Coordinating the NERC PRC-023 Loadability Standard with Out-of-Step Impedance Relaying

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Abstract

The new NERC loadability standard was created to ensure satisfactory safety margins for impedance- and current-based relay settings to avoid cascading outages. Loadability issues have always made protection of long transmission lines with impedance relays somewhat problematic. The problems increase for remote backup protection using zone 3 elements.

Even if a remote backup zone 3 is not used, calculating out-of-step (OOS) application settings is more difficult than for equipment protection. The OOS characteristics tend to encroach on the loadability characteristics before the protection elements because OOS elements have a larger resistive reach than fault protection elements.

Development of dependable and secure OOS relay settings often requires confirmation through significant stability and/or real time digital simulator (RTDS) modeling. This multiplies the effort required for both Protection and Planning engineers.

A spreadsheet solution method has been developed that integrates the NERC loadability characteristic with OOS settings analysis. Variations in Thevenin equivalent system voltages and equivalent source, transfer and receiving bus impedances are included. The resulting "swing band" estimates the maximum range of impedance trajectories during system swing conditions. Appropriate techniques and checks either determine secure OOS settings directly or provide an improved judgment on settings dependability and security, even prior to stability or RTDS modeling.

Long lines protected by impedance relays are a common application and may be more likely to need out-of-step functions than shorter lines. However, many modern relays have selectable protection characteristic shapes and/or programmable logic that can be used to limit the resistive reach of OOS impedance elements to avoid encroachment on protection and loadability characteristics.

Introduction

The August 14, 2003 blackout in northeastern North America has resulted in many new industry standards, the enforcement of which has the force of law, replacing the previous system of voluntary compliance. One of the more challenging new standards for protection engineers is PRC-023-1, Relay Loadability.[1]

By the end of 2006, transmission owners had reported to NERC on their compliance with early versions of this new draft Standard, covering essentially all impedance- and current-based relay tripping functions on the Bulk Electric System (BES). By December 2006, a substantial majority of BES terminals complied with the requirements and nearly all the rest are on a short schedule to become compliant.

NERC reported on compliance at 200 kV and above in December 2006. More than 22,000 terminals were reviewed and 2,530 (~12%) did not conform to the loadability criteria. Most non-compliant terminals (2,293) require some form of mitigation (mostly relay setting changes).[2]

The earlier versions of the loadability requirements included technical exceptions, which evolved into similar compliance methods. The technical requirements cover everything that transmission owners have already had to report, with a few "tweaks" in migrating from "technical exceptions" to "compliance methods."[3] NERC is presently considering FERC comments, but balloting on the next draft has not yet been scheduled.

NERC Loadability Characteristics

The 2003 blackout led NERC to impose loadability limits on all bulk electric system facilities rated 200 kV and higher, plus operationally significant facilities down to 100 kV. Transmission owners began reporting on their compliance with the new loadability criteria at the end of 2004 for zone 3 relay elements. By the end of 2006 transmission owners had reviewed and reported on their compliance for phase distance, out-of-step tripping, out-of-step blocking, switch-on-to-fault, overcurrent, and communication-aided protection schemes.

The simplest compliance method uses 150% of the emergency equipment rating closest to 4-hour duration at 85% of rated voltage and 30% lagging power factor. Meeting requirements of any method is adequate to demonstrate compliance.

The preferred compliance method usually results in the lowest calculated current rating for the specific facility, though the Standard does not require this.

The analysis techniques in this paper assume that the NERC loadability calculations are performed separately.

Out-of-Step Modeling

Calculating out-of-step (OOS) relay settings is more complex than for equipment protection. OOS settings must have a larger resistive reach than line protection elements, but a shorter resistive reach than the loadability characteristic. Relays that include an internal load encroachment function generally do not use it to limit the OOS elements.

System disturbances cause system impedances and voltages to change, often significantly, and always in a dynamic fashion. This is the major reason why stability analysis, which specifically models such changes, has been an important requirement to confirm relay OOS settings. Stability analysis has also been recently supplemented by real time digital simulation (RTDS),[4] which injects the OOS relay with modeled system analog quantities in real time. Both stability and RTDS solutions can include a detailed dynamic model of generator excitation and governor systems, voltage effects on loads, and other dynamic factors such as fast turbine valving, dynamic braking, load shedding, etc.

