EE493 Protection of Power Systems I

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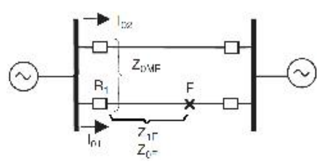
Chapter 5 and 6 of "Power System Relaying", 4th Edition, Wiley, 2014, by S. Horowitz and A. G. Phadke

Protection of parallel lines

Transmission lines that are on the same tower, or paralleled along the same right of way are mutually coupled in their zero-sequence circuits. The small amount of negative- and positive sequence mutual coupling can usually be neglected. The zero-sequence coupling causes an error in the apparent impedance calculation by relays if it is not taken into account.

Consider the fault at F on one of the two mutually coupled lines as shown in the following network. For a phase-a-to-ground fault, the symmetrical component networks are also shown

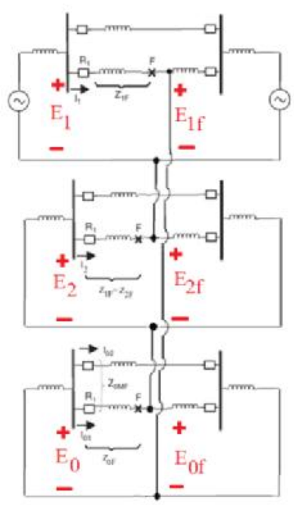


$$E_{1f} = E_1 - Z_{1f} I_1$$

$$E_{2f} = E_2 - Z_{1f} I_2$$

$$E_{0f} = E_0 - Z_{0f} I_{01} - Z_{0mf} I_{02}$$

where I_{01} and I_{02} are the zero-sequence currents in lines 1 and 2, respectively, and Z_{0mf} is the zero-sequence mutual impedance in the faulted portion of the transmission line.



The voltage of phase a at the fault point can be set equal to zero:

$$E_{af} = E_{0f} + E_{1f} + E_{2f} - (E_0 + E_1 + E_2) - Z_{1f}(I_1 + I_2) - Z_{0f}I_{01} - Z_{0mf}I_{02} = 0$$

$$= E_{0f} + E_{1f} + E_{2f} - (E_0 + E_1 + E_2) - Z_{1f}(I_1 + I_2 + I_0 - I_0) - Z_{0f}I_{01} - Z_{0mf}I_{02} = 0$$

$$= E_{0f} + E_{1f} + E_{2f} - (E_0 + E_1 + E_2) - Z_{1f}(I_1 + I_2 + I_0) + Z_{1f}I_0 - Z_{0f}I_{01} - Z_{0mf}I_{02} = 0$$

$$= E_a - Z_{1f}I_a - (Z_{0f} - Z_{1f})I_{01} - Z_{0mf}I_{02} = 0$$

The following compensated phase current is defined

$$I_a' = I_a + \frac{Z_{0f} - Z_{1f}}{Z_{1f}}I_{01} + \frac{Z_{0mf}}{Z_{1f}}I_{02}$$

$$= I_a + \frac{Z_0 - Z_1}{Z_1}I_{01} + \frac{Z_{0m}}{Z_1}I_{02} = I_a + mI_{01} + m'I_{02}$$

And finally, in terms of this modified compensated phase current, the impedance to the fault point is given by

$$E_a - Z_{1f}I_a - (Z_{0f} - Z_{1f})I_{01} - Z_{0mf}I_{02} = 0$$

$$E_a - Z_{1f}I_a' = 0$$

$$\frac{E_a}{I_a'} = Z_{1f}$$

It should be noted that the current from a parallel circuit must be made available to the relay, if it is to operate correctly for a ground fault. This can be accomplished if the mutually coupled lines are connected to the same bus in the substation. If the two lines terminate at different buses, this would not be possible, and in that case one must accept the error in the operation of the ground distance function.

