RELAY LOADABILITY CHALLENGES EXPERIENCED IN LONG LINES

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I. Introduction

Ever since the blackout in the Northeast in 2003, a variety of relay setting methods have been employed with the express purpose of avoiding unnecessary trips caused by power swings and overloads. Protection engineers have used the load encroachment and out-of-step functions to mitigate the overload and swing events. The updated NERC PRC-023-3 R1 states that transmission line relays cannot operate at or below 150% of the highest seasonal facility rating of a circuit. Additionally, R2 states that out-of-step blocking elements should allow tripping of phase protective relays for faults that occur during the loading conditions used to verify transmission line relay loadability per requirement R1. Many microprocessor relays installed today use inner and outer blinders for out-of-step functions. When the standard is applied to very long lines, the loadability point can be located inside Zone 1. If the load is high enough that it encroaches into Zone 1, the out-of-step function will no longer work since the inner and outer blinder will be located outside Zone 2. This paper presents the problems and their solutions to the NERC loadability requirements experienced in long lines. In addition, this paper will provide the derivatives of load encroachment calculations using the mho circle and simulations for an overall better understanding.

II. NERC PRC-023-3

This section presents information and justification for NERC PRC-023-3 Transmission Relay Loadability which show standards regarding loadability setting and out-of-step setting. Transmission relay loadability verification was performed for requirement R1, criteria 1 and 4 and requirement R2. R1verifies the maximum loadability setting and R2 verifies the out-of-step requirement of the standard.

Requirement R1.1 and R1.4 Compliance Definitions

R1. Each Transmission Owner, Generator Owner, and Distribution Provider shall use any one of the following criteria (Requirement R1, criteria 1 through 13) for any specific circuit terminal to prevent its phase protective relay settings from limiting transmission system loadability while maintaining reliable protection of the BES for all fault conditions. Each Transmission Owner, Generator Owner, and Distribution Provider shall evaluate relay loadability at 0.85 per unit voltage and a power factor angle of 30 degrees.

Criteria:
R1.1 Set transmission line relays so they do not operate at or below 150% of the highest seasonal Facility Rating of a circuit, for the available defined loading duration nearest 4 hours (expressed in amperes).

R2 Each Transmission Owner, Generator Owner, and Distribution Provider shall set its out-of-step blocking elements to allow tripping of phase protective relays for faults that occur during the loading conditions used to verify transmission line relay loadability per Requirement R1.

III. R1. Loadability Calculation Verification

According to NERC PRC-023-3, the loadability is calculated by the equation below:

$$Z_{Load\ Encroachment} = \frac{85\%\times(V_{LL})}{\sqrt{3}\times150\%\times I_{Limit}}\times\frac{CTR}{PTR}\ (by\ Criteria\ 1) \qquad \boldsymbol{Eq.1}$$

(Where: $I_{Limit} = Maximum\ Line\ Rating$)

<u>Zmax Calculation</u>

In order to understand load encroachment settings, this section will go through steps from zone area calculation, Zmax, load encroachment calculations with NERC PRC-023-3 R1, and power factor angle explanations.

Description	Value
Nominal Voltage (LL)	345 kV
Highest Seasonal Line Rating (Current)	5000 A
CTR	600
PTR	3000
Conductor Impedance Angle	86 °
Zone 3 Forward	9

Table 1. Line and Relay Information

Description	Setting	Value
Forward Load Impedance (ohms,sec)	ZLF	4.51
Reverse Load Impedance (ohms,sec)	ZLR	4.51
Forward Load Positive Angle (deg)	PLAF	30.0
Forward Load Negative Angle (deg)	NLAF	-30.0
Reverse Load Positive Angle (deg)	PLAR	150.0
Reverse Load Negative Angle (deg)	NLAR	210.0

Table 2. Load Encroachment Settings

The following graph is the Mho circle and load encroachment plot based on the above settings.