Out-of-step modeling requires accounting for the full range of possible system conditions[5] under which the relays must operate, including

- Pre-disturbance generation levels (maximum / minimum)
- System transfer impedance (effectively in parallel with the line being analyzed)[6]
- Equipment outages
- System voltages under normal and stressed conditions
- Appropriate generator reactance
- Equipment loadability characteristics
- Single pole tripping, when used
- Series compensation, when used
- System swing rates
- Locations for OOS tripping and blocking applications
- Transient system response

The first eight of these items can be substantially addressed by an extended version of the traditional static impedance plane analysis. This analysis can also provide some useful insights into the last three dynamic items.

Out-of-Step Analysis on the Impedance Plane

The positive sequence impedance plane is the basis for the most common illustration of OOS functions as well as distance elements. Relay load encroachment has recently joined these functions through inclusion in some relays and commercial fault analysis programs. The new closely related NERC loadability requirements are also readily included in this format.

Determination of the system impedance functions and swing locus is illustrated in Figure 1. In principle, the method is straightforward.

- Plot total system equivalent impedance, Z_T, on the positive sequence impedance plane,

  $Z_T = Z_S\underline{/\Theta_S} + Z_E\,\underline{/\Theta_E} + Z_R\underline{/\Theta_R}$.[5]
  - Equivalent impedance, $Z_E\,\underline{/\Theta_E}$, between the source and receiving buses is the parallel combination of the line and system transfer impedances, beginning at the origin.
  - Source impedance, $Z_S\underline{/\Theta_S}$, is plotted “backwards” from the origin in the third quadrant near the -X axis,
  - Receiving system impedance, $Z_R\underline{/\Theta_R}$, is “forward” from the receiving end of the equivalent line and system transfer impedance in the first quadrant near the +X axis.
- The system swing locus is the perpendicular bisector of the total equivalent system impedance.
- The intersection of the system impedance and swing locus is at the system electrical center.

The swing locus depends on the source and receiving bus equivalent system impedances. These depend on the generation that is actually on line and the transmission system configuration, including any equipment outages. As generators and lines are removed from the system, the source and receiving bus equivalent impedances increase in magnitude and can change in angle. The system transfer impedance will also change, usually increasing in magnitude.

The swing locus also depends on the Thevenin equivalent voltages for the source and receiving systems.[5,6,7] If the receiving system has a lower equivalent voltage, the swing locus is a circle. The intersection of the swing locus with the system impedance characteristic (electrical center) is offset closer toward the receiving end impedance, and curves “up” in the +X direction on the impedance plane. If the source system voltage is lower, the electrical center is offset closer to the source impedance and curves “down” in the -X direction.

System Swing Rates

Power system swings are electro-mechanical phenomena that develop much more slowly than faults. Stability modeling determines the swing rate between areas or between a system and local machines. Typical system swing rates are around 0.2 to 0.5 Hz for inter-area and up to 2 Hz for local (unit or plant against the system) oscillations. The swing rate typically increases for unstable swings on the second and subsequent pole-slip cycles. Common advice for the protection engineer in the absence of "real" swing rate data is to assume a maximum swing rate of to 4 to 7 Hertz.

However, it may not be necessary to perform dedicated stability studies to determine system swing rates. Transmission Planners routinely perform stability studies for many present and possible future system configurations. Simply recording the observed swing rates observed in studies done for other reasons will at least provide a substantial head start toward determining the range of and especially the maximum system swing rates.

The actual system swing rate is usually not critical to calculating satisfactory OOS settings as long as the protection analysis uses a reasonable margin above the fastest system swing rate determined from stability modeling. Use of the fastest modeled swing rate (plus margin) for all line terminals within a system as a single target for OOS relay calculations simplifies analysis and usually provides acceptable OOS settings, even if actual system swing rates are significantly slower.

For example, most swing rates modeled by stability analysis on the author's system range from about 80º to 180º/second. The fastest stable "local" swing rate is about 540º/second. Following discussions between Transmission Planning and Protection Engineers, a value of 900º/second (2.5 Hz) was selected to provide a single target maximum system swing rate, including adequate margin for analysis purposes.

Out-of-Step Trip (OST) and Power Swing Block (PSB) Locations

Stability or RTDS modeling is required to determine preferred OST separation ("islanding") location(s), usually near the system electrical center. The electrical center will move, sometimes significantly, for different system configurations, but fixed OST locations are normally preferred.

A few reasonable "short cuts" can help identify locations where PSB is more likely to be needed. Once the desired OST location is identified, "near by" line terminals are likely candidates to experience power swings.

