

# Methods to Increase Line Relay Loadability



*A Technical Document  
Prepared by the  
System Protection and Control Task Force  
of the  
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<b>INTRODUCTION</b>	<b>1</b>
<b>RECOMMENDATION 8A RATIONALE AND METHODS TO ACHIEVE INCREASED LOADABILITY</b>	<b>1</b>
1. INCREASE THE ANGLE OF MAXIMUM TORQUE (REACH)	2
2. CHANGE THE IMPEDANCE RELAY CHARACTERISTIC FROM A CIRCLE TO A LENS	3
3. ADD BLINDERS TO THE CHARACTERISTIC TO LIMIT REACH ALONG THE REAL AXIS	6
4. OFFSET ZONE 3 INTO THE FIRST QUADRANT	7
5. FOR A QUADRILATERAL CHARACTERISTIC, RESET THE RELAY	8
6. ENABLE THE LOAD ENCROACHMENT FUNCTION	8
<i>Recommendation on Settings for the Load Encroachment Function</i>	10
<i>Load Encroachment Function Settings Example</i>	10
<b>CONCLUSION</b>	<b>12</b>
<b>APPENDIX A — FAULT RESISTANCE ASSESSMENT</b>	<b>1</b>
<i>Using the Law of Tangents:</i>	1
<i>Using the Law of Cosines:</i>	1
<b>APPENDIX B — SYSTEM PROTECTION AND CONTROL TASK FORCE</b>	<b>1</b>

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# INTRODUCTION

This technical document discusses the implementation of protective relaying functions to augment, reposition, and reshape, impedance relays to increase the loadability of relay settings without decreasing protection coverage. This informational guide was prepared by the North American Electric Reliability Council's (NERC) System Protection and Control Task Force (SPCTF) and is intended to provide more insight into recommendations made to increase loadability.

This paper includes the November 2005 paper entitled *Increase Line Loadability by Enabling the Load Encroachment* (Appendix A), expanding on it by presenting additional methods for increasing relay loadability while still maintaining adequate protection. Like the load encroachment method, these techniques can be implemented after evaluating "Zone 3" loadability and "Beyond Zone 3" loadability.

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## RECOMMENDATION 8A RATIONALE AND METHODS TO ACHIEVE INCREASED LOADABILITY

One of the observations made from the August 14, 2003 blackout was that protective relaying should not preclude operator action during extreme system emergencies. It was concluded that following an extreme contingency, the system operators should be allowed up to 15 minutes in which emergency actions, including load shedding, could be performed. To this end, a thermal rating relay loadability recommendation was established, namely 150% of the transmission line's highest seasonal ampere circuit rating that most closely approximates a 4-hour winter emergency rating. This rating is representative of 15 minute emergency ratings already in use by some system operators. Two other system parameters are included in Recommendation 8a, an operational condition of a 0.85 per unit voltage and a power factor angle of 30 degrees (current lagging voltage). Similar to the thermal rating, the 0.85 per unit voltage was an observed value when the system was in an extreme condition, but not in a cascading mode. Similarly, the 30 degree power factor angle was also an observed value while the system was under stress. A 30 degree power factor angle is not an extreme value — some power lines operate at 45 degrees current lagging voltage.

The NERC SPCTF recognizes first and foremost that the power system must be protected. Secondly, that power system protection must not prevent operator action to save the interconnected power system. However, potential operator action is not the only consideration. There may be remedial action/special protection schemes that operate very quickly to restore the system to a secure operating state. These types of schemes do not need 15 minutes, but, generally, only a number of seconds to take action before the zone distance relay times out and trips.

Several methods to increase loadability have been suggested:

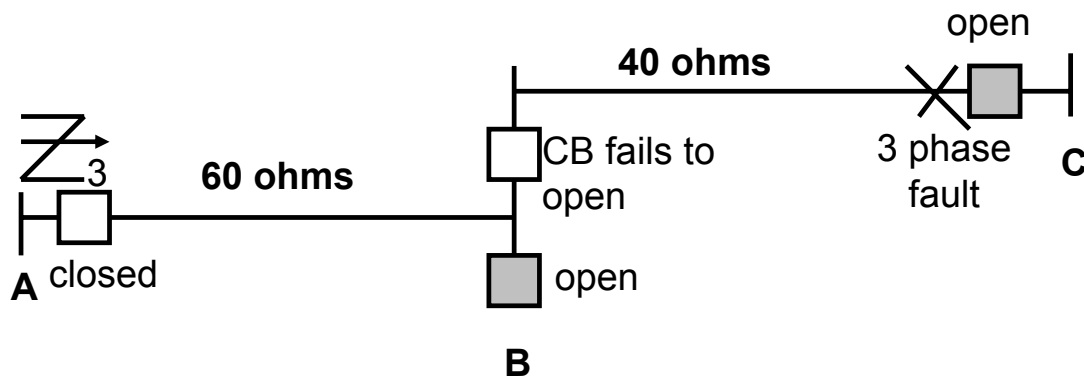
1. Increase the angle of maximum torque (reach).
2. Change the impedance relay characteristic from a circle to a lens.
3. Add blinders to the characteristic to limit reach along the real axis.
4. For remote zone 3 protection, use an impedance relay offset into the first quadrant.
5. For a quadrilateral characteristic, reset the relay.
6. Enable the load encroachment function of the relay.

These techniques are easily demonstrated by example and by graphically plotting the changes to the relay characteristics from the basic mho characteristic. These techniques are presented with the assumption

that the protective relay is a zone 3 relay with a remote backup settings criteria. However, these techniques can also be applied to other load-sensitive phase distance mho-type characteristics. Further, it is assumed that the appropriate local breaker failure relaying is installed, and that relay failure is covered by appropriate measures of redundancy. Figure 1 below represents a portion of a typical 345 kV transmission system. The intent is to show the need for remote zone 3, in the absence of other potential methods such as redundant communications, separate batteries, voltage transformers, etc., that may obviate the need for remote backup. For further details, refer to the NERC paper *Rationale for the Use of Local and Remote (Zone 3) Protective Relaying Backup Systems - A Report on the Implications and Uses of Zone 3 Relays*, dated February 2, 2005.

