System Model and Source Impedance Study for Relay Performance Analysis

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Mark (Yelei) Wang
Hatch Energy
Toronto, ON Canada

Peter (Hong) Wang
TransAlta Energy Corp
Calgary, AB Canada

Danny Lam
Hydro One
Toronto, ON Canada

Presented to

36th Annual

WESTERN PROTECTIVE RELAY CONFERENCE

Spokane, Washington

October 20-22, 2009

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Mark (Yelei) Wang	Peter (Hong) Wang	Danny Lam
Hatch Energy	TransAlta Energy Corp	Hydro One
Toronto, ON Canada	Calgary, AB Canada	Toronto, ON Canada

Abstract

This paper discusses two issues, an improved system model for application of superposition and corresponding source impedance study. Comparing with the classical system model with one line between two sources, the improved system model contains two parallel transmission lines between two terminals sources. This representation is more reasonable than the classical system model by considering the interaction of infeed or outfeed between two terminals. Based on the improved system model, this paper provides an equivalent of source impedance behind relay, and reveals the relationship between the location of line fault and equivalent source impedance, which is further development from the ambiguous definition in IEEE StdC37.113-1999 (2004). Furthermore, an engineering method on how to derive source impedance is provided in this paper as well.

1. Introduction

The frequently used classical system model is an approximate representation of the system and has some drawbacks in simulation of system faults. Greater tolerances will be generated during system fault calculations comparing with physical measurements of the faults. Some conclusions derived from classical system model are not general for its special system configurations.

The main purpose of this paper is to provide "source impedance" study based on the improved system model for system fault calculations on relay performance analysis. This improved system model considers the effect of interaction from the remote source as collective source impedance, which is a function of fault location. After detailed derivations and engineering analysis in this paper, it is feasible to apply this improved system model for engineering applications and will not increase complexity of engineering analysis significantly.

2. Superposition application in system fault calculation and classical system model

The purpose of superposition method is to derive fault current with load effect considered by summing load component and fault component together. This method is especially useful for conducting relay performance analysis for differential protections of transmission lines with heavy load.

In the application of superposition method, one system model with consistent system parameters is used for both prefault load calculation and fault current calculation. In prefault load calculation, the load current and prefault voltage at the fault location are derived as the first step; then the prefault voltage in negative polarity at the fault location is added as a fault source with the original load sources being removed in order to calculate the pure fault current (superposition current) in a pure fault circuit. At the last, the total current is derived by adding both load current and fault current together [6].

Exactly steady state generator synchronous impedances should be used for normal operating conditions to derive load currents and generator subtransient impedances should be employed at fault moment to get fault components. Therefore, superposition method is not very accurate for generator impedances are changed before and after system faults. But for the majority engineering applications in large scale power systems, after equivalence of system parameters, the ignoring dynamic differences between subtransient impedances and steady state synchronous impedances is still acceptable in engineering.

The classical system model consisting two sources of terminals with just one transmission line between two terminals has been used in engineering analysis for decades. Generally, superposition method is to use the classical system model in two scenarios, prefault load scenario and fault scenario, typically described in [2] and [6]. The problem of classical system model is its configuration. This configuration is suitable for normal load scenario but not for fault scenario for the interaction of infeed or outfeed between terminals sources are not considered. In classical system model, the system sources impedances are kept as **CONSTANT** in both prefault load scenario and fault scenario. In fact, for forward fault condition, the source impedance in real system is not only dependent on the prefault system configurations, load condition and changes of generator impedances, but also a function of fault location within the protected line since in most cases two systems are interconnected by more than one tie line. The error of fault calculations based on this system configuration is variable and is changed with respect to the fault location on the line. Also, the constant source impedance simulation is different from the descriptions in Section 3.1.3.34 of IEEE StdC37.113-1999 (2004), in which the Source impedance is defined as "The Thevenin equivalent impedance of an electrical system at the terminal of a transmission line. In network applications, this impedance can vary depending on the location of the fault on the transmission line and the status (i.e., opened or closed) of other terminals associated with the transmission line."