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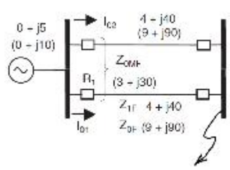
Example: The system shown in the following figure represent two mutually coupled transmission lines, with impedance data as shown in the figure. The zero-sequence impedances are given in parentheses, and the mutual impedance in the zero-sequence circuits of the two transmission lines is *(*3 + j30*)* Ω. The system nominal voltage is 13.8 kV. For a phase-a-to-ground fault at F, the sequence networks are also shown



$$I_1 = I_2 = I_0 = \frac{7967.4}{\underbrace{j5 + (4+j40)\|(4+j40)}_{\text{Positive sequence Thevenin impedance}} + \underbrace{j5 + (4+j40)\|(4+j40)}_{\text{Negative sequence Thevenin impedance}} + \underbrace{j10 + \frac{9+j90+3+j30}{2}}_{\text{Zero sequence Thevenin impedance}}}$$

$$= 66.169\angle -85.23^\circ$$

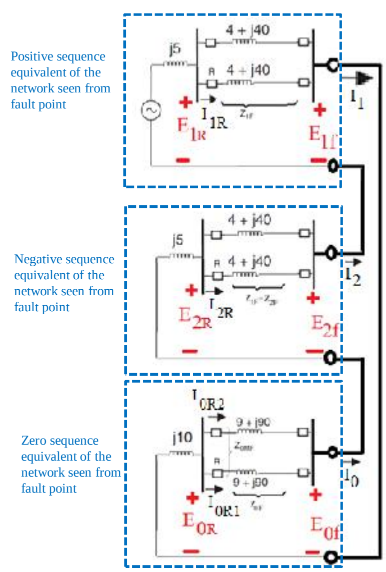
$7967.4 = (13\,800/\sqrt{3})$ is the phase-to-neutral voltage.

It is notable that the Thevenin impedance of two parallel lines with equal impedance of Z for each line and mutual impedance of Zm is 0.5×(Z+Zm)

The currents seen by the relay are half these values because of the even split between the two lines,

$$I_{0R1} = I_{0R2} = 33.085\angle -85.23^\circ$$

$$I_{R1} = I_{R2} = 33.085\angle -85.23^\circ$$



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$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

Therefore, I_a at relay location is $I_a = I_{1R} + I_{2R} + I_{0R1} = 99.25\angle -85.23^\circ$

The zero-sequence compensation factors m and m' are given by

$$m = \frac{Z_0 - Z_1}{Z_1} \qquad m = \frac{9 + j90 - 4 - j40}{4 + j40} = 1.25 \qquad m' = \frac{Z_{0m}}{Z_1} \qquad m' = \frac{3 + j30}{4 + j40} = 0.75$$

The compensated phase a current

$$I'_a = I_a + mI_{01} + m'I_{02} = 165.42\angle -85.23^\circ$$

The symmetrical components of the voltages at the relay location are given by

$$E_{1R} = 7967.4 - j5 \times 66.169\angle -85.23^\circ = 7637.7 - j27.51$$

$$E_{2R} = -j5 \times 66.169\angle -85.23^\circ = -329.7 - j27.51$$

$$E_{0R} = -j10 \times 66.169\angle -85.23^\circ = -659.4 - j55.02$$

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$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} E_0 \\ E_1 \\ E_2 \end{bmatrix}$$

the phase a voltage at the relay location is

$$E_a = E_{1R} + E_{2R} + E_{0R} = 6649.51\angle -0.95^\circ$$

Finally, the impedance seen by the relay Ra is

$$\frac{E_a}{I'_a} = \frac{6649.5\angle -0.95^\circ}{165.42\angle -85.23^\circ} = 4 + j40\ \Omega$$

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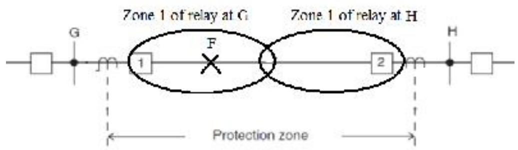
Pilot distance protection

In communication link from remote end of the line exists, it is possible to improve operation of distance relays. For example in the following network if fault happens at point F the relay at bus G operate immediately as the fault has happens at first zone of the relay. However, the relay at bus H sees the relay at its second zone at opens breaker 2 after some delay. Therefore, fault is cleared with some delays. If communication scheme exists relay at bus G can send trip command and trip breaker 2 which means the fault is cleared much faster compared with the conventional methods.