It should be noted that not all existing relays have all of the above mentioned techniques available as settings options. It is up to the relay settings engineer to choose the most appropriate technique(s). The most important point to understand is that the loadability recommendations are not absolute system conditions. They represent a typical system operation point during an extreme system condition. The voltage at the relay may be below the 0.85 per unit voltage and the power factor angle may be greater than 30 degrees. It is up to the relay settings engineer to provide the necessary margin as they do in all relay settings.

**Figure 1: 345-kV System Example**

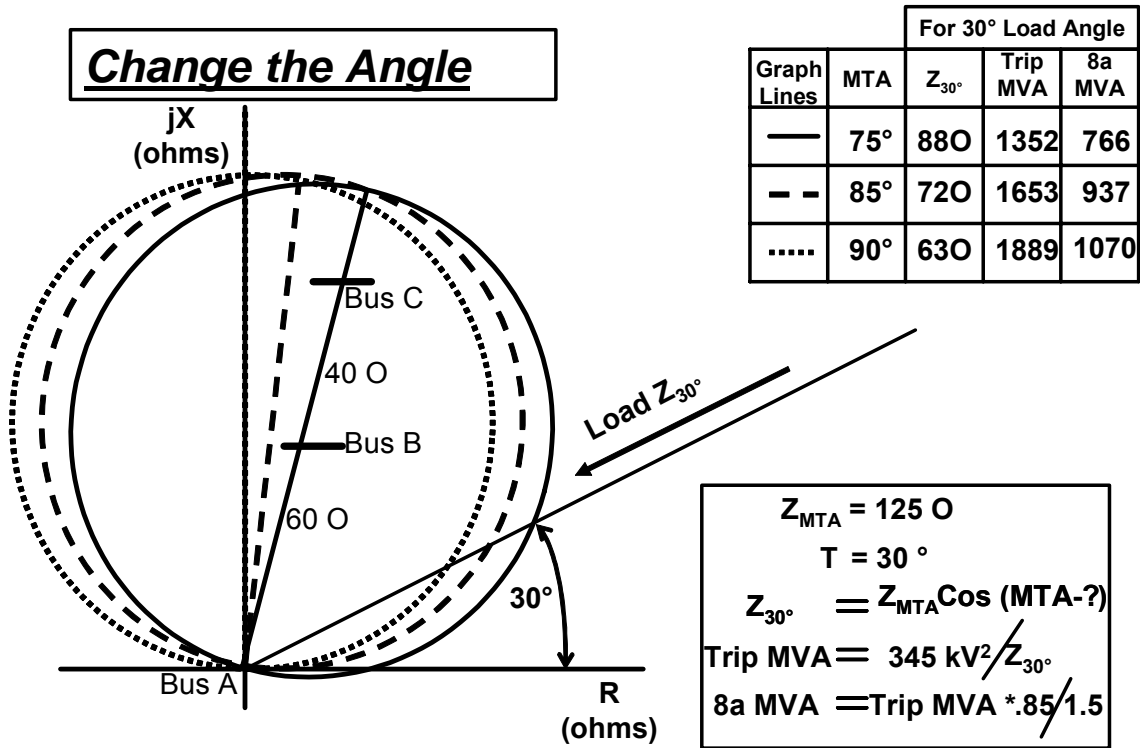


### 1. Increase the Angle of Maximum Torque (Reach)

The method to increasing maximum torque angle is available for many electromechanical, electronic, and digital impedance relays. The mho-type relays have a maximum reach along an angle that typically is close to the angle of the transmission line impedance. This maximum reach angle is referred to as maximum torque angle (MTA). This term is mechanically descriptive for electromechanical relays and has been functionally used to describe the angle of maximum reach for all mho type relays. Contact the relay manufacturer to determine the limits of MTA adjustment if the relay instruction book does not explicitly identify those limits. Increasing maximum torque angle is demonstrated graphically in Figure 2.

In the Figure 2 settings example, the zone 3 relay is being used primarily for remote backup. It is assumed the transmission line from A to B is properly protected by high-speed relaying and backup relaying for all faults. The methods applied in this example to increase loadability apply equally to zone 1, zone 2, and the high-speed impedance transmission line relays.

Figure 2: Adjust Maximum Torque Angle to Increase Loadability



In this example, the remote end of the adjacent line section is covered with a 25% margin. This results in a 125 ohm setting along the angle of maximum torque. In this case the MTA is 75 degrees, a common angle for electromechanical relays. To increase line loading, the MTA angle can be adjusted on some relays as far as 90 degrees. With a 90 degree maximum torque angle, close-in faults involving fault impedance may not be detected; therefore, other relays may have to detect such faults. As indicated in the table in Figure 2, such adjustments can increase line loadability as measured along the 30 degree load apparent impedance line by 40%. If the applied relay has the capability of increasing MTA, this method maintains trip dependability while increasing loadability security with minimum cost implications.