3. Proposed improved system model

An improved system model for superposition method is proposed by adding a parallel line with the protected line between two terminals into the classical model. This new system model can be derived from any complex real system configurations theoretically and can be applied for field applications. The improved system model is shown in Figure 1, in which ZL is the impedance of the protected line. The advantage of the improved system model is to include the infeed effect from the remote end source or outfeed effect from local end source for forward faults on the protected line, which is dependent on fault location. In addition, this system model has been used extensively in laboratories for relay performance analysis and relay type tests.

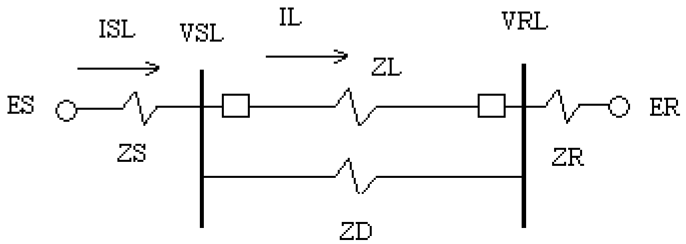

Figure 1

The superposition way with the improved system model is more accurate to evaluate load effect in a complex power system. Based on the proposed improved system model the superposition method is applied in the same way as the classical system model. Below is the description for how to apply superposition method with the proposed improved system model.

a) Start from system model shown in Figure 1 to get load current and prefault system voltage at the specific fault location in Figure 2, see 3.1.
b) Derive pure fault current by removing two power sources and add the prefault voltage in negative polarity at the fault location as a fault source shown in Figure 3, see 3.2.
c) Combine both load and pure fault current together to get actual fault current.

3.1 Prefault load calculation

Take ES as reference.

$$ER = R * e^{-jr} * ES \tag{1}$$

R is a scalar, the magnitude ratio.
r is the angle difference between two sources.

$$ISL = \frac{ES - ER}{ZS + \frac{ZL * ZD}{ZL + ZD} + ZR} = \frac{ES * (1 - R * e^{-jr})}{ZS + \frac{ZL * ZD}{ZL + ZD} + ZR} \tag{2}$$

$$IL = ISL * \frac{ZD}{ZL + ZD} = \frac{ES * (1 - R * e^{-jr}) * ZD}{(ZS + \frac{ZL * ZD}{ZL + ZD} + ZR) * (ZL + ZD)} \tag{3}$$

Prefault bus voltage

$$VSL = ES - ISL * ZS = ES * [1 - \frac{ZS * (1 - R * e^{-jr})}{ZS + \frac{ZL * ZD}{ZL + ZD} + ZR}] \tag{4}$$

This prefault voltage at bus can be used as memorized voltage for polarizing in Mho distance relay. Further analysis in Figure 2 is to get the prefault voltage at the specific fault point on the protected line. k is the percentage of ZL with a value between 0 and 1.

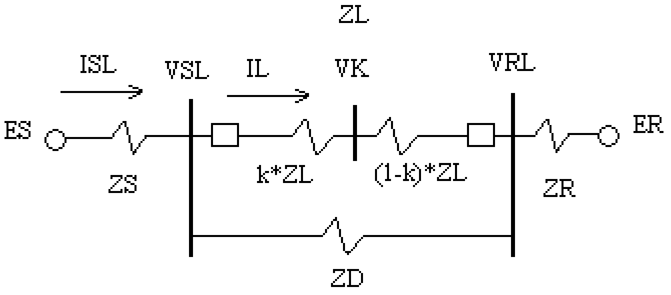

Figure 2

$$VK = VSL - IL*k*ZL = ES - ISL*ZS - IL*k*ZL$$

$$= ES*[1 - \frac{(ZS + \frac{k*ZL*ZD}{ZL+ZD})*(1-R*e^{-jr})}{ZS + \frac{ZL*ZD}{ZL+ZD} + ZR}] \qquad (5)$$

