Phase Rolling and the Impacts on Protection

Denglin (Dennis) Tang – Burns & McDonnell

1700 West Loop South, Houston, TX 77027

Office: (713) 622-0227 Fax: (713) 622-0224

dtang@burnsmcd.com

Abstract: During a utility's construction, phase B conductor and phase C conductor were swapped (rolled) less than one mile away from a substation causing the line protection operate immediately. In the same time, there was another zone 1 distance element operated which is three buses away from the phase rolling line. Typically zone 1 distance is set under reach the protected line. Now it operates with an event three buses away and this phenomena confused the protection engineers. This paper will dig into this event and give out explanation why three buses away under reaching distance element operate. Also due to the fact that there is no power system analysis tool available in the market providing such phase rolling analysis, this paper will use analysis method plus popular software tools to calculate the phase rolling currents and compare them with field measured ones. The results show that the calculated phase rolling currents are much closer to the measured ones from the affected relays.

1. Background

There was a line tripping when it was being energized because of a phase B and C rolling near the substation S2. Simultaneously, another line was tripped also at substation S5 which is three buses away from substation S2. Figure 1 below shows the system diagram for this accident tripping.

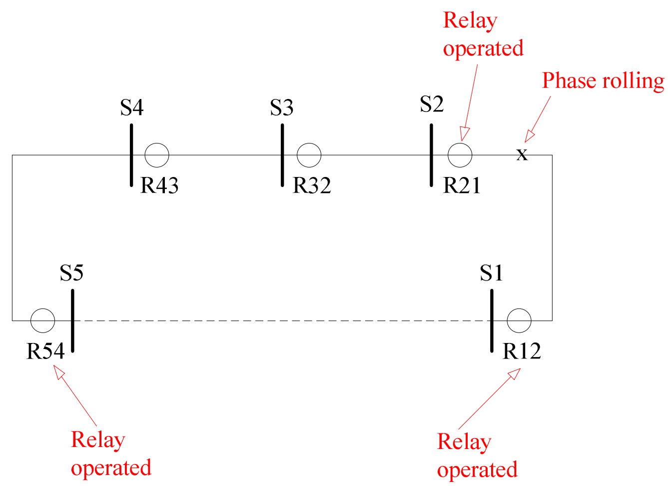


Figure 1. Phase Rolling and Relay Operation

Normally distance zone 1 is set to protect the local line instantaneously. If for whatever reason it has to overreach into next lines, time delay with coordination with next lines protection shall be applied. Following this general philosophy, protection engineers double checked the settings carefully and didn't find there is any settings error. This confused protection engineers. In order to get the phase rolling case understood, this paper is prepared to investigate the details of this phenomenon and give out an explanation to the mis-operation of the relay in substation S5. Also, some characteristics of phase rolling will be revealed during this investigation. Finally, the dedicated calculation on this case will be performed to confirm the relay's operation.

2. Relay Setting and Operation

As the fault is located between substation S1 and S2 according to Figure 1 above, it is not surprised that relays at both substations protecting the subject line operated to isolate the fault. Our focus would be the relay R54 in substation S5 which operated also with the event in topic. In order to verify the operation of the relay R54 in substation S5, we list out related relay's setting and real time operation data as below (all data are present in primary side):

Line impedance: $4.97\Omega\angle 82.96°$

Zone 1 reach: $4.2\Omega\angle 82.96°$

Measured voltage: $V_b = 49.5kV\angle 318.4°$, $V_c = 48.4kV\angle 245.9°$

Measured current: $I_b = 7723.9A\angle 290.9°$, $I_c = 7618.0\angle 111.9°$

The apparent impedance is calculated with the following formula according to the relay manufacturer's (SEL) technical paper "Distance Protection: Pushing the Envelope" [1]:

- Phase distance element impedance measurements

$$\begin{bmatrix} Z_{AB} \\ Z_{BC} \\ Z_{CA} \end{bmatrix} = \begin{bmatrix} \frac{V_A - V_B}{I_A - I_B} \\ \frac{V_B - V_C}{I_B - I_C} \\ \frac{V_C - V_A}{I_C - I_A} \end{bmatrix} \quad (1)$$