The followings are some of possible pilot protection systems schemes

1) Directional comparison blocking
2) Directional comparison unblocking
3) Permissive overreaching transfer trip (POTT)
4) Underreaching transfer trip
5) Permissive underreaching transfer trip (PUTT)

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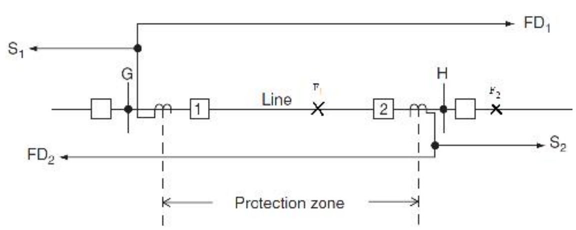
1) Directional comparison blocking



In this scheme a trip is initiated at relay 1 if FD1 sees the fault and no blocking signal is received from S_2. At relay 2 trip is initiated if FD2 sees the fault and no blocking signal is received from S1.

FD1 and FD2 are directional relays and are set to see faults from the bus into and beyond the line. S1 and S2 are directional relays and are set with reversed reach, i.e. to see behind the protected line.

It is notable that this scheme is called “blocking” scheme as the status of the local relay is unblocked during normal condition and is changed to blocked condition during a fault (external faults in this case)

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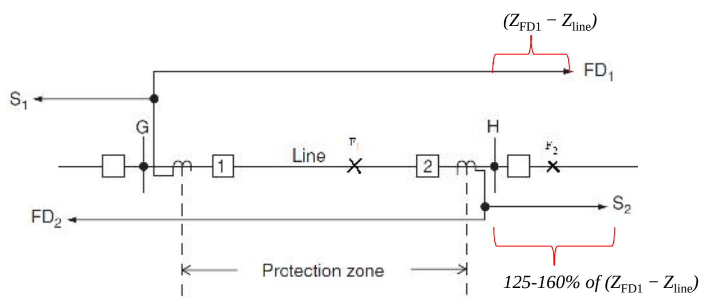
For fault at F1, FD1 and FD2 see the fault. S1 and S2 will not see the fault and will not issue blocking signals. Therefore, FD1 and FD2 trip the breakers 1 and respectively and fault is cleared

For the external fault F2, FD1 at breaker 1 sees the fault, but S2 also sees the fault and sends blocking signal to FD1 and prevents trip signal at Relay1. At breaker 2, FD2 will not see the fault and does not operate

Usually setting of FD1 and FD2 is 175–200% of the protected line section. S2 must overreach the FD1 at the other terminal and is set at 125–160% of $(Z_{FD1} - Z_{line})$.



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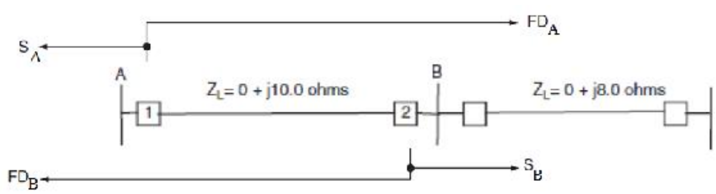
Example: Line section AB is protected by a directional comparison blocking scheme. Calculate the settings of the tripping relay at A and the blocking relay at B.



Set Z_{FD_A} at bus A between 175 and 200% of Z_{line}: $Z_{FD_A} = 17.520\ \Omega$.

Set Z_{S_B} at bus B between 125 and 160% of $(Z_{FD_A} - Z_{line})$ so it will overreach Z_{FD_A} at bus A.