3.2 Pure fault calculation for three phase fault 3LG

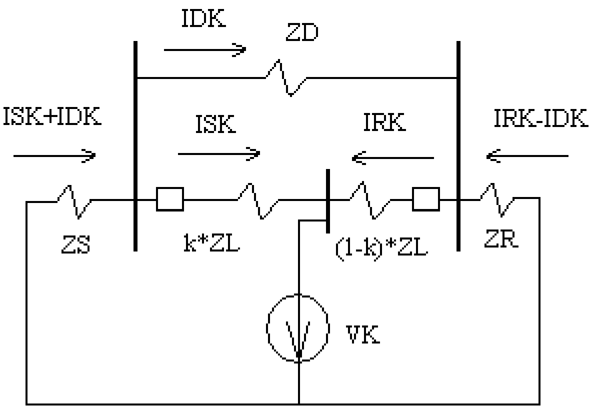

Figure 3

From Figure 3

$$ISK*k*ZL - IRK*(1-k)*ZL - IDK*ZD = 0 \qquad (6)$$

$$ISK*k*ZL + (ISK + IDK)*ZS = VK \qquad (7)$$

$$IRK*(1-k)*ZL + (IRK - IDK)*ZR = VK \qquad (8)$$

The superposition current is derived as ISK in Equation (9).

$$ISK = \frac{ES[1 - \frac{(ZS + \frac{k*ZL*ZD}{ZL+ZD})*(1-R*e^{-jr})}{ZS + \frac{ZL*ZD}{ZL+ZD} + ZR}]*\{ZD*[ZR+(1-k)*ZL]+(1-k)*ZL*(ZS+ZR)\}}{ZD*(k*ZL+ZS)*[ZR+(1-k)*ZL]+ZR*(1-k)*ZL*(k*ZL+ZS)+k*ZL*ZS*[ZR+(1-k)*ZL]}$$

(9)

The total fault current IF is

$$IF = IL + ISK \tag{10}$$

4 Positive sequence source impedance study

4.1 Positive sequence source impedance derivation

Based on the improved system model of Figure 2, the specific point k of the protected line can be regarded as a bus. The system model can be further transformed into a more specific system model from Figure 4 to Figure 6 by using "star-delta transformation" way.

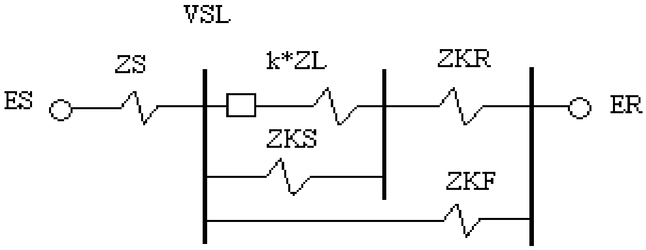

Figure 4

Assume

$$ZE = ZD * ZR + ZR * (1-k) * ZL + (1-k) * ZL * ZD \tag{11}$$

Get

$$ZKS = \frac{ZE}{ZR} \tag{12}$$

$$ZKR = \frac{ZE}{ZD} \tag{13}$$

$$ZKF = \frac{ZE}{(1-k) * ZL} \tag{14}$$

⇓

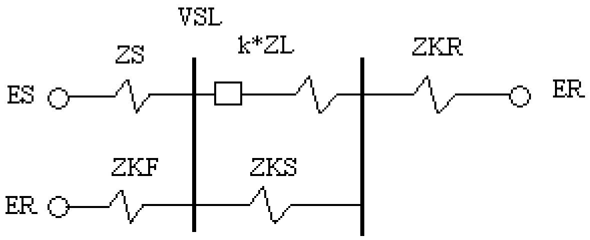

Figure 5

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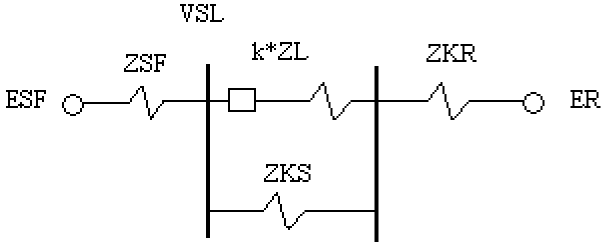

Figure 6

$$ESF = ER + \frac{(ES - ER) * ZKF}{ZS + ZKF} = ES[1 + \frac{ZS * (R * e^{-jr} - 1)}{ZS + ZR + ZD + \frac{ZR}{(1-k) * ZL}}] = F * ES \tag{15}$$