So the apparent impedance could be calculated as below:

$$V_{bc} = 49.5kV\angle 318.4° - 48.4kV\angle 245.9° = 57.9kV\angle 11.3°$$
$$I_{bc} = 7723.9A\angle 290.9° - 7618.0\angle 111.9° = 15341.3A\angle -68.6°$$
$$Z_{bc} = V_{bc} / I_{bc} = 57.9kV\angle 11.3° / 15341.3A\angle -68.6° = 3.77\Omega\angle 79.9°$$

By comparing the calculated apparent impedance with the phase distance zone 1 settings as Figure 2 shown below, it is not hard for us to come to the conclusion that the relay operated correctly according to the relay measured voltages and currents.

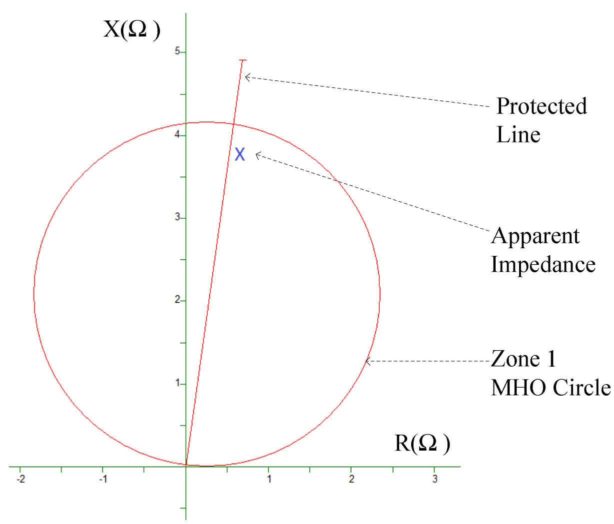


Figure 2. Relay Settings and Operation

3. Phase Rolling Characteristics

From above analysis, we have come to the conclusion that relay has been set and operated correctly according to the measured real time data. Now the question is why the correctly set relay operated overreaching to a line two buses away? In order to answer this question, we have to study the features of phase rolling.

A. Phase rolling is a kind of rare system fault. The only chance of phase rolling occurrence is during the system commissioning time. It could be avoided by verifying the phasing carefully before energizing a new power equipment like a transmission line or a power transformer. On the other hand, the short circuit faults (three phase to ground fault, two phase to ground fault, single phase to ground fault and phase to phase without grounding fault) are most frequent faults in power system and are inevitable during the system operation.

B. Phase rolling don't have conductor contacting and then there is no clear fault location. Generally short circuit fault will have conductors contact between phases or between phase(s) and ground and then always you can find out the exact fault location. The figure 3 demonstrates the scenario of phase rolling.

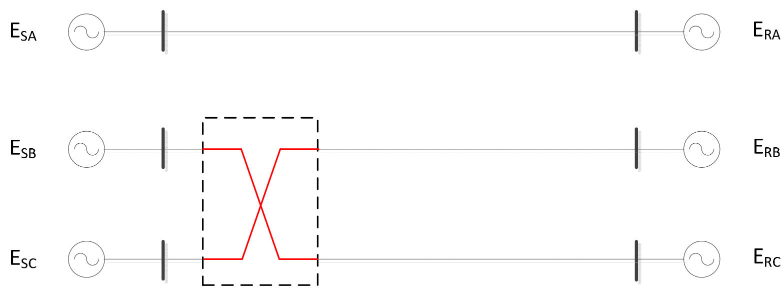


Figure 3. Phase Rolling without a Specific Location

Physically the phase rolling could happen because of the wrong phase connection at a specific pole. However, electrically you cannot tell exactly where the phase rolling occurs. All what you can say is that the phase B at the left side substation is connected to the phase C at the right side substation by mistake.

C. Because of the characteristics above, the apparent impedance at a given line terminal will not depends on the physical location of phase rolling and there is no electrical location of phase rolling at all to depend on. Actually the apparent impedance depends more on the location of the relay than the location of phase rolling. The following section analysis will confirm this point.