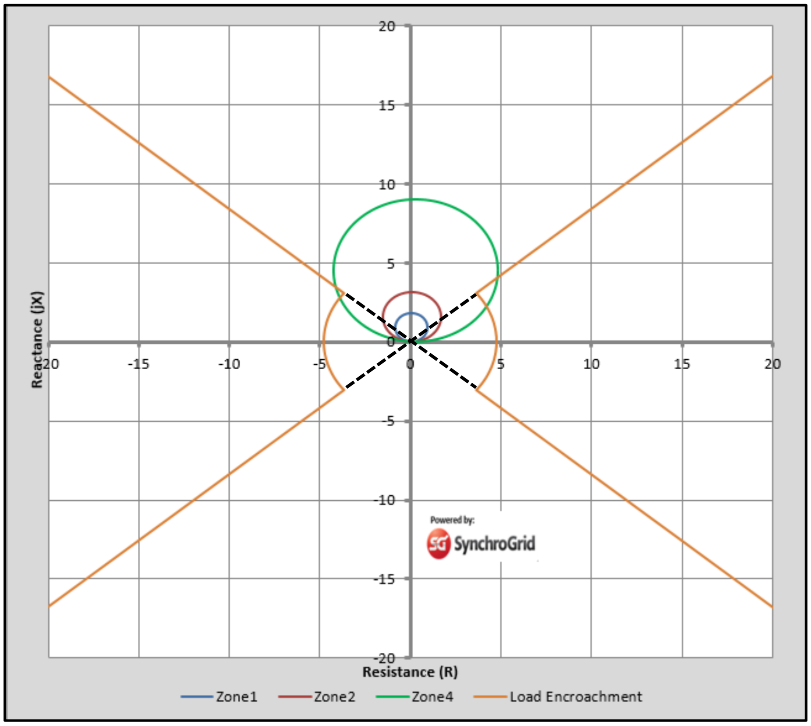

Figure 1. Load Encroachment and mho circle plot

Z3F is used in this example but this can be applied to any zone. NERC PRC-023-3 R1 says "Each Transmission Owner, Generator Owner, and Distribution Provider shall evaluate relay loadability at 0.85 per unit voltage and a power factor angle of 30 degrees". The relay loadability is done to check whether Z3F trips under maximum load conditions. For this, Zmax should be calculated, which is the maximum reach that Z3F needs to be set to before it trips under load conditions. In other words, Zmax is the impendence based on the conductor current limit and it is necessary for Z3F settings when the load encroachment is not used. If load encroachment settings do not exist, Z3F will be set to Zmax. The magnitude of Zmax is calculated below:

$$\left|\overrightarrow{Z_{max}}\right| = \frac{85\%\times V_{LL}}{\sqrt{3}\times 150\%\times I_{limit\ of\ conductor}\times cos\ a}\times\frac{CTR}{PTR} \qquad \boldsymbol{Eq.2}$$

$$= \frac{0.85\times 345\ kV}{\sqrt{3}\times 150\%\times 5000\ A\times cos(86° - 30°)}\times\frac{600}{3000}$$

$$= 8.07$$

Relationship Between Zmax and Zload

The equation above uses 85% of nominal voltage recommendation and power factor angle. Zmax has the same angle as the protected line impedance angle. Therefore, Zmax vector is $\overrightarrow{Z_{max}} = 8.07\angle 86°$. The reason the margins of 85% and 150 % exist in the above equations is due to the NERC standard Criteria 1. Notice that Z3F will trip during maximum load conditions. Therefore, Z3F has to be set to Zmax in this given example case.

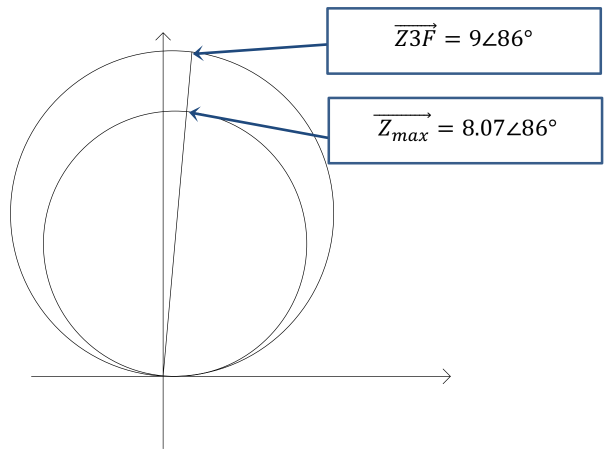

Figure 2. Zone 3 forward and Zmax

The power factor that was mentioned in NERC standard does not have to be considered when we calculate ZLF and ZLR because the equation is only to get the magnitude of the load. The angle is manually set to PLAF, NLAF, PLAR and NLAR. In this example, the power factor is set to 30 degrees, which complies with the NERC standard.

Load Encroachment (Zload) Calculation

The above procedure has helped us to determine the maximum loadability reach, but we also need to evaluate it from the point of view of the power factor angle of 30 degrees. This is done by calculating the load encroachment vector and Zload. Load encroachment setting can be easily calculated if we know Zmax value as follows:

$$\left|\overrightarrow{Z_{load}}\right| = \left|\overrightarrow{Z_{max}}\right| \times \cos a \qquad \boldsymbol{Eq. 3}$$

In order to track how the power factor was applied, it is necessary to understand the relationship between Zload and Zmax. Zmax is the maximum impedance of the line conductor, based on the line rating of the conductor. This impedance also has the same angle as the conductor impedance, 86 degrees. Zload is load impedance based on line rating, however this has a different angle from the line conductor. The angle was given as 30 degrees in this example. The angle between Zmax and Zload is $\boldsymbol{a} = (86° - 30°)$ as shown below.