- The opposite end of the line from the OST location (receiving bus).
- Line terminals at the same bus as the OST location.
- Other line terminals at the receiving bus from the OST location.
- Depending upon system topology, line terminals at one or more additional buses removed from the OST location.

The static analysis described below can refine the list of terminals potentially vulnerable to power swings while also calculating relay settings.

Enhanced Static Out-of-Step Analysis

The OOS modeling method described here is an extension of the traditional impedance plane static analysis.[5] The problem is first solved for maximum generation "strong bus" conditions plus twice more for "weak source bus" and "weak receiving bus" stressed system conditions (e.g. line outages). The three solutions are combined to determine a "swing band" defined by the resulting three swing loci. The swing band is designed to cover the full projected range of the impedance trajectory under stressed system conditions. The general calculation technique may be termed a "strong bus / weak bus" analysis.

"Strong bus" calculations are based on maximum generation conditions with the transmission system intact. A commercial fault calculation program calculates a two-bus equivalent system (source and receiving buses connected by the transfer impedance) with the modeled line out of service.[5] Generator transient reactance is used in this model. Equal source and receiving system equivalent voltages are modeled, $E_S = E_R = 1.0$ per unit. The result is the traditional impedance plane OOS model (Figure 1).

Separate "weak bus" calculations are performed for the source and receiving buses. The objective is a range of swing loci based on the maximum plausible system impedances.

The weak source bus model includes the following changes from the maximum generation system:

- Use minimum generation conditions to calculate the weak source bus equivalent impedance.
- Synchronous generator reactance should be used in the weak source bus equivalent model.
- Model critical equipment outages--at least single, often double or more contingencies (see NERC Standard TPL-001-1 Table 1, Category C).
- Use the maximum generation "strong bus" case for the receiving bus equivalent impedance.
- Weak source system transfer impedance, Z_{TR}, may be modeled to maximize movement of the electrical center. This will happen when Z_{TR} (weak bus) ≤ Z_{TR} (base case). Since the transfer impedance is modeled in parallel with the line impedance, a value as low as $Z_{TR} = 0$ effectively represents the system as very strongly interconnected.
- Equivalent source system voltage represents stressed conditions, while receiving system

voltage represents normal conditions, $E_S < 1.0$ per unit, $E_R = 1.0$ per unit.

- Special case: for series compensated lines, include the capacitive reactance as part of the modeled line impedance. If $Z_{TR} = 0$ is modeled, series capacitance will have no additional effect.

The weak receiving bus model includes similar changes as for the weak source bus, but the system changes are applied at the receiving bus:

- Use minimum generation conditions to calculate the weak receiving bus equivalent impedance.
- Synchronous generator reactance should be used in the weak receiving bus equivalent model.
- Model critical equipment outages--at least single, often double or more contingencies (NERC TPL-001-1 Table 1).
- Use the maximum generation "strong bus" case for the source bus equivalent impedance.
- Weak receiving system transfer impedance may be modeled to maximize movement of the electrical center. This will happen when Z_{TR} (weak) ≥ Z_{TR} (base case). A value as large as $Z_{TR} = \infty$ represents the analyzed line as the only connection between the source and receiving buses.
- Equivalent receiving system voltage represents stressed conditions, while source system voltage represents normal conditions, $E_S = 1.0$ per unit, $E_R < 1.0$ per unit.
- Special case: for single-pole tripped lines, double the line impedance to represent the line during the pole open interval.[5]

Each difference between "strong" and "weak" bus models increases the separation between the electrical centers for the "maximum generation" base case and each separate "weak bus" system. The weak source electrical center moves in the -X direction and the weak receiving bus electrical center moves in the +X direction, away from the base case.

Figure 2 illustrates the effect of system configuration changes on the system swing locus. This Figure shows the line protection zones for a 160-mile, 345 kV line. Equivalent voltages are assumed equal, $E_S = E_R = 1.0$ per unit. The strong bus (base case) swing locus is the heavy central line with a shallow slope down to the right. Below the "strong" system are three successively weaker systems: (1) weak source bus with Z_{TR} from the strong bus case, (2) weak source bus with Z_{TR} from the strong bus case plus 50% series capacitor compensation, and (3) weak source with $Z_{TR} = 0$.

Similar weak receiving bus swing loci plot above the strong bus case: (1) weak source bus with Z_{TR} from the strong bus case, (2) weak source bus with Z_{TR} infinite, and (3) weak source bus with Z_{TR} infinite plus the line is single-pole switched.