Assume

$$F = 1 + \frac{ZS * (R * e^{-jr} - 1)}{ZS + ZR + ZD + \frac{ZR}{(1-k) * ZL}} \tag{16}$$

F is determined by system impedances (ZS, ZR, ZL, and ZD), prefault load condition (r) and fault location (k). ESF has magnitude difference and angle shift from ES due to nonhomogeneous of system impedances, prefault load condition and fault location.

$$ZSF = \frac{ZS * ZKF}{ZS + ZKF} = \frac{1}{\frac{1}{ZS} + \frac{1}{ZD + ZR + \frac{ZR * ZD}{(1-k) * ZL}}} \tag{17}$$

It can be seen that k is inversely proportional to ESF, and proportional to ZSF.

By using system model described in Figure 6, a 3LG fault is assumed as shown in Figure 7.

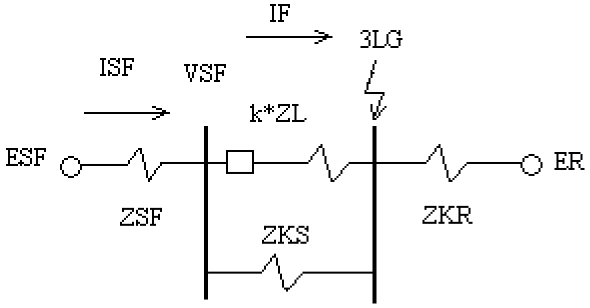

Figure 7

$$ISF = \frac{ESF}{ZSF + \frac{k * ZL * ZKS}{k * ZL + ZKS}} \tag{18}$$

$$IF = ISF * \frac{ZKS}{k * ZL + ZKS} = \frac{ESF}{k * ZL + ZSF * (1 + \frac{k * ZL}{ZKS})} \tag{19}$$

Both (10) and (19) are the same.

Bus fault voltage

$$VSF = IF * k * ZL \tag{20}$$

This real time fault voltage at bus can be used as partial polarizing voltage in Mho distance relay applications.

From (19),

$$ESF = IF * [k * ZL + ZSF * (1 + \frac{k * ZL}{ZKS})] = VSF + IF * ZSF * (1 + \frac{k * ZL}{ZKS}) \tag{21}$$

Equation (21) can be expressed in Figure 8. $IF * ZSF * (1 + \frac{k * ZL}{ZKS})$ is the voltage drop across equivalent system source impedance behind the relay and $ZSF * (1 + \frac{k * ZL}{ZKS})$ is the equivalent system source impedance. For clarification, Figure 8 is transformed from the improved system model and is effective for the interested source impedance only.

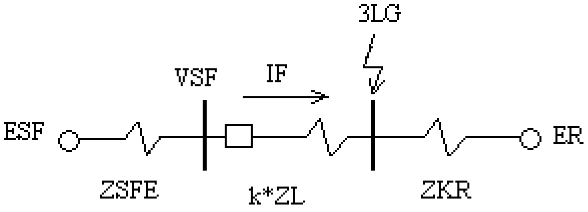

Figure 8

The source impedance ZSFE behind the relay in the protected line is valid for forward faults. It is apparent impedance with infeed effect of remote end source or outfeed effect of local end source considered, and it is inversely proportional to the fault current through relay.

$$ZSFE = ZSF * (1 + \frac{k * ZL}{ZKS}) = ZSF * \frac{ISF}{IF} \tag{22}$$

4.2 Analysis of the relationship between source impedance ZSFE and fault location k

For simplification it is assumed that all impedances are not much nonhomogeneous. Therefore, it is acceptable to mainly consider the magnitude of impedances.

From equation (17), k is proportional to ZSF.

$$\frac{k*ZL}{ZKS}=\frac{ZR*k*ZL-\dfrac{ZR+ZD}{ZR}}{ZR*ZD+ZL*(ZR+ZD)} \tag{23}$$

k is proportional to $\dfrac{k*ZL}{ZKS}$.

ZS, ZR, ZD and ZL can be regarded as known in the analysis.