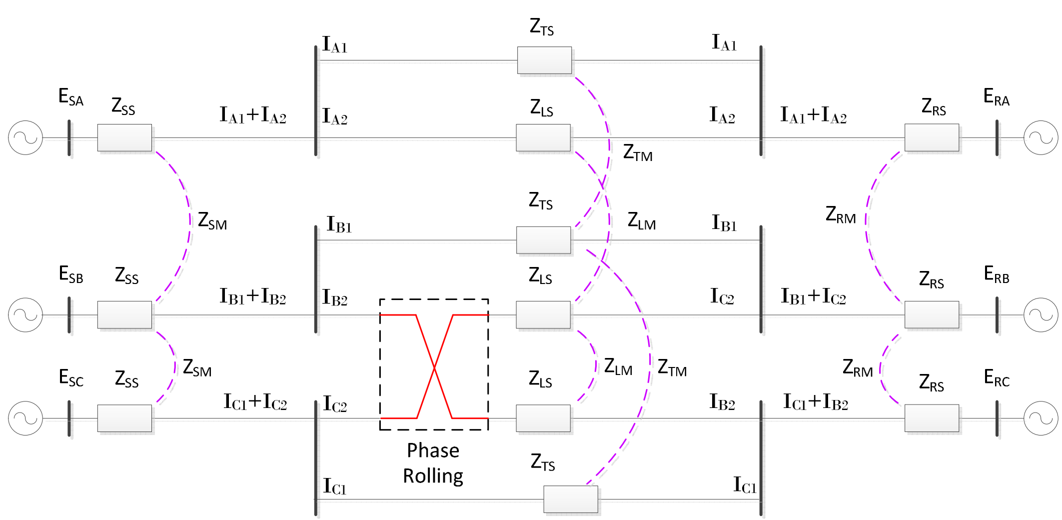
Because of characteristic A (phase rolling is a rare phenomenon), researches have been focused on the short circuit, balanced and unbalanced, and phase losing, but just not phase rolling. Not surprisingly, the well accepted symmetrical component theory is applicable to all kinds of short circuits without considering the phase rolling situation.

For the same reason, relays are designed without taking care of phase rolling. Therefore, there is no way to expect a relay to calculate the location of the phase rolling and to make a decision to trip or not. All what the relay will do is to use the measured voltage and current to calculate the apparent impedance and make a trip/no trip decision assuming this is a short circuit fault. Therefore, any trip on a phase rolling is not a reliable trip.

4. Solving the Theoretical Voltage/Current for Phase Rolling

So far we have checked the relay settings and its operation to the phase rolling and discussed the characteristics of the phase rolling. Here we will perform an analysis to find out the voltage and current at a given relay location under a phase rolling condition. The calculated voltage and current will be compared with the relay's real time data to validate the relays measuring and operation.

Due to the fact that phase rolling is not expected to occur during the system normal operation, there is neither specific analytical theory available nor analysis tool available in the software market. So we have to use the general electrical theories to solve such problem. Not losing the generality, we draw the system configuration as Figure 4, with details around the phase rolling area.



(Mutual are shown for phase A-B & B-C only for simplicity)

E_{SA}, E_{SB}, E_{SC} – Equivalent source potential

E_{RA}, E_{RB}, E_{RC} – Remote equivalent source potential

Z_{SS}, Z_{RS} – Equivalent self-impedances behind the relay and behind the remote terminal

Z_{SM}, Z_{RM} – Equivalent mutual impedances between phases behind the relay and behind the remote terminal

Z_{LS}, Z_{TS} – Subject line and transfer self-impedances

Z_{LM}, Z_{TM} – Subject line and transfer mutual impedances between phases

I_{A1}, I_{B1}, I_{C1} – Currents through the transfer impedances

I_{A2}, I_{B2}, I_{C2} – Currents through the subject relay (phase designation swapped at remote terminal)

Figure 4. System Equivalence with Phase Rolling

All other areas of the system are equaled with infinite systems and equivalent impedances. Since during the phase rolling time, the currents are high enough to be comparable with shirt circuit fault currents, so all the assumptions used for a short circuit analysis will be applicable here also. For example, the generator's sub-transient impedances shall be used with the voltage behind this impedance constant during the phase rolling; the system is symmetrical except the discussed phase rolling, etc.