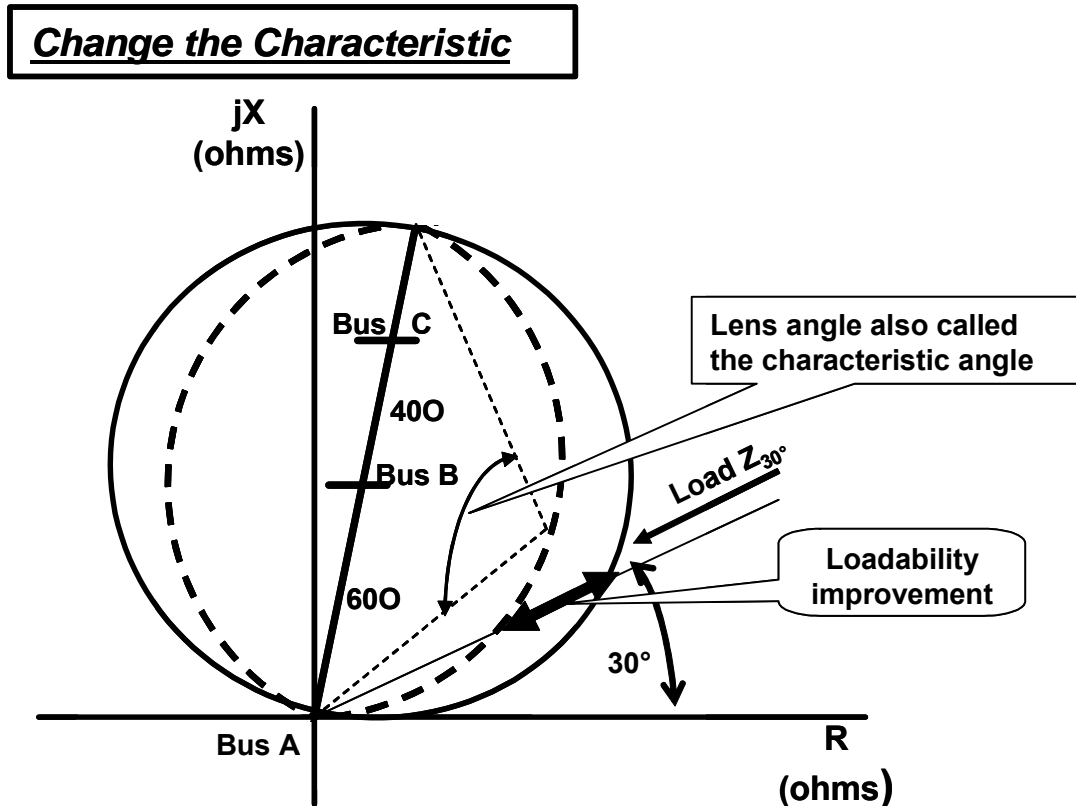
## 2. Change the Impedance Relay Characteristic From a Circle to a Lens

In the late 1970s and early 1980s, a need emerged for extremely fast operating protective relays to permit the installation of large base-load generators on the 200 kV and above transmission systems. These relays, with statistically measured operating times of 1 cycle, together with 2 cycle clearing circuit breakers, allowed for the reduction in fault clearing and critical clearing times necessary for the connection of these large units, typically 1,200 MW and above.

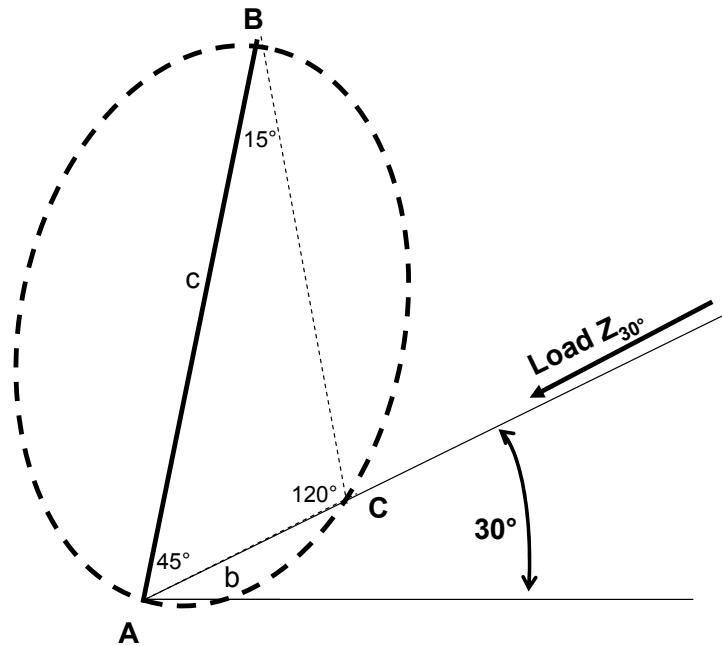
That vintage of protective relays was designed using discreet electronic components. Usually, they performed their measuring based on the comparison of operating and polarizing (reference) quantities. One method of protection using electronic relays was a mho distance type relay. That relay's characteristic could easily be modified from a mho (circle) characteristic to a lens just by adjusting the coincident (characteristic) timer. The lens decreases the susceptibility an impedance-based relay has to tripping on stable power swings. Often that type of relay was

adjusted from a mho to a lens to meet the transmission system owner's requirements to maintain immunity to recoverable power swings. The lens characteristic also accommodates more line loading as the example in Figure 3 demonstrates. Again, the manufacturer of the relay should be consulted before applying this method. It may be necessary to address the issues of speed and arc resistance accommodation with the manufacturer. A lens-type characteristic is offered in many digital relays. It is sometimes applied with an offset from the origin.

Figure 3: Adjust Mho Circle to a Lens to Increase Loadability



Using the same system example from Figure 1, the loadability improvement due to the change in the characteristic shape of the relay can be measured by a decrease in load impedance along the 30 degree load line. The adjustment method is just an increase in coincidence (characteristic) timer setting within the electronic relay. From geometry, the angle inscribed within a lens will yield a constant angle. If the figure were a circle, the angle would be 90 degrees. For a lens, the angle is greater than 90 degrees. Any side of a triangle can be determined if one side and its angles are known using the law of sines. In this case, the side of interest is the one along the load line and the side known is the impedance along the maximum reach. Let the maximum torque angle be 75 degrees as in the first example. Let the angle of the lens be adjusted to be 120 degrees.