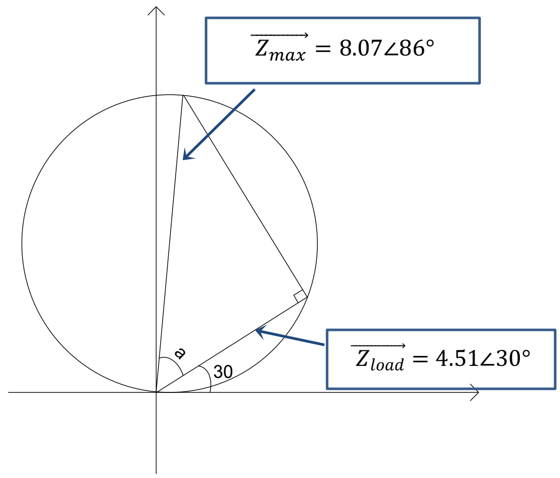

Figure 3. Relationship between Zmax and Zload

According to Eq.2, $\overrightarrow{Z_{max}} = 8.07\angle 86°$.

By using trigonometry, the Zload vector can be calculated:

$$cos\ a = \frac{\left|\overrightarrow{Z_{load}}\right|}{\left|\overrightarrow{Z_{max}}\right|}$$

$$\left|\overrightarrow{Z_{load}}\right| = \left|\overrightarrow{Z_{max}}\right| \times \cos a \text{ (Power factor is applied here)}$$

$$\left|\overrightarrow{Z_{load}}\right| = 8.07 \times cos(86° - 30°) = 4.51$$

$$\therefore \overrightarrow{Z_{load}} = 4.51\angle 30°$$

$$\left|\overrightarrow{Z_{load}}\right| = \frac{85\% \times V_{LL}}{\sqrt{3} \times 150\% \times I_{limit\ of\ conductor}} \times \frac{CTR}{PTR}$$

$$= \frac{0.85 \times 345\ kV}{\sqrt{3} \times 150\% \times 5000\ A} \times \frac{600}{3000}$$

$$= 4.51\ Ohms$$

The same result will be shown as when the angle was considered. It can be proven no matter what angle is chosen because the magnitude of Zload is the same. This is why we use the load encroachment setting to calculate the maximum MVA.

ZLF and ZLR indicate the magnitude of load encroachment. This magnitude is set to 85% of the minimum load impedance based on 150% of the line limit based on NERC PRC-023-3, as mentioned before. The angle of the load encroachment was set by PLAF, NLAF, PLAR and NLAR setting based on standards, not the power factor calculation. The magnitude of load encroachment can only affect the MVA of load no matter what the angle is. This is because all points on the load encroachment magnitude circle, which is the orange line below, have the same MVA magnitude. This is proven by the following formula:

$$\frac{(0.85\times V_{LL})^2}{(Z_{Load\ Encroachment})^*}\times\frac{CTR}{PTR}\ (*:\ conjugate) \qquad \textbf{Eq. 6}$$

$$=\frac{(0.85\times 345kV)^2}{4.51\angle-\alpha°}\times\frac{600}{3000}=3820.05\angle\alpha°\ \text{MVA}$$

As load encroachment angle is changing, the loadability MVA is moving on the orange circle. In this example, since the angle is 30°, the MVA will be $3820.05\angle 30°$. However, the magnitude is always 3820.05 MVA no matter what the angle is. In order to help in understanding this concept, some important points are indicated in Figure 4.