$Z_{FD_A} = 17.5$: Z_{S_B} at bus B $= 1.25(17.5 - 10) = 9.375\ \Omega$

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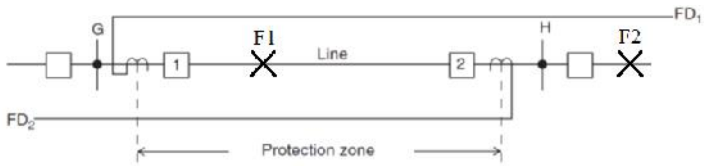
2) Directional comparison unblocking



In the previous scheme (i.e. Directional comparison blocking) the blocking signal is transmitted only when an external fault occurs and during normal condition no blocking signal is transmitted. Therefore, a malfunction in the communication link can not be detected during normal condition. This is because during normal condition no signal is transmitted therefore there is no way to determine if not receiving signal is due to failure of communication link or because no fault has occurred outside of the line.

If a malfunctioning occurs in communication link, in the case of external faults blocking signal is not received from remote terminal, which causes the relay to mis-trip. The failure of the ommunication link will go unnoticed until a false trip occurs during an external fault. To avoid this, in directional comparison unblocking scheme a low-energy continuous carrier signal (which is called guard signal) is transmitted as a check on the communication link. Under normal conditions, this blocking signal is sent continuously. The frequency shifts to a trip frequency when a fault occurs inside the protected line and blocking signal is stopped. For faults outside the protected line still locking signal is transmitted.

During an internal fault, the tripping relay FD1 and FD2 at each end causes the transmitter to shift to the unblocking frequency and stop sending blocking signal, allowing the circuit breaker to trip.

In this scheme Breaker 1 is opened if FD1 sees the fault and no blocking signal is received from remote end. FD1 and FD2 are usually set 150% of the line

As this scheme does not need a trip signal from remote end of the line to operate, this scheme can be implemented in PLC-based communication link.

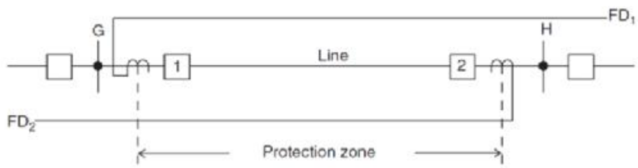
For fault at F2, FD1 sees the fault. However, FD2 does not see the fault and does not stop transmitting blocking signal from bus H to the relay at bus G. Therefore, FD1 is blocked from operation and breaker 1 is not opened.

For fault at F1, FD1 sees the fault. FD2 also sees the fault and stops the transmission of blocking signal from bus H. Therefore, FD1 operates and trip breaker 1.

It is notable that this scheme is called “unblocking” scheme as the status of the local relay is blocked during normal condition and is changed to unblocked condition during a fault (internal faults in this case)

3) Permissive overreaching transfer trip

If the communication channel is independent of the power line, a tripping scheme is a viable protection system.



Referring to above figure, directional overreaching relays FD1 and FD2 send tripping signals to the remote ends. Note that only an internal fault will cause both directional overreaching relays to operate; an external fault at either terminal will be seen by only one of the two directional overreaching relays. Therefore, the relay at 1 issues trip command if the local overreaching relay (i.e. FD1) sees the fault and a tripping signal is received from the remote terminal (i.e. FD2 sees the fault as well). It is notable that in this scheme the guard frequency must stop, allowing its contact to close, and the trip frequency must be received. If the trip frequency is not received the relay does not operate. Therefore, this schem is not applicable for PLC(power line carrier)-communication link as during internal faults trip command can not be sent as the communication link (i.e. power line) is failed

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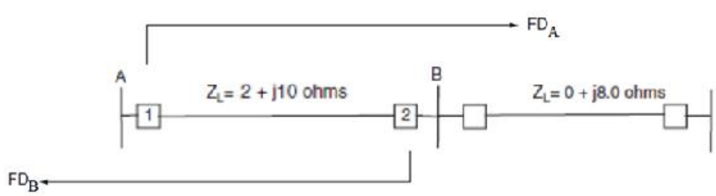
Example: Consider the transmission line shown in the following figure protected by a POTT scheme. Calculate the settings of the relay at A and B



At bus A, Z_{DFA} equals 150% × Z_{line} or $1.5 \times (2 + j10) = 15.3\angle 79°$ ohms.