**Figure 4: Calculate Lens Loadability**

Then by the law of sines:

$$\frac{c}{\sin C} = \frac{b}{\sin B}$$

Substituting the reach of the relay for  $c$  and the lens angle of 120 degrees for  $C$ , the impedance magnitude along the 30 degree angle line can be calculated as:

$$\frac{125 \Omega}{\sin 120^\circ} = \frac{b}{\sin 15^\circ}$$

where  $b = 37.3$  ohms.

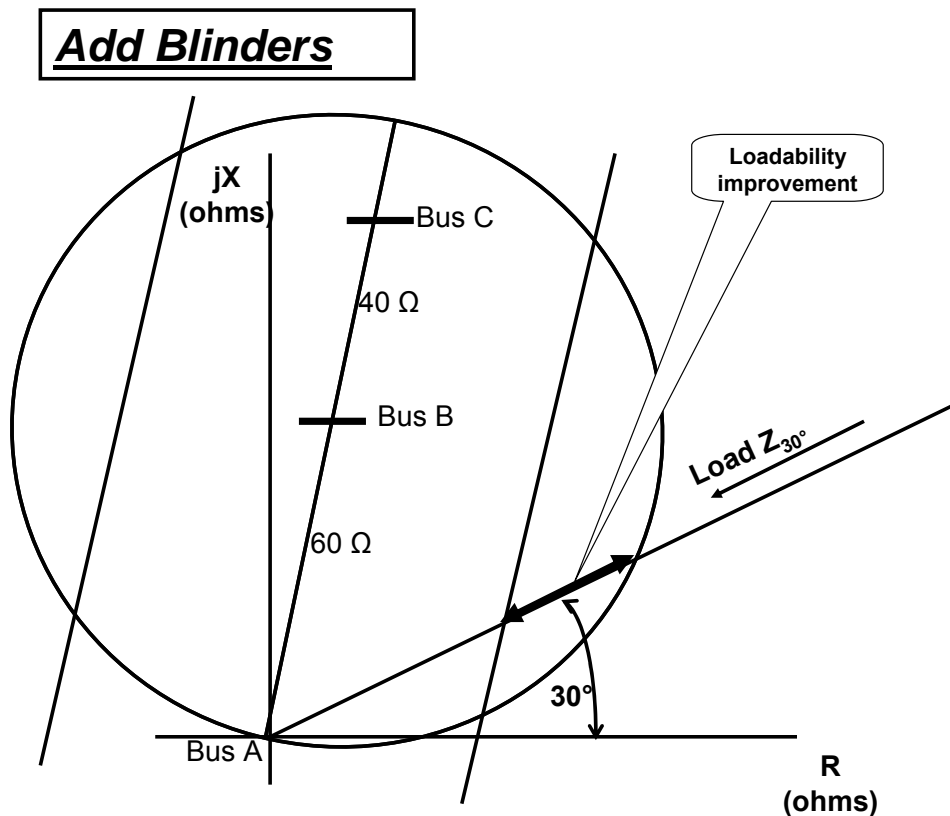
From the table in Figure 2, this compares to an impedance of 88 ohms along the 30 degree load angle line for the remote zone 3 mho circle with MTA of 75 degrees. For a 345 kV line, a 37.3 ohms load impedance along the 30 degree load line corresponds to a trip MVA of 3,191 MVA and 1,808 MVA using NERC Recommendation 8a requirements of 0.85 pu voltage and 150% of the transmission line's highest winter ampere circuit rating that most closely approximates a 4-hour rating.

### 3. Add Blinders to the Characteristic to Limit Reach Along the Real Axis

Most of the material in this section is drawn from IEEE Standard C37.113 *Guide for the Protection of Transmission Lines*. See that standard for a more extensive discussion of this topic.

Some manufacturers provide a relay element called a blinder that can be added in series with its mho relay to constrain operation along the R impedance axis. Others provide this function internally. Figure 5 depicts the blinder characteristic.

Figure 5: Add Blinders to the Mho Characteristic



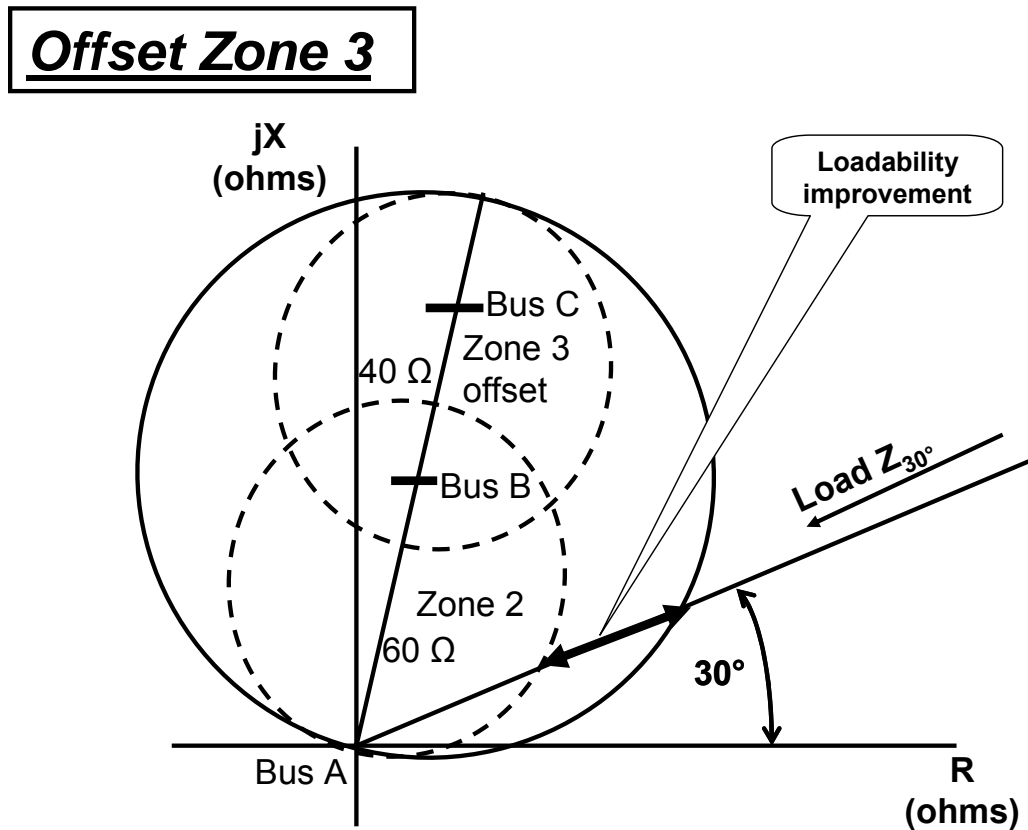
The increase in loadability can be set by adjusting the blinder closer to the origin. The relay will trip only if the measured impedance falls within the two blinders and the relay's mho characteristic. The loadability improvement can be measured along the load line. Figure 5 shows the blinder with an angle paralleling the maximum reach line of the relay. This is because this relay element is often used to trip transmission lines for unstable swings while decreasing the likelihood of tripping for stable swings. The application is often used when it is known that an unstable swing will penetrate the protected transmission line. The blinder is used to initiate tripping for an unstable swing and logic is included to trip when the swing locus exits either the left or right blinder after sequentially passing through both blinders. This implies that the swing has passed through 180 degrees. An inherent advantage of this scheme is that the tripping will be initiated for a closing angle and therefore a decreasing recovery angle across the circuit breaker.



