Increase Line Loadability by Enabling Load Encroachment Functions of Digital Relays

North American Electric Reliability Council

Prepared by the
System Protection and Control Task Force
of the
NERC Planning Committee

Approved by NERC's Planning Committee

December 7, 2005

Table of Contents

Introduction

This informational document discusses the implementation of a load encroachment function to a mho element impedance relay to increase the loadability of relay settings without decreasing protection coverage. The NERC System Protection and Controls Task Force (SPCTF) prepared this guide to provide additional insight into recommendations made to increase loadability related to the review and mitigation of relay loadability problems being conducted on the EHV transmission system (200 kV and above) and on Operationally Significant Circuits (100 kV to 200 kV) under the *Protection System Review Program — Beyond Zone 3* report, approved by the Planning Committee in September 2005.

Recommendation 8a Loadability Rationale

One of the observations made from the August 14, 2003 blackout investigation was that protective relaying should not preclude operator action during extreme system emergencies. It was felt that the operator should have 15 minutes subsequent to an extreme contingency in which emergency actions including load shedding could be performed. To this end, a thermal rating recommendation was established, namely 150% of the transmission lines long time thermal 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, a voltage of operational concern equal to 0.85 per unit and a power factor angle of 30 degrees current lagging voltage. Just like the thermal rating, the voltage value of 0.85 was an observed value when the system was in an extreme condition but not in a cascading mode. Finally, the same is true for the 30 degree power factor angle. Thirty (30) degrees is not an extreme value. In fact, some power lines operate at 45 degrees current lagging voltage.

NERC SPCTF recognizes first and foremost that the power system must be protected. Secondly, the power system protection must not prevent operator actions to save the interconnected power system. 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. Those schemes do not need 15 minutes but generally a number of seconds to take action before the zone distance relay times out and trips.

Several techniques to increase loadability are 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 1st quadrant
5. Enable the Load Encroachment Function of the relay

Not all existing relays have all of the above techniques as settings options. It is up to the relay settings engineer to choose the most appropriate technique. 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 is done in all relay settings.

This paper addresses enabling the Load Encroachment Function option to clarify its application. Enabling Load Encroachment is a technique that can be implemented after evaluating “Zone 3” loadability and “Beyond Zone 3” loadability. A subsequent paper will address the remaining functions.

Enabling 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 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 emergency switching operations. For instance, the load encroachment feature of the relay could be set at exactly 150% of the Emergency Ampere Rating of the circuit, and 0.85 voltage at a 30 degree power factor angle. A one or two degree difference in angle could cause the relay to operate much below the 150% requirement. Even though a 30 degree power factor angle during the August 14, 2003 disturbance was about the highest power factor angle observed leading up to the unstable power swing between Michigan and Ontario, the industry should not assume this angle will 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.

There is some downside to widening the load encroachment arc in that the relay would be less sensitive to detecting and 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[1]. This theoretical limit causes line currents to lag voltage by 45 degrees which corresponds to a relay measured impedance with angle of +45 degrees. The following example describes one methodology to implement this recommendation.

As relay engineers evaluate lower voltage lines in the “Beyond Zone 3” 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 for lower voltage lines should have at least a 5 to 10 degree margin relative to line angle.

1 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.

Load Encroachment Function Settings Example

Given the 345 kV system in *Figure 1*, set a load encroachment function to work in conjunction with the zone 3 relay at bus A.