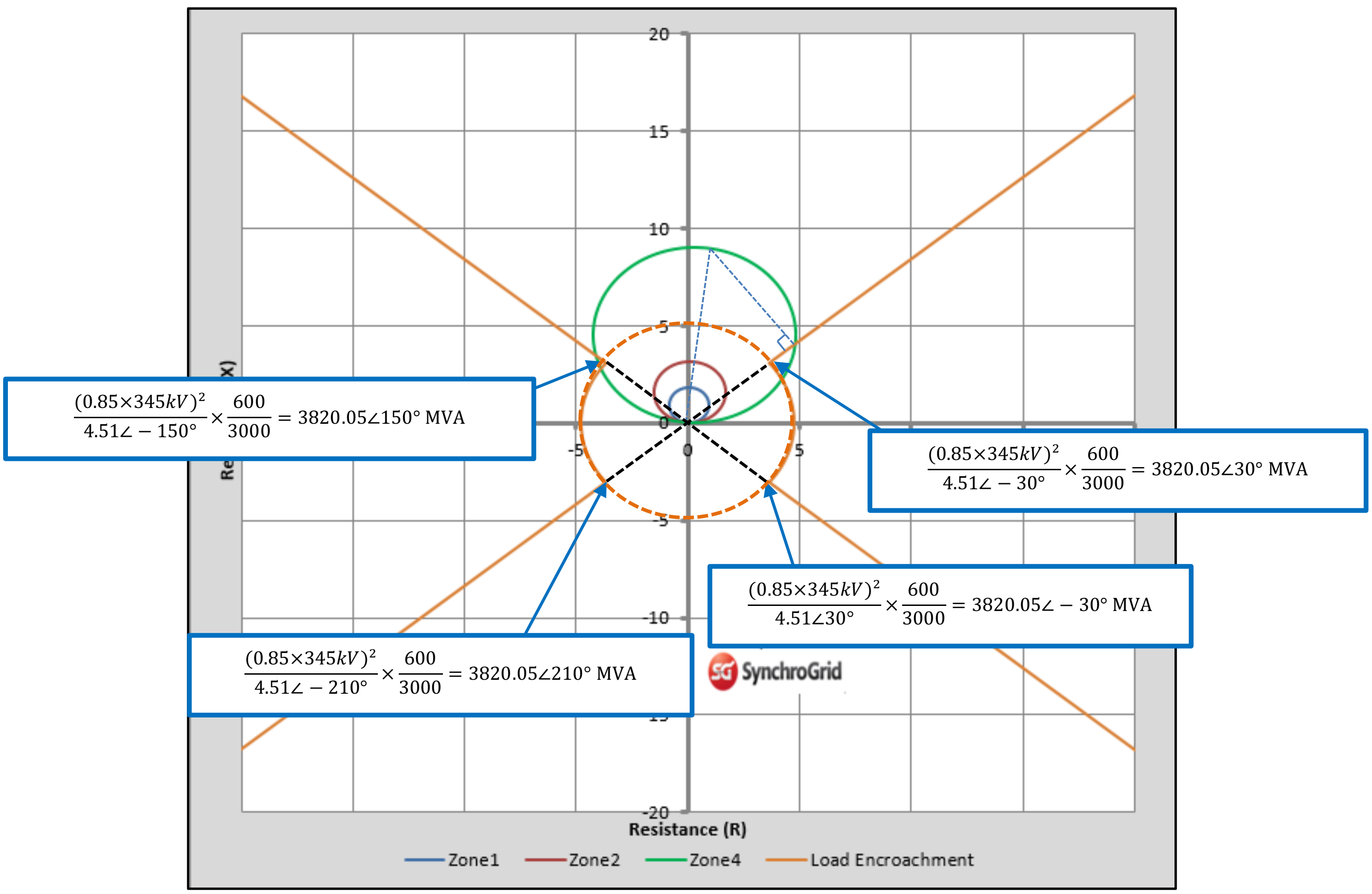

Figure 4. MVA of Loadability

IV. R2. Out-of-Step (OOS) Calculation Verification

Based on R2, the OOS blocking function should allow the distance relay to trip for faults that occur during the loading condition to comply with R1. The microprocessor relay literature states that "The relay disables out-of-step blocking automatically when a fault occurs during a power swing". [(2)] This is true for unsymmetrical faults, but for symmetrical faults, the OOS functions is not disabled.

The loadability limit of the relay is usually located outside the OOS outer blinder which allows the OOS block function to work properly. If the maximum load as described in R1 is located between the inner and outer blinder of the OOS function, the OOS function will block the phase distance elements until the OOS function resets. Also, if the maximum load of the line has passed the inner and outer blinder and is within the load encroachment area, the OOS function will block the phase distance element until the OOS function resets. Even after the function resets and the load encroachment has traveled beyond the inner blinder, the OOS function will no longer work. This is a problem encountered in very long lines when applying load encroachment limits. This can be shown in Figure 5 below.