#### 4. Offset Zone 3 into the First Quadrant

Relay loadability improvements are generally for relays that also respond to three-phase faults. Some relays are packaged such that they have different elements that respond to phase-to-phase, three-phase, and phase-to-ground faults. In addition, there are some relay elements that respond to three-phase faults only that can be offset from the origin. These elements have been included in electro-mechanical relays manufactured for many years and some digital relays also contain this function. Fully-offset mho relays are ideal for remote backup protection in that they are immune to line loading, as depicted in Figure 6. Their disadvantage is that a fully-offset mho relay will only cover a small portion of the protected line depending on the offset. They are truly applied as remote backup protection.

Figure 6: Add a Remote Zone 3 Fully Offset Element

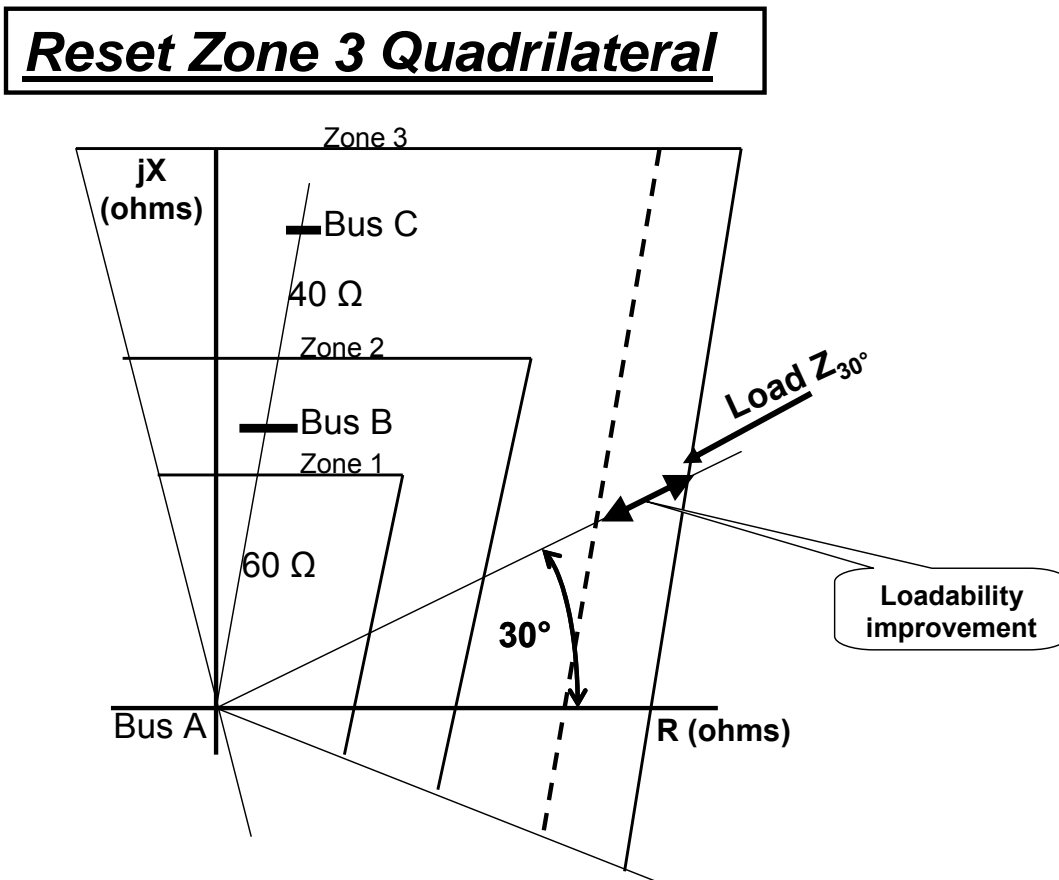


In this example, the remote backup relay (shown as a solid circle) is replaced by an offset zone 3 relay (shown as dashed circle) to provide the needed fault detection for the Figure 1 example. The zone 2 relay (also shown as a dashed circle) must be included as backup to protect the entire line. This protection, in total, takes on a classic “figure 8” configuration to replace the zone 3 from a coverage perspective. The measurement in improvement in loadability therefore, now depends on the zone 2 apparent impedance along the load line. From the example, zone 2 can be set 125% of the line impedance or  $1.25 \times 60 \text{ ohms} = 75 \text{ ohms}$  at 75 degrees. Then the Recommendation 8a trip MVA improves from 766 MVA to 1,272 MVA, using the equations of Figure 2.