System equivalent source potentials E_{SA}, E_{SB}, E_{SC} E_{RA}, E_{RB} and E_{RC} could be assumed to be the rated system voltage or actual system operation voltage. System equivalent impedances Z_{SS}, Z_{RS}, Z_{SM}, Z_{RM}, Z_{LS}, Z_{TS}, Z_{LM} and Z_{TM} could be calculated from the regular system model using a popular software tool. Since most software give out the equivalent impedance in sequence, the self-impedance and the mutual impedances could be calculated from the following formula:

$$Z_S = (Z_0+2Z_1)/3$$

$$Z_M = (Z_0-Z_1)/3$$

Where,

Z_S, Z_M – Self and mutual impedances

Z_1, Z_0 – Positive and zero sequence impedances

Phase currents I_{A1}, I_{B1}, I_{C1}, I_{A2}, I_{B2} and I_{C2} are the unknowns which we need to calculate out. This process is the core part of the subject discussion. Since there is no software tool available in the market for such purpose, the Kirchhoff Voltage Low (KVL) shall be used to solve the phase currents. The formulas below could be developed from Figure 4:

$Z_{SS}*(I_{A1}+I_{A2}) + Z_{SM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) + Z_{TS}*I_{A1} + Z_{TM}*(I_{B1}+I_{C1}) + Z_{RS}*(I_{A1}+I_{A2}) + Z_{RM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) = E_{SA}-E_{RA}$

$Z_{SS}*(I_{A1}+I_{A2}) + Z_{SM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) + Z_{LS}*I_{A2} + Z_{LM}*(I_{B2}+I_{C2}) + Z_{RS}*(I_{A1}+I_{A2}) + Z_{RM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) = E_{SA}-E_{RA}$

$Z_{SS}*(I_{B1}+I_{B2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{C1}+I_{C2}) + Z_{TS}*I_{B1} + Z_{TM}*(I_{A1}+I_{C1}) + Z_{RS}*(I_{B1}+I_{C2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{C1}+I_{B2}) = E_{SB}-E_{RB}$

$Z_{SS}*(I_{B1}+I_{B2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{C1}+I_{C2}) + Z_{LS}*I_{B2} + Z_{LM}*(I_{A2}+I_{C2}) + Z_{RS}*(I_{C1}+I_{B2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{B1}+I_{C2}) = E_{SB}-E_{RC}$

$Z_{SS}*(I_{C1}+I_{C2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{B1}+I_{B2}) + Z_{LS}*I_{C2} + Z_{LM}*(I_{A2}+I_{B2}) + Z_{RS}*(I_{B1}+I_{C2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{C1}+I_{B2}) = E_{SC}-E_{RB}$

$Z_{SS}*(I_{C1}+I_{C2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{B1}+I_{B2}) + Z_{TS}*I_{C1} + Z_{TM}*(I_{A1}+I_{B1}) + Z_{RS}*(I_{C1}+I_{B2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{B1}+I_{C2}) = E_{SC}-E_{RC}$

Re-sort above formulas by the unknown phase currents:

$(Z_{SS}+Z_{TS}+Z_{RS})*I_{A1} + (Z_{SS}+Z_{RS})*I_{A2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{B1} + (Z_{SM}+Z_{RM})*I_{B2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{C1} + (Z_{SM}+Z_{RM})*I_{C2}= E_{SA}-E_{RA}$

$(Z_{SS}+Z_{RS})*I_{A1} + (Z_{SS}+Z_{LS}+Z_{RS})*I_{A2} + (Z_{SM}+Z_{RM})*I_{B1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{B2} + (Z_{SM}+Z_{RM})*I_{C1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{C2} = E_{SA}-E_{RA}$

$(Z_{SM}+Z_{TM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{RM})*I_{A2} + (Z_{SS}+Z_{TS}+Z_{RS})*I_{B1} + (Z_{SS}+Z_{RM})*I_{B2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{C1} + (Z_{SM}+Z_{RS})*I_{C2}= E_{SB}-E_{RB}$

