the short-circuited end of the line are given in Table I.

These equations for the sequence currents can be used to determine the zone of protection afforded by different relays at the source end. For example, overcurrent relays at the source end set for 1.2 pu current will pick up if $\lambda = 0.59$ for a line-to-line fault, i.e., only when the fault is in the nearest 59 per cent of the line. Such calculations will show in every case that the relays at the source end are not capable of detecting all the faults.

For complete protection of line and source equipment it becomes necessary to use some additional scheme for fault detection. Examination of the currents at the short-circuited end of the line will lead to the method proposed for detecting faults anywhere on the line.

Faults as Seen From the Short Circuited End

Referring again to Table I and calculating the line currents at the short-circuited end for unsymmetrical faults, these will be found unbalanced even though the faults are near the short-circuited end. This unbalance can be used for fault detection.

For a line-to-line fault the ratio of maximum to minimum phase currents at the short-circuited end will be 2 regardless of line and source impedances. For a line-to-line-to-ground fault this ratio will be greater than 2. Standard phase unbalance relays applied at the short-circuited end will detect these faults occurring anywhere along the line.

A line-to-ground fault on the short-circuited line will also cause unbalanced line currents at the short-circuited end. From the relations given in Table I it is seen the $I_{a2'}$ and $I_{a0'}$ do not approach 0 as λ approaches 1. The ratio of maximum to minimum line current for this case cannot be expressed as a simple ratio in terms of circuit parameters.

The example given in Appendix II illustrates the method of solution for a line-to-ground fault on the line. The curves of line currents versus point of fault can be used to determine the ratio of maximum to minimum current to be used to verify the operation of the phase balance current relays for this type of fault.

Summary

The following statements regarding protection of lines during sleet melting by the short-circuit method may thus be made:

1. Certain types of protective relays at the source end must be removed from service before sleet melting by the short-circuit method.
2. Source end relays left in service will only detect faults occurring on a portion of the line.
3. Small unbalances or overcurrents which cannot be detected by the source end relays may damage the lines or other equipment because they are already operating at or near their thermal capacity.
4. The method proposed using phase balance current relays at the short-circuited end of the line in addition to the source end relays can detect unsymmetrical faults occurring on any part of the line.
5. The proposed arrangement of relaying provides generator protection within the limits prescribed by the short-circuit section of ASA-C50.⁷

Appendix I. Determining Sequence Currents and Predicting Relay Response

Considering the unsymmetrical faults (line to line, line to ground, and double line to ground) relays sensitive to negative-sequence currents, ground currents, or unbalance between phase currents may be applied in addition to the overcurrent relay. Connecting positive-, negative-, and zero-sequence networks in parallel gives the equivalent circuit for a double-line-to-ground fault at point *W*. Solving for I_{a1} yields

$$I_{a1} = \frac{E_{S1}}{Z_{S1} + \lambda Z_{L1} + \frac{1}{\frac{1}{(1-\lambda)Z_{L1}} + \frac{Z_{S2} + Z_{L1}}{(1-\lambda)(Z_{L1})(Z_{S2} + \lambda Z_{L1})} + \frac{Z_{S0} + Z_{L0}}{(1-\lambda)Z_{L0}(Z_{S0} + \lambda Z_{L0})}} \quad (5)$$

Let

$$\gamma_F = \frac{Z_{S1} + \lambda Z_{L1}}{Z_{S1} + Z_{L1}} \quad (6)$$

$$\gamma_2 = \frac{Z_{S2} + \lambda Z_{L1}}{Z_{S2} + Z_{L1}} \quad (7)$$

$$\gamma_0 = \frac{Z_{S0} + \lambda Z_{L0}}{Z_{S0} + Z_{L0}} \quad (8)$$

Substituting equations 1, 7, and 8 into equation 5 gives the positive-sequence current at the source end. Thus

$$I_{a1} = \frac{Z_{S1} + Z_{L1}}{Z_{S1} + \lambda Z_{L1} + \left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)} \quad (9)$$