## 5. For a Quadrilateral Characteristic, Reset the Relay

Some digital relays allow the user to select a mho or a quadrilateral characteristic. Older electronic relays required the user to choose between a mho and a quadrilateral relay style. One of the settings is the reach of the relay along the R (resistive) axis. The impact of relay sensitivity to load and fault resistance is a part of the quadrilateral's setting and application guides. For long lines, quadrilateral characteristics allow the user to set the relay as needed along the relay's characteristic angle and then choose a resistive reach so as to minimize the impact of load encroachment while maintaining coverage for fault resistance. In this example, the resistive reach of the various relay zones are set independently of each other. Check your owner's manuals to make sure this is true for the relay being reset.

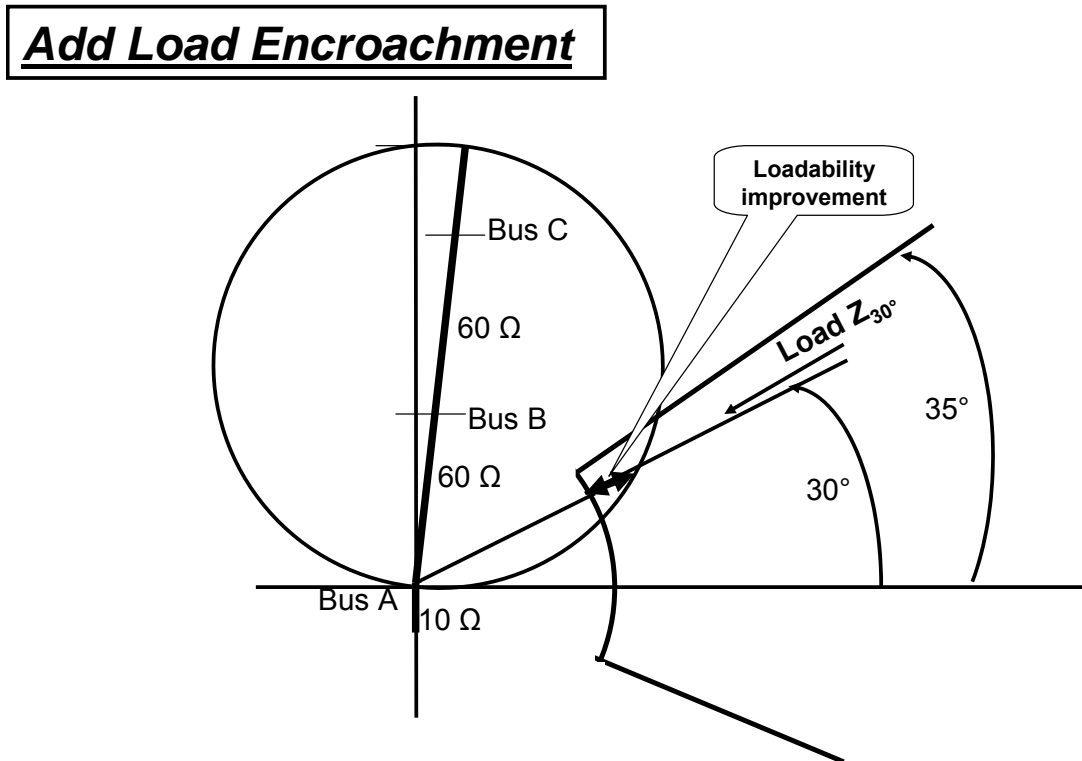
Figure 7: Reset Zone 3 Quadrilateral along the Resistive Axis



## 6. Enable the Load Encroachment Function

The use of load encroachment function to increase relay loadability was first presented in the NERC SPCTF paper entitled *Increase Line Loadability by Enabling the Load Encroachment*, dated November, 2005. This section includes the discussion portion of the load encroachment white paper. The resistive reach discussion is included as an appendix.

Figure 8: Enable the Load Encroachment Function



Enabling load encroachment features on existing relays will increase line loadability. The load encroachment function boundary line should not be set at exactly 30 degrees. Setting the boundary line for the load encroachment enabling angle exactly at 30 degrees creates a loadability discontinuity that could pose a threat to system security by allowing relay operation while the operator is performing the emergency switching operations. For instance, the load encroachment feature of the relay could be set at exactly 150% and 0.85 per unit voltage at a 30 degree power factor angle. A 1 or 2 degree difference in angle could cause the relay to operate much below the 150% requirement. During the August 14, 2003 disturbance, a 30 degrees power factor angle was observed prior to the unstable power swing between Michigan and Ontario. The 30 degree power factor angle observed may not be a maximum in future disturbances.

The margin recommended by the blackout investigation team is defined by a mho characteristic that accommodates 150% of the line rating at 85% voltage and 30 degree power factor angle. With this characteristic, there is no concern over minor variations in any of the quantities. Minor variations in the power factor angle become a concern only when a discontinuity is introduced by the load encroachment function. In order to mitigate this concern, a margin is recommended in setting the load encroachment function to keep the discontinuity at least 5 degrees from the conditions of concern observed on August 14, 2003.

There is some downside to widening the load encroachment arc in that the relay would be less sensitive to picking up for faults with very high arc resistance. However, the load encroachment should only be applied where three-phase fault conditions with arc resistance is less of a concern, such as medium and long length transmission lines. For short transmission lines, there should be substantial margin between the setting of the relay and the loadability of the line without the need of a load encroachment function.