In summary, k is proportional to collective impedance ZSFE.
Per above analysis, the improved system model can provide a better representation on impacts of fault location on the protected line than the classical system model. Under forward faults conditions, the source impedance behind relay is a proportional function of fault location *k* on the protected line. The farther fault location is, the greater source impedance will be.

5 **Example**

$$\angle(mag,ang)=mag*(\cos(ang.\mathrm{deg})+j*\sin(ang.\mathrm{deg}))$$

Assume

$ES=1.05\angle 30$	$ER=1\angle 0$
$ZS=0.35\angle 85$	$ZR=0.5\angle 83$
$ZL=0.6\angle 80$	$ZD=0.2\angle 82$

$$ZSFE(k)=\frac{ZS*\dfrac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}{ZS+\dfrac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{(1-k)*ZL}}*[1+\frac{k*ZL}{\dfrac{ZD*ZR+(1-k)*ZL*(ZR+ZD)}{ZR}}]$$

The curve of relationship between source impedance and fault location is shown in Figure 9.

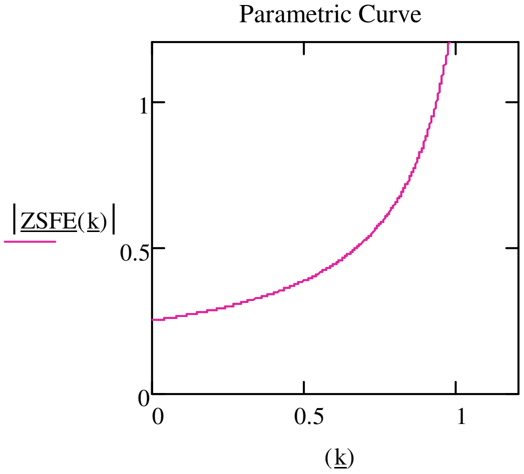

Figure 9

6 Engineering applications for source impedances

In engineering applications, it is easy to use short circuit calculation software to get subtransient or transient source impedances for both positive and zero sequence networks.

6.1 Subtransient positive sequence source impedance

Generator subtransient impedances can be used to derive subtransient source impedances. The source impedance for a fault at the distance zone 1 reaching point is more interesting for relay performance analysis in actual field applications. A 3LG fault at zone 1 reaching point is assumed.

$$Z1source = \frac{E}{I1local} - Z1setting \tag{24}$$

In Per Unit value, $E = 1$ or any assumed value.

From equation (24), it can be found that, assuming both E and Z1setting are known, the farther the fault location is, the less Ilocal will be, the more Z1source will be. This result is different from the method of source impedance calculation provided in [3].

6.2 Subtransient zero sequence source impedance

In the similar way to the positive sequence scenario, zero sequence source impedance can be derived. A 1LG at zone 1 reaching point is assumed.

$$Z0source = \frac{V0local}{I0local} \tag{25}$$

It can be found that when fault location is farther, I0local is less, but V0local is less as well. So $Z0source = \frac{V0local}{I0local}$ does not have a constant tendency and will change from case to case.

6.3 Transient positive sequence source impedance

Per [4], transient generators impedances are used for the calculations. The equivalent two-port network as seen from the two ends of the interested line can be derived by removing the interested protected line, and then the line impedance can be reintroduced in parallel with the equivalent transfer impedance.

The directly calculated source impedance from short circuit software is not the real source impedance behind the relay in protected line. It is suggested to use the method shown in equation (22) to get the real apparent source impedance for the analysis.

7 Derivation of Mho distance relay impedance circle based on improved system model

The classical derivation of Mho impedance circle is based on the classical system load model. It shows that the transient offset circle is dependent on the source impedance in constant. However, based on the proposed improved system model, the transient offset and shift of Mho distance element circle are also related to the fault location *k*.

7.1 Derivation of Mho phase distance relay based on improved system model

Based on the improved system model, Mho phase distance relay impedance circle can be derived by assuming a 3LG bolt fault (3LG) at k in Figure 7.

$$ZK = k * ZL \tag{26}$$

From equation (19), (22) and (26),

$$IF = \frac{F * ES}{ZK + ZSFE} \tag{27}$$

Mho distance elements work as torque elements with cosine phase comparator. The two inputs of the comparator are shown as follows,

$$T1 = IF * Zset - V = F * ES * \frac{Zset - ZK}{ZK + ZSFE} \tag{28}$$

$$T2 = VP = Vm1 = h * e^{-jm} * ES \tag{29}$$

Zset is the positive impedance reach setting.
IF is phase fault current measured by relay.
V is real time phase fault voltage at bus measured by relay.
Vp is polarizing voltage.