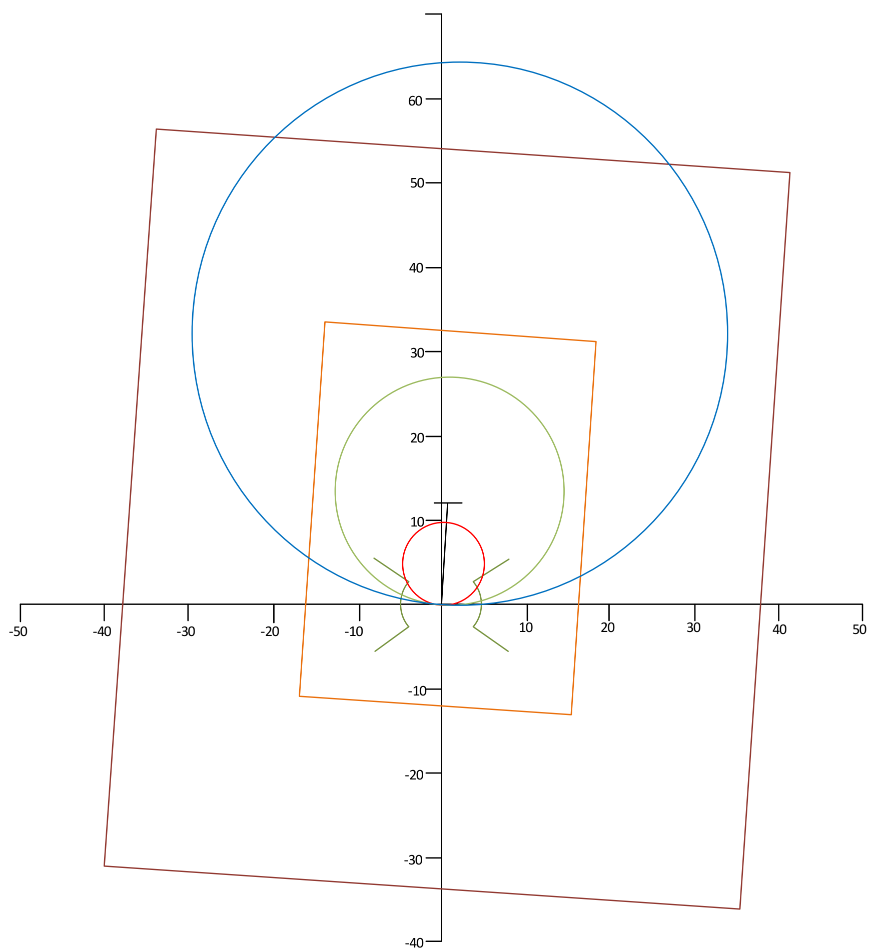

Figure 5. Load Encroachment and OOS Setting for a Long Line

The OOS function can be used to block Zone 1, Zone 2, and Zone 3 Forward. The OOS settings are done for a given slip frequency, typically 5 Hz. The span between inner and outer blinders need to be long enough to allow the relay to detect the power swing condition at a minimum 0.5 cycle. Typically, the inner blinder is placed outside zone 2, and the outer blinder is placed inside the load impedance to avoid overlapping between OOS region and load encroachment.

Case I: OOS Setting Blinder Calculation and Load Encroachment Limit Inside Outer Blinder

Let us now review an OOS example where the blinders are not set properly and where the load encroachment limit is located slightly passed the outer blinder. This will be used to calculate the OOS setting based on compliance with both PRC-023-3 R1 and R2. By showing how to fix the OOS setting calculation based on coordination with zone 2 and load encroachment region, the calculations for OOS will be verified. The load encroachment values have been previously calculated based on maximum rating capabilities.

The basic system and relay information is as follows:

Description	Value
ZL1 (Protected line impedance, secondary, positive sequence)	2.03Ω∠ 86°
Z1MAG (Magnitude of protected line, secondary)	2.03 Ω
Z1ANG (Angle of protected line, secondary):	86°
Z1P (Zone 1 pickup, secondary)	1.63Ω
Z2P (Zone 2 pickup, secondary	3.5Ω
ZLoad (Load impedance, secondary)	4.29Ω∠35°
PTR (PT ratio)	3000
CTR (CT ratio)	600
ZSrc1 (Local source impedance, secondary, positive sequence)	2.87Ω∠86°
ZSrc2 (Remote source impedance, secondary, positive sequence)	3.13Ω∠86°
Fnom (nominal power system frequency)	60Hz
Fslip (Slip frequency)	5Hz

Table 3. OOS Setting Information

Table 4 shows the list of the current setting values of the example.

Description	Setting	Current Value
Enable Out-of-Step Elements	EOOS	Y
Block Zone 1	OOSB1	Y
Block Zone 2	OOSB2	Y
Block Zone 3	OOSB3	N
Block Zone 4	OOSB4	N
Out-of-Step Block Time Delay	OSBD	1.00
Enable Out-of-Step Tripping	EOOST	N
Out-of-Step Zone 6 Reactive - Top	X1T6	6.7
Out-of-Step Zone 5 Reactive - Top	X1T5	5.5
Out-of-Step Zone 6 Resistive - Right	R1R6	3.9
Out-of-Step Zone 5 Resistive - Right	R1R5	1.8
Out-of-Step Positive Sequence Current Supervision (Amp	50ABCP	1.00

secondary)		
Neq.-Seq. Current Unblock Delay	UBD	0.50

Table 4. Existing Setting Values

The plot in figure 6 shows the example out-of-step characteristics that present a challenge to the loadability standard. The inner blinder is inside the zone 2 area and the outer blinder overlaps with the load encroachment limit. If the load has crossed the outer blinder and a symmetrical fault develops before the OOS reset timer, the OOS function will block the phase distance elements. This presents a challenge to the standard requirement. Therefore, the inner and outer blinders need to be modified so that the inner blinder is outside zone 2 and the outer blinder does not overlap with the load encroachment limit point.