$(Z_{SM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{A2} + (Z_{SS}+Z_{RM})*I_{B1} + (Z_{SS}+Z_{LS}+Z_{RS})*I_{B2} + (Z_{SM}+Z_{RS})*I_{C1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{C2} = E_{SB}-E_{RC}$

$(Z_{SM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{A2} + (Z_{SM}+Z_{RS})*I_{B1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{B2} + (Z_{SS}+Z_{RM})*I_{C1} + (Z_{SS}+Z_{LS}+Z_{RS})*I_{C2} = E_{SC}-E_{RB}$

$(Z_{SM}+Z_{TM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{RM})*I_{A2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{B1} + (Z_{SM}+Z_{RS})*I_{B2} + (Z_{SS}+Z_{TS}+Z_{RS})*I_{C1} + (Z_{SS}+Z_{RM})*I_{C2} = E_{SC}-E_{RC}$

Figure 5. Formulas Sorted by Phase Currents

With six formulas, the six unknown phase currents should be able to be solved out.

After solving out the phase currents, it wouldn't be hard to calculate the voltages at each buses by applying the Ohm's Law.

5. Sample Calculation from a Real Case

To verify the accuracy of above phase rolling solution, real case system model was used to calculate the currents. Here are the details.

$E_{SA} = 1.025*138kV/\sqrt{3}\angle 0°$, $E_{SB} = 1.025*138kV/\sqrt{3}\angle -120°$, $E_{SC} = 1.025*138kV/\sqrt{3}\angle 120°$
$E_{RA} = 1.025*138kV/\sqrt{3}\angle 0°$, $E_{RB} = 1.025*138kV/\sqrt{3}\angle -120°$, $E_{RC} = 1.025*138kV/\sqrt{3}\angle 120°$
$Z_{SS} = 25.15\Omega \angle 86.04°$, $Z_{SM} = 4.62\Omega \angle -94.67°$
$Z_{RS} = 1.91\Omega \angle 85.96°$, $Z_{RM} = 0.12\Omega \angle -93.10°$
$Z_{LS} = 3.05\Omega \angle 77.79°$, $Z_{LM} = 1.37\Omega \angle 72.62°$
$Z_{TS} = 25.47\Omega \angle 74.69°$, $Z_{TM} = 12.57\Omega \angle 68.25°$

Applying above voltages and impedances values to the formulas shown in Figure 5 and solving them with Mathcad software, we can find out the phase currents.

$Ia1 := 0$

$Ia2 := 0$

$Ib1 := 0$

$Ib2 := 0$

$Ic1 := 0$

$Ic2 := 0$

Given

$$\left(52.28e^{1.406i}\right)\cdot Ia1+\left(27.06e^{1.502i}\right)\cdot Ia2+\left(8.16e^{1.019i}\right)\cdot Ib1+\left(4.74e^{4.632i}\right)\cdot Ib2+\left(8.16e^{1.019i}\right)\cdot Ic1+\left(4.74e^{4.632i}\right)\cdot Ic2 = 0$$

$$\left(27.06e^{1.502i}\right)\cdot Ia1+\left(30.08e^{1.487i}\right)\cdot Ia2+\left(4.74e^{4.632i}\right)\cdot Ib1+\left(3.42e^{4.720i}\right)\cdot Ib2+\left(4.74e^{4.632i}\right)\cdot Ic1+\left(3.42e^{4.720i}\right)\cdot Ic2 = 0$$

$$\left(8.16e^{1.019i}\right)\cdot Ia1+\left(4.74e^{4.632i}\right)\cdot Ia2+\left(52.28e^{1.406i}\right)\cdot Ib1+\left(25.03e^{1.502i}\right)\cdot Ib2+\left(8.16e^{1.019i}\right)\cdot Ic1+\left(2.71e^{4.623i}\right)\cdot Ic2 = 0$$

$$\left(4.74e^{4.632i}\right)\cdot Ia1+\left(3.42e^{4.720i}\right)\cdot Ia2+\left(25.03e^{1.502i}\right)\cdot Ib1+\left(30.08e^{1.487i}\right)\cdot Ib2+\left(2.71e^{4.623i}\right)\cdot Ic1+\left(3.42e^{4.720i}\right)\cdot Ic2 = 141450e^{4.712i}$$