### Recommendation on Settings for the Load Encroachment Function

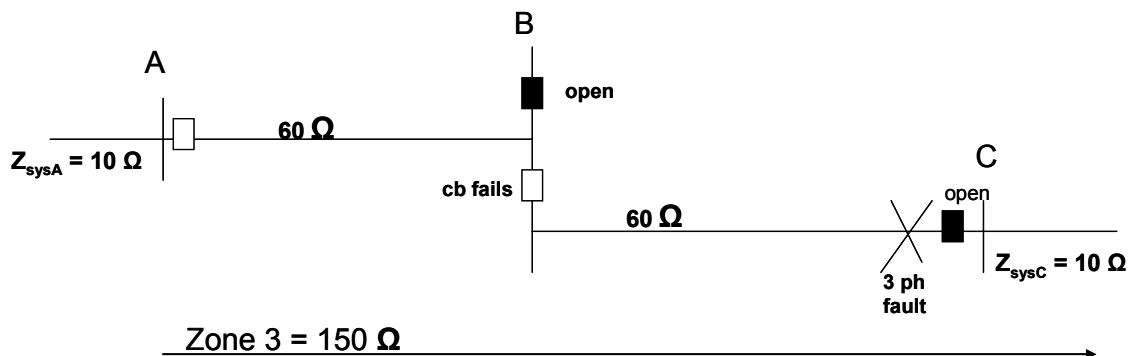
For the bulk electrical system 200 kV and above, the load encroachment feature should be set with its boundary line in the first quadrant between +35 and +45 degrees to take relay settings margin into consideration. This segment of the power system generally has lines with line impedance angles 75 degrees or greater. Forty-five degrees is the expected power factor angle at the theoretical maximum power transfer for steady state conditions, i.e. 90 degrees power flow angle across a transmission line<sup>1</sup>. This theoretical limit causes line currents to lag voltage by 45 degrees which corresponds to a relay measured impedance with angle of +45 degrees.

As relay engineers evaluate lower voltage lines in the “Beyond Zone 3” loadability review program, they may encounter critical lines at 100 kV to 200 kV with impedance angles considerably below 75 degrees, for example closer to 60 degrees. The need for relay margin exists for all relay settings. The use of load encroachment features for lower voltage lines should have at least a 5 to 10 degree margin relative to line angle. The following example describes one methodology to implement this recommendation.

### Load Encroachment Function Settings Example

Given the 345-kV system in the one line diagram in Figure 9, set a load encroachment function to work in conjunction with the zone 3 relay at bus A. Note Figure 9 is slightly different from Figure 1. This example demonstrates a calculation method to check for arc resistance accommodation.

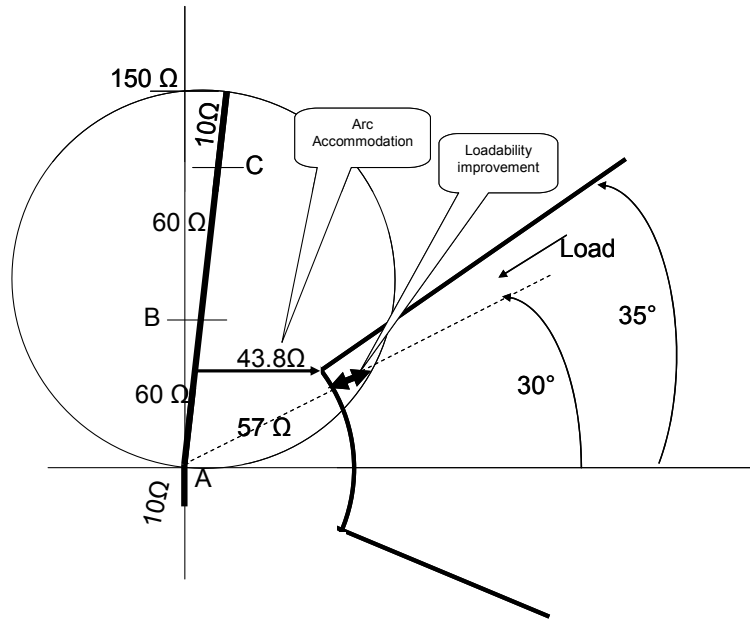
Figure 9: Load Encroachment Function Settings Example



The zone 3 relay at bus A is applied to the 60 ohm line. An adjacent line at bus B is also 60 ohms. The zone 3 relay at bus A is set at 150 ohms and 85 degrees to detect a three-phase line end fault near bus C in the event that the common circuit breaker at bus B fails with a margin of 30 ohms. The line A-B loadability is 150% of the emergency thermal limit of the transmission line (150% of 2,000 amps = 3,000 amps) at a 0.85 per unit voltage, resulting in a load impedance of 57 ohms at 30 degrees. A load encroachment function is enabled to permit the emergency line current.

<sup>1</sup> For a derivation of theoretical maximum power transfer which includes an explanation on the relationship of current angle with respect to voltage and on the relationship of voltage angle across a power system, see Appendix A, Exceptions, in the NERC document: *Protection System Review Program Beyond Zone 3* available at [www.NERC.com](http://www.NERC.com).

Figure 10: Encroachment Settings on the R-X Diagram



The encroachment function eliminates a portion of the relay's tripping circle in the area that will provide the necessary increase in line loadability. The magnitude of this improvement is indicated by the short line segment between the relay's circle and the load encroachment characteristic. There is no impact to the relay's reach along the maximum torque angle. However, fault resistance accommodation needs to be assessed. See Appendix A.

## CONCLUSION

In the review of zone 3 relays completed December 31, 2004, the transmission protection owners reported that 17.3% of the 10,914 relay terminals reviewed required mitigation for conformance with the relay loadability requirements of NERC Recommendation 8a. However, only 2.6% of those terminals required equipment replacements. This technical paper describes many of the techniques relay practitioners used to increase loadability without the need for protective relaying equipment replacements. These measures were either intended to be permanent or intended to be a part of a strategy designed to implement temporary exceptions as plans were implemented to reach a final technical solution.

The NERC SPCTF included the following discussion in its paper, *Relay Loadability Exceptions – Determination and Application of Practical Relaying Loadability Ratings*:

### Temporary Exceptions

Temporary Exceptions allow for a delayed implementation schedule for facilities that require modification due to the inability to complete the work within the prescribed time frame because of facility clearance (equipment maintenance outages) or work force issues. Temporary exceptions may also be granted for application of temporary mitigation plans until full implementation can be achieved.