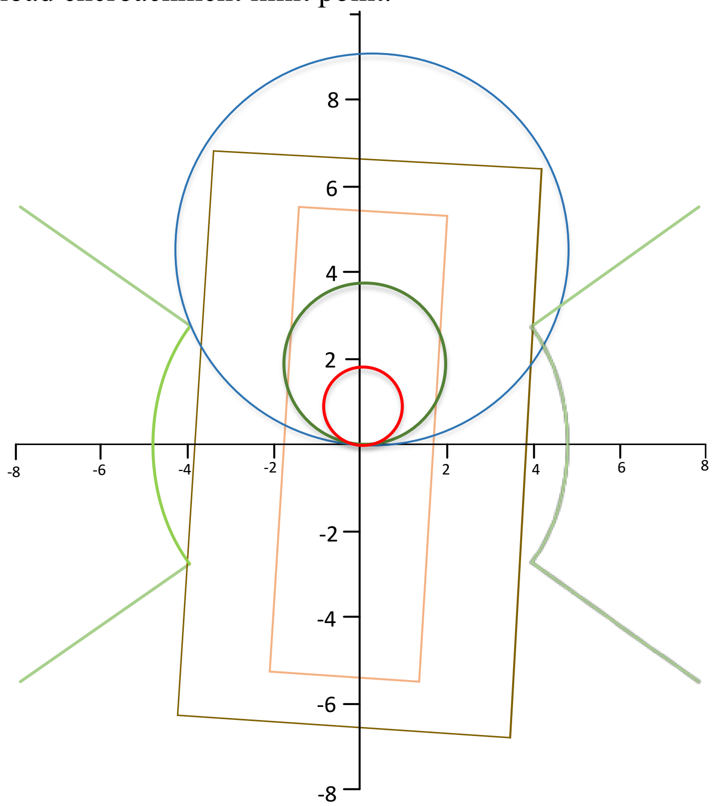

Figure 6. Example of an Incorrect Setting of OOS and Load Encroachment

By showing how to fix the OOS setting calculation of the relay based on coordination with load encroachment, the calculations for OOS will be verified as below:

$$R1R5\ (Inner\ right\ blinder) = 120\% * \frac{Z2P}{2} \qquad \textbf{Eq. 7}$$

$$= 2.1\ \Omega$$

$$R1R6\ (Outer\ right\ blinder) = 90\% * |ZLoad| * cos(35° + 90° - 86°) \qquad \textbf{Eq. 8}$$

$$= 3.0\ \Omega$$

$$X1T5\ (Inner\ top\ blinder) = 120\% * Z2P \qquad \textbf{Eq. 9}$$

$$= 4.2\ \Omega$$

$$X1T6\ (Outer\ top\ blinder) = X1T5 + (R1T6 - R1T5) \qquad \textbf{Eq. 10}$$

$$= 4.2 + 3.0 - 2.1 = 5.1\ \Omega$$

$$Zt\ (Transfer\ impedance, secondary, positive\ sequence) = ZSrc1 + ZL1 + ZSrc2 \qquad \textbf{Eq. 11}$$

$$= 2.87\Omega\angle 86° + 2.03\Omega\angle 86° + 3.13\Omega\angle 86° = 8.03\Omega\angle 86°$$

$$Ang_{R5}(Angle\ of\ R5) = 2 * tan^{-1}(\frac{|Zt|}{2 * R1R5}) \qquad \textbf{Eq. 12}$$

$$= 2 * tan^{-1}\left(\frac{8.03}{2 * 2.1}\right) = 124.78°$$

$$Ang_{R6}(Angle\ of\ R6) = 2 * tan^{-1}(\frac{|Zt|}{2 * R1R6}) \qquad \textbf{Eq. 13}$$

$$= 2 * tan^{-1}\left(\frac{8.03}{2 * 3}\right) = 106.46°$$

$$OSBD\ (OOS\ block\ time\ delay) = \frac{(Ang_{R5} - Ang_{R6}) * F_{nom}}{F_{slip} * 360\ °/\text{cycles}} \qquad \textbf{Eq. 14}$$

$$= \frac{(124.78 - 106.46) * 60}{5 * 360} = 0.69 = 0.75 \text{ Cycles (in increments of 0.25 cyclces)}$$

Finally, the setting of the relay needs to be fixed as in Table 5.

Description	Setting	Current Value	Fixed Value
Enable Out-of-Step Elements	EOOS	Y	-
Block Zone 1	OOSB1	Y	-
Block Zone 2	OOSB2	Y	-
Block Zone 3	OOSB3	N	-

Block Zone 4	OOSB4	N	-
Out-of-Step Block Time Delay	OSBD	1.00	***0.75***
Enable Out-of-Step Tripping	EOOST	N	-
Out-of-Step Zone 6 Reactive - Top	X1T6	6.7	***5.1***
Out-of-Step Zone 5 Reactive - Top	X1T5	5.5	***4.2***
Out-of-Step Zone 6 Resistive - Right	R1R6	3.9	***3.0***
Out-of-Step Zone 5 Resistive - Right	R1R5	1.8	***2.1***
Out-of-Step Positive Sequence Current Supervision (Amp secondary)	50ABCP	1.00	-
Neq.-Seq. Current Unblock Delay	UBD	0.50	-

Table 5. Fixed OSS Setting Values

The corrected inner blinder is out of zone 2 and the corrected outer blinder does not overlap the load encroachment setting anymore as shown in figure 7. This is an acceptable setting and a common way of having load encroachment and blinder settings. However, if a three phase symmetrical fault evolves from the maximum load conditions, the relay cannot detect the fault since the OOS function will block the differential relay.