$$\left(4.74e^{4.632i}\right)\cdot Ia1+\left(3.42e^{4.720i}\right)\cdot Ia2+\left(2.71e^{4.623i}\right)\cdot Ib1+\left(3.42e^{4.720i}\right)\cdot Ib2+\left(25.03e^{1.502i}\right)\cdot Ic1+\left(30.08e^{1.487i}\right)\cdot Ic2 = 141450e^{1.571i}$$

$$\left(8.16e^{1.019i}\right)\cdot Ia1+\left(4.74e^{4.632i}\right)\cdot Ia2+\left(8.16e^{1.019i}\right)\cdot Ib1+\left(2.71e^{4.623i}\right)\cdot Ib2+\left(52.28e^{1.406i}\right)\cdot Ic1+\left(25.03e^{1.502i}\right)\cdot Ic2 = 0$$

$$\mathrm{Find}(Ia1,Ia2,Ib1,Ib2,Ic1,Ic2) = \begin{pmatrix} -0.153+1.426i \\ 0.095-1.067i \\ 5.313\times10^{3}+693.172i \\ -8.611\times10^{3}-902.537i \\ -5.312\times10^{3}-695.677i \\ 8.61\times10^{3}+907.982i \end{pmatrix}$$

Figure 6. Screenshot of Mathcad Equation Solving

From the Mathcad screenshot, the solved phase B line current is (-8611-903i)A and the phase C line current is (8610+908i)A. Comparing with corresponding measured values I_b = 7723.9A∠290.9° and I_c = 7618.0∠111.9°, the simulation error is around 10% approximately which should be acceptable considering that the original system model is conservative.

6. Further Discussion

Cross feeding: in case there is other cross feeding branch between the studied relay and the phase rolling line (Figure 7), still the discussed method could be used to calculate the currents in the phase rolling line. The currents through the relay could be distributed between the relay branch and cross feeding branch from the phase rolling section currents.

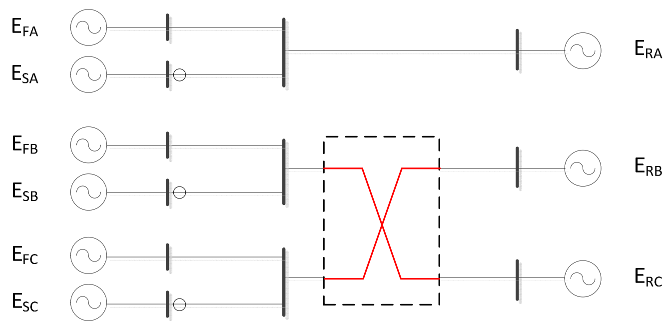


Figure 7. System Equivalence with Cross Feeding

What really matters: security vs. dependability. We've already understood that the phase rolling is a rare phenomenon during commissioning time. And the apparent impedance the relay see depends mostly on the location of the relay. There is nothing protection engineers can do with the mis-operation in non-phase rolling lines since the relays were designed for short circuit faults so far. However, protection engineers do need to pay attention to the dependability of the relay on the phase rolling line. It is preferable that the relay can trip off the phase rolling line immediately to reduce the impact of the phase rolling on the system.

7. Conclusion

Phase rolling is not a frequent fault in power system. There is no dedicated software tool available in the market to perform related analysis. However, if such situation happen and the protection engineer prefer to confirm the relay's operation, handy script like MS VBA or Mathcad could be employed with the aid of popular software tools (Aspen Oneliner, Electrocon CAPE, ETAP, etc.) to do the calculation following the steps provided in this paper. Further, it is the protection engineer's responsibility to make sure the protection system to trip off the phase rolling line as soon as possible, if instantaneous tripping is not possible.

8. References

[1]. Distance Protection: Pushing the Envelope, by Edmund Stokes-Waller, SEL's technical paper.

[2]. Power System Analysis and Design, by J. Duncan Glover, M. S. Sarma, T. J. Overbye.