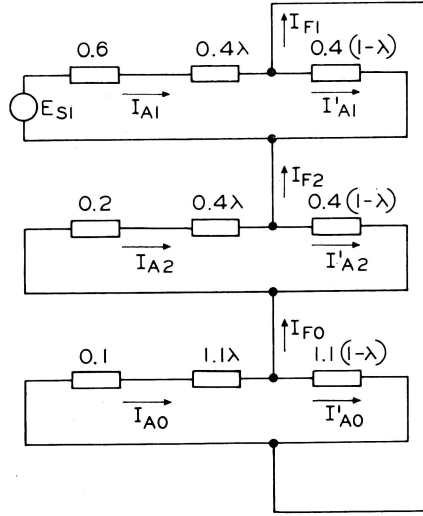


Fig. 3. Connection of sequence network for example

Also

$$I_{a2} = -\frac{E_{S1} - I_{a1}(Z_{S1} + \lambda Z_{L1})}{Z_{S2} + \lambda Z_{L1}} \quad (10)$$

or substituting equations 1 and 9 into equation 10 gives

$$I_{a2} = -\frac{(1-\lambda)Z_{L1}}{(Z_{S2} - \lambda Z_{L1})\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)} \quad (11)$$

Similarly

$$I_{a0} = -\frac{(1-\lambda)Z_{L1}}{(Z_{S0} + \lambda Z_{L0})\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})1}{(Z_{L0})\gamma_0}\right)} \quad (12)$$

The foregoing sequence currents at the source end are given in Table I. Source end sequence currents are also given for the line-to-line and line-to-ground faults in this table. In all three of the fault conditions discussed it is noted that

$$\lim_{\lambda \rightarrow 1} I_{a1} = 1 \quad (13)$$

$$\lim_{\lambda \rightarrow 1} I_{a2} = 0 \quad (14)$$

$$\lim_{\lambda \rightarrow 1} I_{a0} = 0 \quad (15)$$

For faults occurring near the faulted end of the line the current unbalance at the source end becomes small and the faults become impossible to detect with source end relays.

These equations for the sequence currents can be used to determine the zone of protection afforded by different types of relays at the source end. Consider, e.g., a line-to-line fault with $Z_{L1} = Z_{S1} = Z_{S2}$ and overcurrent relays at the source end set at 1.2 pu current. For this condition equation 7 yields the following relationship

$$\gamma_2 = \frac{1+\lambda}{2} \quad (16)$$

$$I_{a1} = \frac{2}{1+\lambda + \frac{(1-\lambda)}{\left(1 + \frac{2}{1+\lambda}\right)}} \quad (17)$$

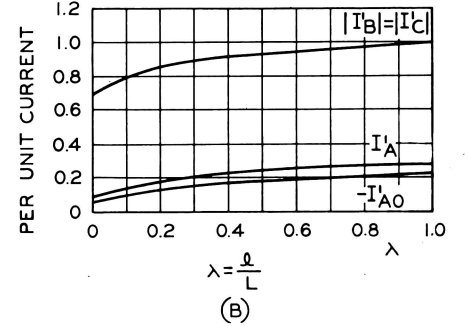
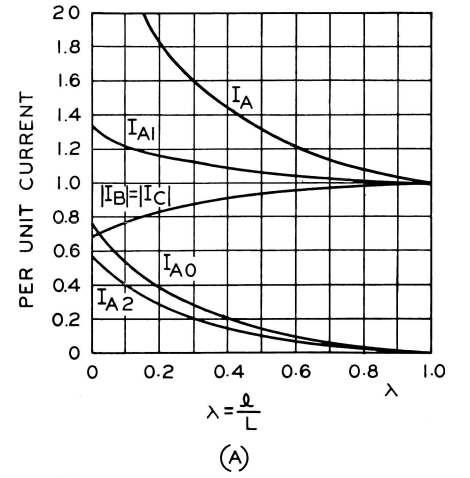


Fig. 4. Variation of line and sequence currents with fault location:

A—Source end
B—Short-circuited end

Simplifying

$$I_{a1} = \frac{3+\lambda}{2(1+\lambda)} \quad (18)$$

Also

$$I_{a2} = -\frac{(1-\lambda)(3+\lambda)}{(1+\lambda)\left(1 + \frac{2}{1+\lambda}\right)2(1+\lambda)} \quad (19)$$

or

$$I_{a2} = -\frac{(1-\lambda)}{2(1+\lambda)} \quad (20)$$

Using equations 18 and 20 to obtain the line currents yields

$$I_{a2} = I_{a1} + I_{a2} = 1.0 \quad (21)$$

$$I_b = a^2 I_{a1} + a I_{a2} = \frac{3a^2 + a^2\lambda - a + a\lambda}{2(1+\lambda)} \quad (22)$$

$$I_c = a I_{a1} + a^2 I_{a2} = \frac{3a + a\lambda - a^2 + a^2\lambda}{2(1+\lambda)} \quad (23)$$

Solving for the magnitude of I_b and I_c gives

$$|I_b| = |I_c| = \frac{\sqrt{13+2\lambda+\lambda^2}}{2(1+\lambda)} \quad (24)$$

To determine the zone of protection substitute $|I_b| = |I_c| = 1.2$ into equation 24. This gives

$$1.2 = \frac{\sqrt{13+2\lambda+\lambda^2}}{2(4+\lambda)} \quad (25)$$

Solving equation 25 gives $\lambda=0.59$. Thus any line-to-line faults occurring on the 41 per cent of the line nearest the 3-phase-to-ground short circuit will not be detected. The zone of protection can also be established for line-to-ground and double-line-to-ground faults by the use of the relations given in Table I. In all cases the relays at the source end are not capable of detecting faults at all points along the line.

The double-line-to-ground fault conditions as seen by the source end relays were derived in equations 5 through 12. It is now necessary to determine the effects of the fault upon the currents at the short-circuited end of the line. Solving first for the sequence components of the currents at the short-circuited end gives

$$I_{a1}' = \frac{E_{S1} - I_{a1}(Z_{S1} + \lambda Z_{L1})}{(1 - \lambda)Z_{L1}} \quad (26)$$

Substituting equations 1 and 9 into equation 26 gives

$$I_{a1}' = \frac{Z_{S1} + \lambda Z_{L1} + \frac{(1 - \lambda)Z_{L1}}{\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})}{(Z_{L0})} \frac{1}{\gamma_0}\right)} - (Z_{S1} + \lambda Z_{L1})}{(1 - \lambda)Z_{L1}} I_{a1}$$

or

$$I_{a1}' = \frac{1}{\left(1 + \frac{1}{\gamma_2} + \frac{(Z_{L1})}{(Z_{L0})} \frac{1}{\gamma_0}\right)} I_{a1} \quad (27)$$

Similarly

$$I_{a2}' = I_{a1}' \quad (28)$$

$$I_{a0}' = \frac{(Z_{L1})}{(Z_{L0})} I_{a1}' \quad (29)$$

For faults near the short-circuited end the foregoing currents remain unbalanced. This unbalance may thus be used for fault detection.

Solving now for the line currents gives

$$I_a' = I_{a1}' + I_{a1}' + \frac{(Z_{L1})}{(Z_{L0})} I_{a1}'$$

$$I_b' = a^2 I_{a1}' + a I_{a1}' + \frac{(Z_{L1})}{(Z_{L0})} I_{a1}'$$

$$I_c' = a I_{a1}' + a^2 I_{a1}' + \frac{(Z_{L1})}{(Z_{L0})} I_{a1}'$$

or

$$I_a' = \left(2 + \frac{Z_{L1}}{Z_{L0}}\right) I_{a1} \quad (30)$$

$$I_b' = I_c' = \left(-1 + \frac{Z_{L1}}{Z_{L0}}\right) I_{a1} \quad (31)$$

Taking the ratio of maximum to minimum line current gives

$$\frac{|I_a'|}{|I_b'|} = \frac{2 + \frac{Z_{L1}}{Z_{L0}}}{1 - \frac{Z_{L1}}{Z_{L0}}} \quad (32)$$

Since the ratio of Z_{L1} to Z_{L0} is less than 1, equation 32 may be expressed as

$$\frac{|I_a'|}{|I_b'|} > 2 \quad (33)$$

Thus standard phase unbalance relays applied at the short-circuited end will detect double-line-to-ground faults occurring anywhere along the line.