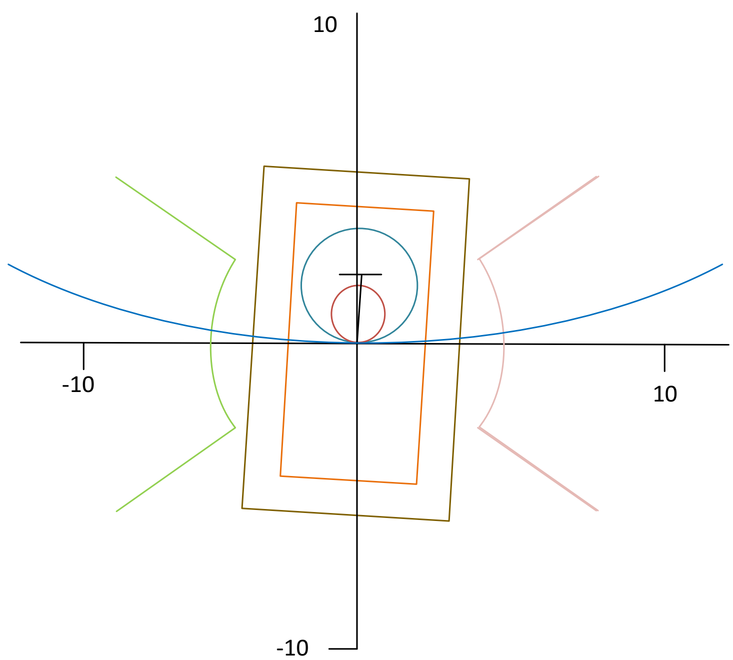

Figure 7. Corrected OOS setting plot

Case II: OOS Setting Calculation and Load Encroachment Limit Beyond Inner Blinder

There are cases in long line applications where the loadability limit can encroach into the zone 1 mho circle and the OOS blinders are not outside the load encroachment zone as in case I. This presents a problem since the standard requires that the relay still trip when the OOS settings are applied. Since the maximum load has passed the OOS blinders and a symmetrical fault evolves before the OOS timer is reset, the fault won't be cleared.

Below are the settings for the load encroachment and OOS where this case is observed.

$$Delay\ 1\ Pickup\ (PSBD, OOS\ block\ time\ delay):=1.0\ Cycles \qquad \boldsymbol{Eq.15}$$

$$Zt\ (Transfer\ impedance, secondary, positive\ sequence) = ZSrc1 + ZL1 + \text{ZSrc2} \qquad \boldsymbol{Eq.16}$$

$$= 2.65\Omega\angle 86° + 10.81\Omega\angle\ 86° + 1.85\Omega\angle 86° \ = \ 15.31\Omega\angle 86°$$

$$Inner\ Rgt\ Bld\ \ (INBS, Inner\ right\ blinder) = 120\% * \frac{Z2P}{2} \qquad \boldsymbol{Eq.17}$$

$$= 14.6\ \Omega$$

$$Ang_{in}(Angle\ of\ Inner\ Blinder) = 2 * tan^{-1}(\frac{|Zt|}{2 * INBS}) \qquad \boldsymbol{Eq.18}$$

$$= 2 * tan^{-1}\left(\frac{15.31}{2 * 14.58}\right) = \ 55.4°$$

$$Ang_{out}(Angle\ of\ Outer\ Blinder) = Ang_{in} - PSBD * \frac{F_{slip} * 360}{F_{nom}}\ (by\ Eq.14) \qquad \boldsymbol{Eq.19}$$

$$= 55.4 - 1 * \frac{5 * 360}{60} = \ 25.4°$$

$$Outer\ Rgt\ Bld\ \ (OTBS, Outer\ right\ blinder) = \frac{|Zt|}{2 * \tan(Ang_{out}/2)} \qquad \boldsymbol{Eq.20}$$

$$= 34.0\ \Omega$$

Outer line blinder was calculated from blocking time delay and inner blinder angle. Middle blinders do not have to be set because this setting is a two-step mode which matters only for the outer and inner lines. Left blinders are same as right blinders.

$$Fwd\ Reach\ (XINBS, Inner\ top\ blinder) = 120\% * Z2P \qquad \boldsymbol{Eq. 21}$$

$$= 29.2\ \Omega$$

$$Quad\ Fwd\ Out\ (XOTBS, Outer\ top\ blinder) = X1NBS + (OTBS - INBS) \qquad \boldsymbol{Eq. 22}$$

$$= 29.2 + 34.0 - 14.6 = 48.6\ \Omega$$

$$Rev\ Reach\ (XINBS\_R, Inner\ Bottom\ blinder) = ZL1 \qquad \boldsymbol{Eq. 23}$$

$$= 10.81\ \Omega$$

$$Quad\ Rev\ Out\ (XOTBS\_R, Outer\ Bottom\ blinder) = XINBS\_R + (OTBS - INBS) \qquad \boldsymbol{Eq. 23}$$

$$= 30.21\ \Omega$$

The recalculated settings are shown in Table 6.