There are angle and magnitude differences between the prefault bus voltage and ES for load. For simplifying equation (28) and (29), only prefault voltage is considered as polarizing in this derivation.

For Mho element operation, there is

$$\begin{aligned} &T = \mathrm{Re}(T1 * T2^{*}) = T1 * T2 * \cos(\phi t1 - \phi t2) \geq 0 \rightarrow \cos(\phi t1 - \phi t2) \geq 0 \\ &\rightarrow -90 \leq \phi t1 - \phi t2 \leq 90 \rightarrow -90 \leq Arg(\frac{T1}{T2}) \leq 90 \end{aligned} \tag{30}$$

$$\begin{aligned} &-90 \leq Arg(\frac{T1}{T2}) = Arg(\frac{F * ES * \frac{Zset - ZK}{ZK + ZSFE}}{h * e^{-jm} * ES}) \\ &= Arg(\frac{Zset - ZK}{ZK + ZSFE}) + Arg(\frac{F}{h * e^{-jm}}) = \alpha + \beta \leq 90 \end{aligned} \tag{31}$$

By subtracting β in all sides,

$$-90 - \beta \leq \alpha \leq 90 - \beta \tag{32}$$

$$\alpha = Arg(\frac{Zset - ZK}{ZK + ZSFE}) \tag{33}$$

α is the impedance circle with offset of ZSFE as expansion of the circle, which relates to fault location. The offset is the apparent source impedance.

$$\beta = Arg(\frac{F}{h * e^{-jm}}) \tag{34}$$

β is a circle shifting right or left with respect to the prefault load. It is also related to fault location. The normal impedance circle with offset and shifting is shown in Figure 10.

If prefault load is not considered and the system is homogeneous, $m = r = 0$ and $e^{-jm} = e^{-jr} = 1$.

$$F = 1 + \frac{ZS * (R-1)}{ZS + ZR + ZD + \frac{ZR}{(1-k) * ZL}}$$ and $h * e^{-jm} = h$ are scalar.

$$\beta = Arg(\frac{F}{h * e^{-jm}}) = 0$$

This impedance circle with offset of source impedance only is shown in Figure 11.