***All applications for temporary exceptions should include sufficient justification for the delay in mitigation as well as a mitigation plan with a planned schedule for completion.***

For those facilities that are substantially outside the Recommendation 8A loadability requirements, the transmission protection system owner (TPSO) should have done everything practical with existing equipment to mitigate nonconforming relays and maximizing loadability before applying for temporary exceptions.

Such mitigation includes but is not limited to:

1. Elimination of unnecessary protection functions (beyond applicable protection needs)
2. Adjusting the maximum torque angle on the relay
3. Resetting of relays as possible while still meeting established protection practices

Every effort should be made to mitigate nonconforming critical lines as soon as possible on a priority basis.

It is essential that these strategies do not decrease transmission line and system protection while at the same time improving transmission system loadability security.

## APPENDIX A — FAULT RESISTANCE ASSESSMENT

The degree of accommodation of arc resistance for a three-phase arcing fault for any of the loadability improvement methodologies can be determined geometrically using the law of tangents and cosines. Refer to the section on load encroachment enabling for this particular example.

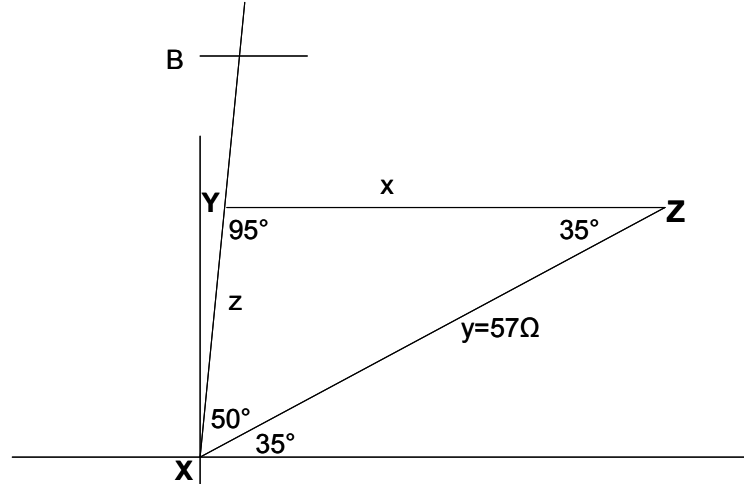


Figure A-1: Determining Arc Resistance Accomodation

### Using the Law of Tangents:

In any triangle, the difference of any two sides is to their sum as the tangent of half the difference of the opposite angle is to half the sum of these angles.

$$\frac{y - z}{y + z} = \frac{\tan \frac{1}{2}(Y - Z)}{\tan \frac{1}{2}(Y + Z)}$$

$$y = 57 \Omega$$

$$Y = 95^\circ$$

$$Z = 35^\circ$$

Solving for  $z$ , the distance from the relay where arc resistance is least accommodated:

$$z = 32.8 \Omega$$

### Using the Law of Cosines:

The square of any side of a triangle equals the sum of the squares of the other two sides less twice the product of these two sides times their included angle.

$$x^2 = y^2 + z^2 - 2yz \cos(X)$$

$$y = 57 \Omega$$

$$z = 32.8 \Omega$$

$$X = 50^\circ$$

In the equation below,  $x$  is a line segment that represents the deepest penetration of the load encroachment characteristic. It represents the magnitude of a three-phase fault arc resistance

$$x = R_{arc} = 43.8 \Omega$$

Arc resistance is generally calculated using empirically determined equations, such as

$$R_{arc} = 440 \times \frac{L}{I}$$

where  $I$  is measured between 70 amps and 20,000 amps.

$L$  is the measurement between conductors in feet. This is an empirical formula taken from the book: *Protective Relaying – Principles and Applications* by J. Lewis Blackburn. A similar empirical equation  $R_{arc} = 8,750 \times \frac{L}{I^{1.4}}$  is presented by A.R. van Warrington in *Applied Protective Relaying*.  $L$  is in feet,  $R$  is in ohms, and  $I$  is current measured between 1,000 and 30,000 amps.

Some practitioners consider the extension of the arc length with wind velocity and time if the fault is not cleared in high-speed (0.2 seconds or less).

$$L = L_0 + (3 \times \text{wind velocity} \times \text{time})$$

Velocity is measured in miles/hour,  $L$  is measured in feet. This empirical equation is provided in the *Art and Science of Protective Relaying* by Mason.

In this example, a three-phase fault  $32.8 \Omega$  from the relay location at A results in the fault location with the least arc accommodation due to the deployment of the load encroachment function. The spacing between line conductors is 22 feet. Using  $R_{arc} = 440 \times \frac{L}{I}$ , and assuming high-speed clearing the arc resistance would be 2.1 ohms. (Recalculating the three-phase fault with the arc resistance included will not appreciably lower the current for a 2.1 ohm arc resistance.) Now assume a wind velocity of 30 mph and the fault persists for 1 second.

$$L = L_0 + 3 \times 30 \times 1 = 112 \text{ feet}$$

Using this new arc length and  $R_{arc} = 440 \times \frac{L}{I}$ ,

$$R_{arc} = 440 \times \frac{112}{4,672} = 10.5 \Omega$$

(Recalculating the three-phase fault with the arc resistance included will not appreciably lower the current for a 10.5 ohm arc resistance.)

It is possible that the arc resistance as detected by the relay at the origin could increase with in-feed from the other end of the line. For a fault at the end of the line from substation A – substation B, the arc resistance could be double, 21 ohms, in this example, which is still less than the 43.8 ohms identified on the figure. Finally, it is possible that the arc resistance can appear partly inductive to the relay at A due to differences in prefault voltage magnitudes and power flow. This can be considered in the margin calculation.



## APPENDIX B — SYSTEM PROTECTION AND CONTROL TASK FORCE

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