Setting	Current Value	Fixed Value
Function	Enabled	-
Source	LINE (SRC 4)	-
Shape	Quad Shape	-
Mode	Two Step	-
Supv	0.200 pu	-
Fwd Reach	28.82 ohms	***29.2***
Quad Fwd Mid	33.07 ohms	-
Quad Fwd Out	37.32 ohms	***48.6***
Fwd Rca	86 deg	-
Rev Reach	12.00 ohms	-
Quad Rev Mid	16.25 ohms	-
Quad Rev Out	20.50 ohms	***30.21***
Rev Rca	86 deg	-
Outer Limit Angle	120 deg	-
Middle Limit Angle	90 deg	-
Inner Limit Angle	60 deg	-
Outer Rgt Bld	12.00 ohms	***34.0***
Outer Lft Bld	12.00 ohms	***34.0***
Middle Rgt Bld	7.75 ohms	-
Middle Lft Bld	7.75 ohms	-
Inner Rgt Bld	3.50 ohms	***14.6***
Inner Lft Bld	3.50 ohms	***14.6***
Delay 1 Pickup	0.033 s	***0.017***
Delay 1 Reset	0.050 s	-

Delay 2 Pickup	0.017 s	-
Delay 3 Pickup	0.009 s	-
Delay 4 Pickup	0.017 s	-
Seal-In Delay	0.400 s	-
Trip Mode	Delayed	-
Block	OFF	-
Target	Self-reset	-
Event	Enabled	-

Table 6. Recalculated Setting Values

The corrected inner blinder is out of zone 2. The corrected inner and outer blinders still overlap the load encroachment region but there is no way around this. The new out-of-step is shown in figure 8.

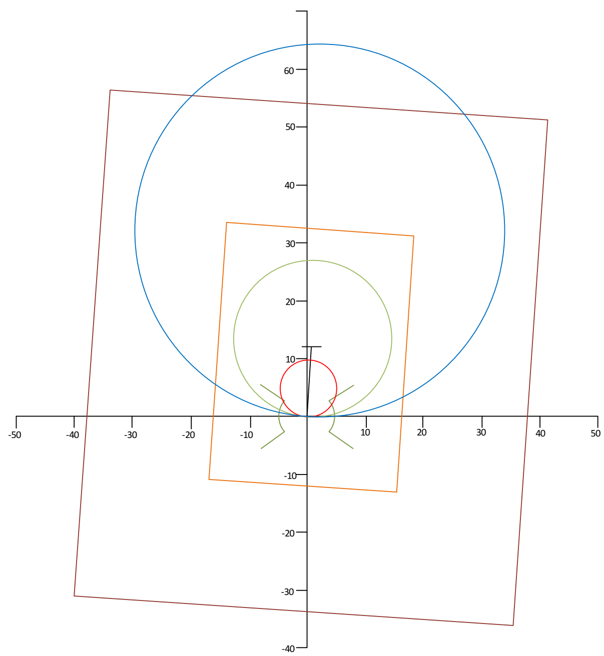

Figure 8. Plots of Recalculated Setting

Since the load impedance is smaller than that of zone 2, it is impossible to set the outer blinder with the philosophy that the outer line should be smaller than load impedance with margin. For this case, "If the load region encroaches into the distance element and one wants to block under swings, then it is impossible to place the PSB characteristics between the load and distance regions, and one cannot apply the conventional PSB blocking function. A more modern relaying system with 'load encroachment' capabilities could be required." (4)

Since there is no guaranteed that the relay will operate correctly for this type of case, we need to rely on other types of algorithms to ensure that the relays will trip for faults at maximum load conditions and when the OOS function is set. Most terminals are designed with complete isolated and redundant systems that include a line current differential and a step distance relay with high speed communications. "At the same time, the differential scheme is unaffected by external effects such as faults, load and power swings". (3) Even if the OOS function blocks during loadability limit conditions, the line differential will still trip during faults. In addition, the OOS function can be disabled based on the best engineer judgment.

V. Conclusion

As discussed throughout this paper, the employment of load encroachment and OOS blinders make it difficult to ensure that the relay will operate for symmetrical faults when these two functions are enabled and still comply with the standard. The use of current differential relays solves this issue when these type of relays are available. The relay engineer can also decide to disable the OOS function based on the utility engineer best judgment.

VI. References

[1] System Protection and Control Task Force of the North American Electric Reliability Council, "Increase Loadability by Enabling Load Encroachment Functions of Digital Relays," December 2005.

[2] Schweitzer Engineering Laboratories, 421 Instructional Manual.

[3] "Guide for Application of Digital 2 Line Current Differential Relays 3 Using Digital ommunication." IEEE Power En gineering Society Power System Relay Committee Special Report, New York, NY; 2015.

[4] "Power Swing and Out-of-Step Considerations on transmission" IEEE Power Engineering Society Power System Relay Committee Special Report, New York, NY; 2005.

VII. Author Biographies

Seunghwa Lee holds a Bachelor's of Science degree in Electrical Engineering from Seoul National University, in South Korea. He also received a Masters of Engineering degree in Electrical Engineering from Texas A&M University with concentration in Power Systems. In 2014, Seunghwa became a registered professional engineer in the State of Texas (License No.118682). He is currently working on all projects related to power protection.

Joe Perez received his B.S. degree in Electrical Engineering from Texas A&M University in 2003. Joe is the author of many relay application notes and has presented technical papers at WPRC, Texas A&M and Georgia Tech Relay Conferences. Joe is the owner of SynchroGrid, a registered professional engineer in the state of Texas and a member of PSRC, IEEE, and PES. Joe resides in the Bryan/College Station area. He can be contacted at jperez@synchrogrid.com.