Stressed System Equivalent Voltages

The range of voltages across a transmission system under normal conditions is typically within a few percent of the nominal value. If the maximum system voltage is 1.05 per unit, the minimum will usually be about 1.00 per unit. However, major disturbances result in a stressed system, with much larger voltage differences.

Most of the NERC loadability compliance methods assume 0.85 per unit voltage to represent stressed system conditions. NERC recognized that this lower-than-normal static value adds security against undesired distance relay tripping during emergency conditions, but probably does not represent worst-case conditions.

Western Electricity Coordination Council (WECC) Standards include several additional criteria required during stability analyses following fault clearing. These requirements are listed in the WECC version[8] of NERC Standard TPL-001-1 Table 1. Transient voltage sag may not exceed:

- 30% at any transmission bus,
- 25% at a load bus,
- 20% at any bus for longer than 20 cycles for a Category B (single contingency) outage, or
- 20% at any bus for longer than 40 cycles for a Category C (multiple contingency) outage.

Figure 3 shows these effects on the swing locus with the voltage ratio varying from 1.0 (equal voltages) down to 0.5 (strong bus = 1.0, weak bus = 0.5). This Figure models the same line as shown in Figure 2 with the same "strong" swing locus. The weak source system is configured with Z_{TR} from the strong case and receiving system equivalent voltage, $E_R = 1.00$ per unit. The successively weaker swing loci plotted below the base case represent equivalent source voltages, E_S, between 1.00 and 0.50 per unit.

Weak receiving bus swing loci plot above the strong bus case. The equivalent source bus voltage is $E_S = 1.00$ with weak receiving bus equivalent voltages, E_R, between 1.00 and 0.50 per unit.

Static Methods Improve Analysis Margin

The individual changes from the "strong" base case to the "weak bus" cases are intended to over-estimate movement of the system electrical center. Unequal (stressed) system equivalent voltages have a similar effect. This technique builds margin into the static analysis and increases confidence in the result, even before confirmation through stability/RTDS analysis.

For example, minimum generation conditions will often affect both source and receiving buses more or less equally for strongly or moderately interconnected systems and may result in little or no change in the position of the electrical center of the system (e.g. see Appendices B and C). However, combining the (larger) minimum generation source impedance and (smaller) maximum generation receiving impedance will always offset the modeled system electrical center and weak source swing locus in the -X direction.

The weak bus impedance and stressed system voltage models provide maximum separation between weak source and receiving bus swing loci by six separate techniques.

- The "strong" bus uses maximum generation impedances versus minimum generation impedances for the "weak" bus.
- The "strong" case uses generator transient reactance, while synchronous reactance should be used for the "weak" cases.
- System contingency outages may be different (with larger net effect) for separate weak source and receiving bus models.
- The effect of changes in system transfer impedance may be maximized.
- Substantial differences in system equivalent voltages may be modeled.
- The effects of single-pole tripping and series compensation are included.

The analysis technique increases margins not usually included in a static model to better approximate the results of stability or RTDS analysis. The first "margin" method is built into the technique, while the remaining methods may be individually used, according to the application and engineer's judgment. Use of transient versus synchronous generator reactance and special cases for series capacitors and single pole tripping typically result in step changes in the system model, while the selection of system contingencies, "weak" system transfer impedances and stressed system voltages provide more continuous choices. These methods improve confidence that dynamic system response will stay within the static "swing band" model.

Relay Out-of-Step Characteristics

Numerous impedance-based OOS relay characteristics are possible, but the most common are either concentric polygons or a form of concentric mho circles or lenses.

Manufacturers use different specific OOS characteristics and algorithms. But most relays use positive sequence impedance for most calculations. Most OOS algorithms use two (sometimes three) concentric characteristics. Some (usually) older schemes use the largest forward protection zone as the inner OOS characteristic.

The OOS characteristic must fit between the protection and loadability characteristics without encroaching on either. Achieving this goal can be especially difficult for long lines protected by a traditional forward-reaching zone 3 mho element.

The traditional method to determine relay settings and document OOS characteristics uses the impedance plane analysis described in general terms below and illustrated in Figure 1.