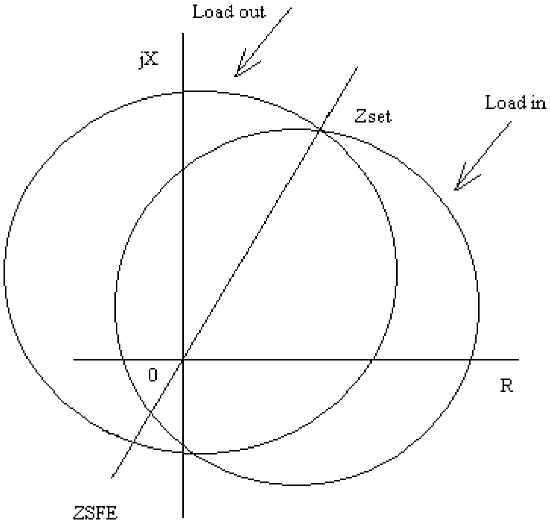

Figure 10

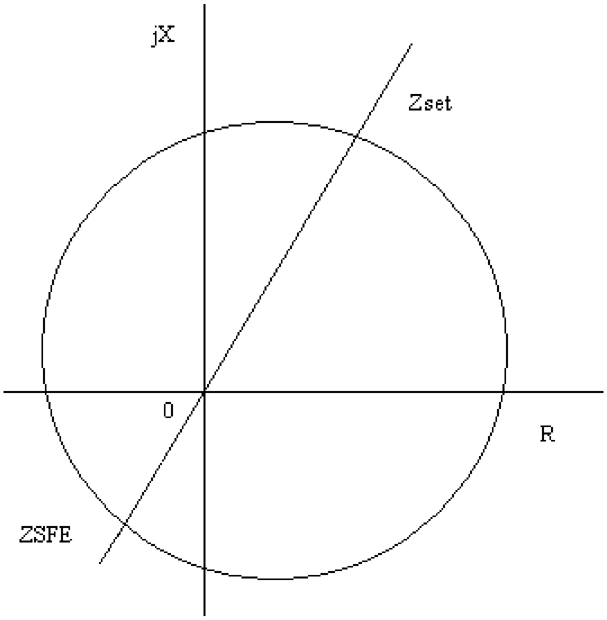

Figure 11

7.2 Derivation of Mho ground distance relay based on improved system model

Based on the improved system model, Mho ground distance relay impedance circle can be derived in Figure 12 by assuming a A phase to ground fault (1LG) at k.

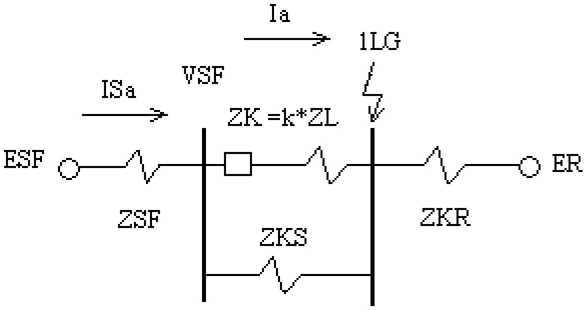

Figure 12

$$IF = IFa + Kl * 3I0F \tag{35}$$

$$ISF = ISa + Ks * 3I0S \tag{36}$$

$$Kl = \frac{ZL0 - ZL1}{3 * ZL1} \tag{37}$$

$$Ks = \frac{ZS0 - ZS1}{3 * ZS1} \tag{38}$$

$$IF1 = \frac{IS1 * ZKS1}{ZK1 + ZKS1} \tag{39}$$

$$IF0 = \frac{IS0 * ZKS0}{ZK0 + ZKS0} \tag{40}$$

$$IFa = IF1 + IF2 + IF0 = 2 * IF1 + IF0 \tag{41}$$

$$ISa = IS1 + IS2 + IS0 = 2 * IS1 + IS0 \tag{42}$$

$$\frac{ISF}{IF}=1+\frac{2*IF1*\frac{ZK1}{ZKS1}+IF0*(3*Ks+3*Ks\frac{ZK0}{ZKS0}+\frac{ZK0}{ZKS0}-3*Kl)}{2*IF1+IF0*(1+3*Kl)} \tag{43}$$

For simplifying analysis, assume

$$\frac{ZL1}{ZL0}=\frac{ZK1}{ZK0}=\frac{ZKS1}{ZKS0}=\frac{ZS0}{ZS1} \tag{44}$$

There is

$$\frac{ISF}{IF}=1+\frac{1}{\frac{ZD+ZL*\frac{ZR+ZD}{ZR}}{ZK}-\frac{ZR+ZD}{ZR}} \tag{45}$$

With the above assumptions, $\frac{ISF}{IF}$ should be more than 1 and is proportional to fault location.

The farther fault location is, the greater ZK and $\frac{ISF}{IF}$ is.

$$Va=IF*ZK \tag{46}$$

$$ESFa=Va+ISF*ZSF=IF*(ZK+ZSF*\frac{ISF}{IF})=IF*(ZK+ZSFE) \tag{47}$$

Mho distance elements work as torque elements of a cosine phase comparator. The two inputs of the comparator are shown as follows.

$$T1=IF*Zset-Va=F*ESa*\frac{Zset-ZK}{ZK+ZSFE} \tag{48}$$

$$T2=VP=Vm1=h*e^{-jm}*ESa \tag{49}$$

Zset is the positive impedance reach setting.