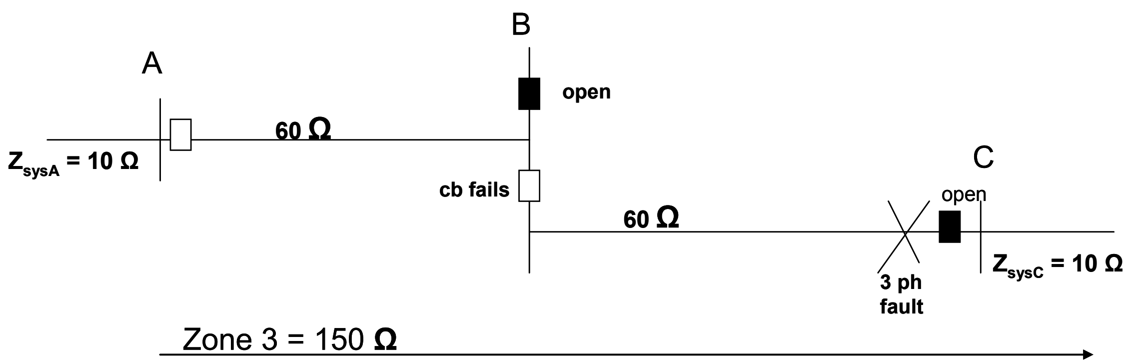

Figure 1 — Load Encroachment Function Settings Example

Zone 3 relay at Bus A is applied to the 60 ohm line. An adjacent line at substation B is also 60 ohms. The Zone 3 relay at substation A is set at 150 ohms and 85° to detect a three phase line end fault near substation C in the event that the common circuit breaker at substation 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 0.85pu voltage resulting in a load impedance of 57 ohms at 30 degrees. A load encroachment function is enabled to permit the emergency line current.

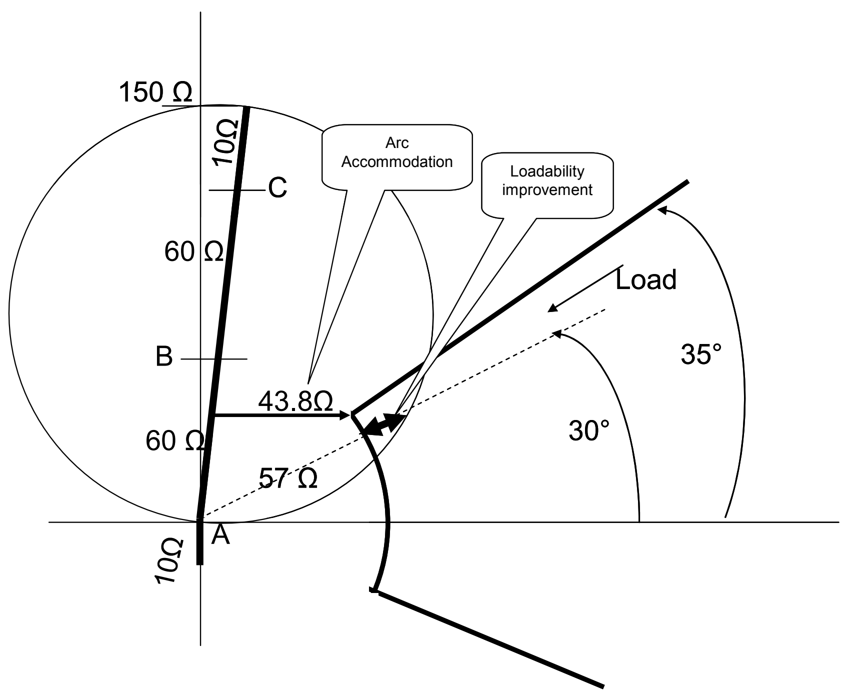

Figure 2 —Encroachment Settings on the R-X Diagram

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.

Fault Resistance Assessment

The degree of accommodation of the load encroachment characteristic for the arc resistance for a three phase arcing fault can be determined geometrically using the law of Tangents and Cosines:

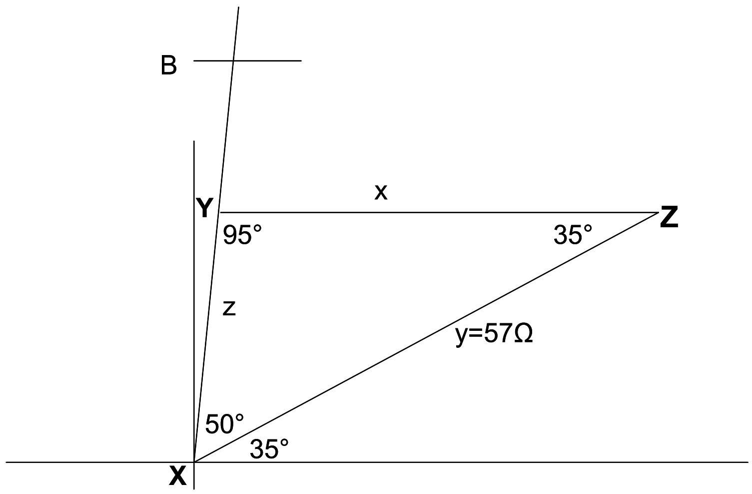

Figure 3 —Determining Load Encroachment Arc Resistance Accommodation

A. 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.

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

$$y = 57\Omega$$

$$Y = 95°$$

$$Z = 35°$$

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

$$z = 32.8\Omega$$

B. Using the Law of Cosines:

The square of any side of a triangle equals the sum of the squares of the other 2 sides less twice the product of these two sides times their included angle.

$$x^2 = y^2 + z^2 - 2yz\cos(X)$$
$$y = 57\Omega$$
$$z = 32.8\Omega$$
$$X = 50°$$

"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 is

$$R_{arc} = 8750 \times \frac{L}{I^{1.4}}$$

presented by A.R. van Warrington in *Applied Protective Relaying*. L is in feet, R_{arc} 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).

$$L = L_0 + 3 \times Wind\ Velocity \times Time$$

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 C. Russell Mason.

In this example, a 3 phase fault 32.8Ω 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*L/I, and assuming high speed clearing, the arc resistance would be 2.1 ohms. (Recalculating the 3 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.

$$L = 22 + 3 \times 30 \times 1 = 112\ feet$$

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

$$R_{arc} = 440 \times \frac{112}{4672} = 10.5\ Ohms$$

(Recalculating the 3 phase fault with the arc resistance included will not appreciably lower the current for a 10.5 ohm arc resistance.)

Finally, 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 *Figure 2*. Finally, it is possible that the arc resistance can appear partly inductive to the relay at A due to differences in pre-fault voltage magnitudes and power flow. The inductive effect on arc resistance can be considered in the margin calculation.

Conclusion

Setting the load encroachment function to accommodate 150% of emergency line load will allow adequate line coverage for 3 phase arc resistance even when including wind velocity of 10 mph.

Appendix A — System Protection and Control Task Force

Charles W. Rogers
Chairman / ECAR Representative
Principal Engineer
Consumers Energy Co.

W. Mark Carpenter
Vice Chairman / ERCOT Representative
System Protection Manager
TXU Electric Delivery

John Mulhausen
FRCC Representative
Florida Power & Light Co.

Joseph M. Burdis
MAAC Representative
Senior Consultant / Engineer, Transmission and Interconnection Planning
PJM Interconnection, L.L.C.

William J. Miller
MAIN Representative
Consulting Engineer
Exelon Corporation

Deven Bhan
MAPP Representative
System Protection Engineer
Western Area Power Administration

Philip Tatro
NPCC Representative
Consulting Engineer
National Grid USA

Philip B. Winston
SERC Representative
Manager, Protection and Control
Georgia Power Company

Fred Ipock
SPP Representative
Senior Engineer – Substation Engineering
City Utilities of Springfield, Missouri

David Angell
WSCC Representative
System Protection & Communications Leader
Idaho Power Company

John L. Ciufo
Canada Member-at-Large
Team Leader – P&C / Telecom
Hydro One, Inc.

W. O. (Bill) Kennedy
Canada Member-at-Large
b7kennedy & Associates, Inc.

Jim Ingleson
ISO / RTO Representative
Senior Engineer
New York Independent System Operator

Evan T. Sage
Investor Owned Utility
Senior Engineer
Potomac Electric Power Company

Gary L. Kobet
Federal
Project Specialist – System Protection
Tennessee Valley Authority

Bob Stuart
NERC Blackout Investigation Team
Principal T&D Consultant
EleQuant

Tom Wiedman
NERC Blackout Investigation Team
Consultant to NERC

Henry Miller
ECAR Alternate
Principal Electrical Engineer
American Electric Power

Baj Agrawal
WECC Alternate
Principal Engineer
Arizona Public Service Company

Jon Daume
WECC Alternate
System Protection & Control Engineer
Bonneville Power Administration

Robert W. Cummings
Staff Coordinator
Director – Reliability Performance and Engineering Support
North American Electric Reliability Council