- Plot the system impedance, swing locus, distance, and loadability characteristics on the positive sequence impedance diagram.
- Plot the OOS characteristic inside the loadability characteristic but outside the largest distance protection zone.
- The outer resistive characteristic should be closer to the origin than the measured impedance at fault clearing (see Appendix B).
- Determine the angle subtended at the intersection of the swing locus with the outer OOS characteristic across the system impedance. Measure angles to the right and left of the system impedance separately.
- Determine the angle subtended at the intersection of the swing locus with the inner OOS characteristic across the system impedance. Measure angles to the right and left of the system impedance separately.
- For OST applications, compare the inner OOS (power) angle to 120º. A larger inner angle adds security for the OST decision.
- Subtract the “outer” angle from the “inner” angle separately for the left and right sides of the characteristic.
- Divide the estimated OOS timer setting into each angle difference to calculate the relay swing rate in degrees/second.
- Compare the calculated relay swing rates to the target system swing rate, e.g. 900º/second.
- Compare the inner (or middle) OOS characteristic to the estimated fault arc resistance (OOS should be larger).
- Modify the OOS resistive reaches and/or timer settings, and return to the first step as needed

to improve agreement between the target and calculated relay swing rates and OOS timer results.

More separation between inner and outer OOS characteristics generally results in a higher calculated relay swing rate, allows a longer OOS timer setting, or both.

The author's analysis technique remains conceptually similar to this description, except that solutions are required for weak source and receiving bus conditions as well as for the maximum generation case. The object is to achieve similar results across the entire swing band for six calculated relay swing rates instead of only two for the maximum generation case.

Fault Swing Rate

It is useful to determine a minimum "fault swing rate" as seen by the relay. The fault swing rate is the slowest rate of apparent angular change as the impedance trajectory moves from the load region to the fault location. The fault swing rate allows a direct comparison among Transmission Planners' system swing rates, loadability, and fault conditions. If the system or calculated relay swing rate exceeds the fault swing rate, an impedance-based relay will not dependably distinguish between faults and swings.

Faults develop very quickly, often described as migrating "instantaneously" on the impedance plane from the pre-fault load point to a location on the transmission line. This timing may well be very nearly true for the actual fault current, but relays require a longer time to recognize the changed system conditions.

The time necessary for elements to assert in modern microprocessor relays is affected by digital filtering and the manufacturer's specific algorithms. The results are often included in relay instruction manuals or may be available upon request as relay element pickup timing curves plotted as a function of distance element reach for a family of curves of constant source impedance ratio (SIR). Higher SIR with fault location closer to the element setting results in longer pickup time.

As an example, assume that pre-fault system conditions include a 40º power angle across the system impedance with the line load at the edge of the NERC Loadability characteristic. When a fault occurs, the impedance migrates to a point on the line impedance (ignoring arc resistance), forming a 180º “triangle” with the system impedance locus during the time it takes the fault to develop and be recognized by the relay. The manufacturer's data for SIR=30 at 80% of distance element reach is 1.75 cycles. The "fault swing rate” is then

$$\begin{aligned}\omega_f &= (180^\circ - 40^\circ)/1.75 \text{ cycle}\\ &= 140^\circ/0.029167 \text{ sec}\\ &= 4{,}800^\circ/\text{second.}\end{aligned}$$

The fault swing rate depends on the relay algorithm, system impedance and the NERC loadability rating impedance. In general, the fault swing rate will be minimized for initial load near a 90º power angle and for a relay that uses a relatively large time step for OOS calculations.

The author's experience indicates a minimum fault swing rate of about 3,000º/second for the relays in use on the author's system. This is comfortably higher than the maximum 7 Hz (~2500º/sec) "Planning" swing rate sometimes recommended (above).

Minimum PSB/OST Timer

Security for the setting for the PSB/OST timer must also be considered. Most modern relays have minimum OOS timer settings between zero and one cycle. If the timer setting is too short, the PSB or OST function may assert before the relay has time to distinguish between a system swing and a fault.

One aspect of this is the fault swing rate discussed above. The same digital filtering and relay algorithm characteristics also limit the timer settings required to achieve security. While the fault swing rate calculation determines the upper limit for system swing rates recognizable by the relay, a setting below the minimum secure PSB or OST timer could result in inappropriate blocking for actual faults.