For Mho elements operation,

$$T=\mathrm{Re}(T1*T2^{*})=T1*T2*\cos(\phi t1-\phi t2)\geq 0\rightarrow\cos(\phi t1-\phi t2)\geq 0$$

$$\rightarrow -90\leq\phi t1-\phi t2\leq 90\rightarrow -90\leq Arg(\frac{T1}{T2})\leq 90$$

$$\begin{aligned}-90\leq Arg(\frac{T1}{T2})&=Arg(\frac{F*ESa*\frac{Zset-ZK}{ZK+ZSFE}}{h*e^{-jm}*ESa})\\&=Arg(\frac{Zset-ZK}{ZK+ZSFE})+Arg(\frac{F}{h*e^{-jm}})=\alpha+\beta\leq 90\end{aligned} \tag{50}$$

By subtracting β in all sides $-90-\beta\leq\alpha\leq 90-\beta$

Here, $\alpha = Arg(\frac{Zset - ZK}{ZK + ZSFE})$ is impedance circle with offset of ZSFE as expansion of the circle and it is dependent on fault location. The offset is just the apparent source impedance. The farther fault location is, the greater the equivalent source impedance and the more offset of impedance circle will be.

$\beta = Arg(\frac{F}{h * e^{-jm}})$ is a circle shifting right or left per prefault load condition and it is also related to fault location.

In general, Mho ground distance element performs similar to Mho phase element. Its equivalent source impedance or impedance circle offset is a function of fault location *k*. The farther fault location is, the greater source impedance and the more impedance circle offset will be.

8 Source impedance application discussion

In distance relay analysis, people are more interested in relay measurement performances, such as overreach, underreach and ground resistance coverage for ground elements. Per [3], [5] and [7], the source impedance has great impact on the measurement issues. But these analyses were based on classical system model.

Assuming Mho distance element taking prefault positive sequence voltage as its polarizing signal, such as SEL relay, some observations are summarized below.

1) Both Mho phase and ground elements have the same characteristic in their relationship between their source impedances and fault location. The farther fault location is, the greater local positive sequence source impedance will be. Also, the expansion of transient offset circle of Mho distance element and the coverage of grounded resistance of Mho ground element will be greater.

2) On the other hand, for both Mho and Quadrilateral ground elements, the farther fault location is the greater local system impedance and local SIR will be. But at the same time the remote source impedance will be less, and the remote infeed will be more that causes the coverage of grounded resistance of ground element to be less.

3) It seems that both 2 and 3 have opposite effect. Generally the major effect is from remote end infeed to amplify the grounded resistance and make the coverage of grounded resistance of local ground elements less.

4) It is necessary to consider the system configuration change. For example, if the line at the remote end trips firstly, the infeed from remote source will disappear. In this case, the coverage of grounded resistance will become bigger. But the previous remote end source will become part of the local source. The local source impedance becomes smaller correspondingly, and the expansion of transient offset circle of Mho ground distance element will be less. The final effect on the coverage of grounded resistance of local Mho relay is dependent on fault location and is similar to point 3) above. Quadrilateral ground element is different from Mho element and can get benefit from this effect directly.

9 Conclusions

1) An improved system model is proposed. It considers the infeed effect of remote end source or outfeed effect of local end source on local relay in fault calculation. If a fault is near to local end, infeed from remote end source exists. On the other hand, if a fault is near to remote end, outfeed from local end source appears. Therefore, the improved system model is more reasonable and more accurate system representation comparing with the classical system model for relay performance analysis.

2) Based on the improved system model, source impedance can be derived as a proportional function of fault location on protected line.

3) The source impedance has great impacts on the expansion of transient offset of the Mho distance elements impedance circle. The maximum offset of circle is the source impedance and it is proportional to fault location.

4) Also,the source impedance is useful for current reversal determination in series compensated line protection, for current reversal occurs when the net reactance from one of the sources to the fault point is capacitive.

5) It appears that the equivalent system impedance behind relay is proportional to fault location. The farther fault location is, the more equivalent system impedance will be. Also, the SIR (source-to-impedance ratio) will be bigger and consequently the CVT transient effect will be higher. This effect is especially interested in CVT applications for possible transient overreach at zone 1 reaching setting point of Mho distance elements.

6) The improved system model can be transformed into a two terminal system model with just one protected transmission line between two sources, similar to classical system model configuration. But the parameters of system, including source potential, source impedances and line impedance are changed with respect to fault location.

7) The improved system model is feasible for engineering application without significantly increasing complexity of calculations.

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