At bus B, $Z_{DFB} = 150\% \times Z_{line}$ or $1.5 \times (2 + j10) = 15.3\angle 79°$ ohms.

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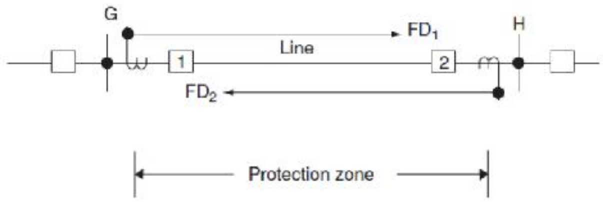
4) Underreaching transfer trip



If a fault occurs within the reach setting of the directional underreaching relay FD1, it will trip circuit breaker 1 directly. This relay is set the same as a zone 1 in conventional distance relays (i.e. 80-85% of the impedance of the line). In addition, FD1 shifts the transmitted signal from the guard frequency to the trip frequency and trips breaker 2. In this scheme the breaker 1 is opened if either FD1 sees the fault or a trip signal comes from FD2. Breaker 2 is opened if either FD2 sees the fault or a trip command comes from FD1.

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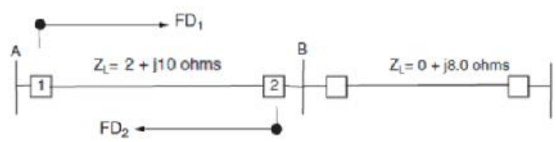
Example: Consider the transmission line shown in the following figure which is protected by the underreaching transfer trip scheme. Calculate the settings of the underreaching relays.



At bus A, FD1 should be equal to 80–850% of *Z*line. If we use 85%, then FD1equals $0.85 \times (2 + j10)$ or $8.67\angle 79$ ohms. At bus B, FD2 also equals $0.85 \times (2 + j10) = 8.67\angle 79$ ohms

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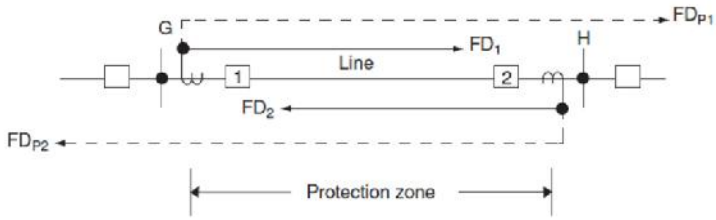
5) Permissive underreaching transfer trip (PUTT)



In the previous scheme (underreaching transfer trip), any transient or noise may appear as a trip command from remote end and causes incorrect operation of relays. To prevent such mis-trips, overreaching FDs are added as shown in above figure.

In this scheme Breaker 1 is opened if either of the following two cases happen

a) FD_1 sees the fault

Or

b)FD_{P1} sees the fault and trip signal comes from remote end (i.e. FD2 sees the fault)

FD1 is set similar to Zone 1 in conventional distance relays (i.e. 80-85% of the line)

FDP1 is set as 150% of impedance of the line

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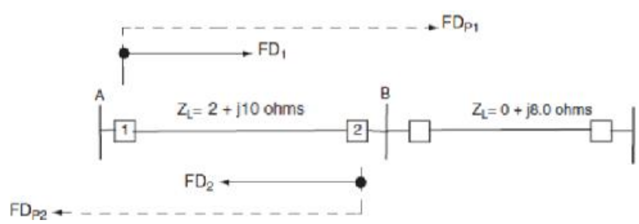
Example: Consider the transmission line shown in the following figure with section AB protected by a permissive underreaching transfer trip (PUTT) scheme. Calculate the settings of the relays



At bus A

ZFD1=0.85*(2+j*10)=

ZFDP1=1.5*(2+j*10)=

At bus B

ZFD2=0.85*(2+j*10)=

ZFDP2=1.5*(2+j*10)=

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