For a line-to-line fault the ratio of maximum to minimum line current becomes

$$\frac{|I_a'|}{|I_b'|} = 2 \quad (34)$$

Thus, regardless of the line and source impedances or the point at which the fault occurs, the maximum line current at the short-circuited end is twice the minimum line current assuring operation of phase unbalance relays at the short-circuited end.

Appendix II. Method of Solving Line-to-Ground Fault

Since the ratio of maximum to minimum line currents at the short-circuited end cannot be given in a simple expression for a line-to-ground fault, an example will be given showing the method of solution. For the purpose of simplifying the example, the resistances have been neglected. The following reactances are used:

$$\begin{aligned} X_{S1} &= 0.6 \text{ pu} & X_{L1} &= 0.4 \text{ pu} \\ X_{S2} &= 0.2 \text{ pu} & X_{L2} &= 0.4 \text{ pu} \\ X_{S0} &= 0.1 \text{ pu} & X_{L0} &= 1.1 \text{ pu} \end{aligned}$$

The equivalent circuit is given in Fig. 3. Substituting sequence impedances into equations 6, 7, and 8 yields

$$\gamma_1 = \frac{0.6 + 0.4\lambda}{1.0} \quad (35)$$

$$\gamma_2 = \frac{0.2 + 0.4\lambda}{0.6} \quad (36)$$

$$\gamma_0 = \frac{0.1 + 1.1\lambda}{1.2} \quad (37)$$

Substituting these values into the expressions given in Table I for the sequence currents for a line-to-ground fault gives

$$I_{a1} = \frac{0.75 + 1.53\lambda}{0.558 + 1.722\lambda} \quad (38)$$

$$I_{a2} = \frac{0.32(1 - \lambda)}{(0.558 + 1.722\lambda)} \quad (39)$$

$$I_{a0} = \frac{0.44(1 - \lambda)}{(0.558 + 1.722\lambda)} \quad (40)$$

$$I_{a1}' = \frac{0.27 + 1.53\lambda}{0.558 + 1.722\lambda} \quad (41)$$

$$I_{a2}' = -\frac{0.16 + 0.32\lambda}{0.558 + 1.722\lambda} \quad (42)$$

$$I_{a0}' = -\frac{0.04 + 0.44\lambda}{0.558 + 1.722\lambda} \quad (43)$$

Solving for line currents gives

$$I_a = \frac{1.51 + 0.77\lambda}{0.558 + 1.722\lambda} \quad (44)$$

$$|I_b| = |I_c| = \frac{\sqrt{0.148 + 1.392\lambda + 3.658\lambda^2}}{0.558 + 1.722\lambda} \quad (45)$$

$$I_a' = \frac{0.07 + 0.77\lambda}{0.558 + 1.722\lambda} \quad (46)$$

$$|I_b'| = |I_c'| = |I_b| = |I_c| \quad (47)$$

Curves showing variation in currents as a function of the point at which the fault occurs are given in Fig. 4. From Fig. 4(A) it can readily be seen that ground faults occurring in approximately the last 20 per cent of the line will not be detected from the source end. The ground current is almost zero so that ground relays are inoperative and the conductor current is insufficient to operate overcurrent relays which are set for a pickup of about 120 per cent of the current required for sleet melting.

Fig. 4(B), however, shows the phase current at the short-circuited end to be of sufficient magnitude and unbalance to operate a phase balance current relay for unintentional line-to-ground faults anywhere on the line. This then provides a means of tripping the short-circuited end breaker which, when opened, changes the nature of the unintentional fault so that it can be detected and cleared from the source end.

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