This author's suggested minimum OOS setting begins with the distance element pickup time from the SIR curves and rounds the result up to the end of the relay OOS calculation interval (the fault swing rate transition time). The minimum secure PSB/OST delay then adds at least one relay calculation interval. The typical result is about two cycles for most relays. This time delay is in line with other recommendations.[9]

Fault Arc Resistance

Arcing faults have a characteristic resistance directly related to arc length and inversely related to fault current. The Blackburn[10] and Warrington[11] equations are commonly used to calculate primary arc resistance,

$$R_{arc} = 440\, L / I$$

where L = arc length (feet)
I = fault current (amps)

and

$$R_{arc} = 8750\,(L + 3ut) / I^{1.4}$$

where u = wind speed (miles per hour)
t = arc duration time (seconds)

The minimum arc length, L, is the phase-to-phase spacing of the line. The fault current includes the contributions from all line terminals.

Clearly, these widely used empirical equations do not provide identical results. A conservative approach uses the larger result.

For example, a 230 kV line has 18-foot phase spacing and experiences a 10,000 amp fault. Blackburn's primary arc resistance calculation is about 0.8 Ω and Warrington's result is 0.4 Ω (ignoring wind speed and arc duration time).

Since arc resistance and current are inversely related, high-fault-duty systems are less affected by fault resistance. Low system fault duties result in larger arc resistance, which is more likely to affect relay settings.

Spreadsheet Solution

The constellation of considerations makes a spreadsheet a good solution platform, and several versions were developed. Some versions accommodate more than one relay type (e.g. different relays from a single manufacturer). A detailed description of the spreadsheet organization is included in Appendix A.

Specific examples comparing this spreadsheet technique with stability modeling results are included in Appendix B for the system described in Appendix B of reference 5, and Appendix C for a recent OST application by a utility to back up a remedial action scheme.

The following spreadsheet versions were developed for relays used on the author's system:

- SEL 321, 311, 421
- SEL 121G
- SEL 300G, Beckwith M3425A
- General Electric SLL, OST1000, UR
- GEC (now Areva) Optimho
- Westinghouse (now ABB) KS

Coordinating OOS Settings with Loadability and Protection Characteristics

Short and medium length lines seldom require additional considerations to ensure that the OOS characteristics do not encroach on either the line protection or the loadability characteristics. However, long lines, especially if they include remote backup tripping with a forward reaching zone 3 mho element, will often overlap the OOS with protection and/or loadability characteristics. The technique described below is not limited to long lines, though it will more often be needed for such applications.

The engineer must set the outer OOS resistive characteristic shorter than the line loadability, even if this setting results in apparent encroachment on zone 3 or other protection zones. A secure minimum OST / PSB timer setting may then force the inner OOS characteristic to encroach on zone 2 or even zone 1.

Load encroachment relay characteristics can limit the resistive coverage of protection elements. If the OOS characteristics can also be set to only encroach on the delayed zone elements, the delay may be enough to coordinate. However, the actual, rather than maximum (target) system swing rate would then impose an effective upper limit on the zone timer.

Relay Logic Modifications

Some relays include user-selectable phase protection and OOS element shapes (lens, quadrilateral, etc) that can be set with a shorter resistive reach than mho elements. These element shapes should be tried to determine whether the OOS characteristic then avoids encroaching on the protection elements while maintaining adequate fault resistance reach. If OOS elements still encroach on protection elements or only the mho shape is available, a different approach is required to coordinate operation.

Electro-mechanical and electronic relays often limited protection element resistive reach with "blinders." Blinders seem to be used less for modern transmission relays, at least for some popular models. But blinders are still sometimes recommended for transmission relays[9,12,13] and often used by generator OOS relays.

Many newer microprocessor relays allow combining internal relay elements with logical operators to create new or modified applications. While the OOS elements are set to avoid the loadability characteristic, logic programming uses the OOS elements to "blind" the resistive reach of the "encroached" protection elements.

Figure 4 illustrates a PSB application on a 345 kV, 160-mile line on the author's system requiring this logic. Both OOS characteristics encroach on protection elements and forward reaching zone 4 encroaches on line loadability. The following logic (using one manufacturer's logic equation format) blinds zone 4 to OOS and loadability encroachment while providing for phase protection trips:

SV4 = M4P*(50Q4 + X6ABC)
SV4PU = Zone 3 time delay, e.g. 40 cycles
SV4DO = 0.00
TR = M1P + M2PT + SV4T + . . .

The relay phase distance elements do not distinguish between phase-to-phase and 3-phase events, so the negative sequence overcurrent supervision, 50Qn, element is "ANDed" with the zone phase element (MnP) to identify phase-to-phase faults, M4P*50Q4. This modified phase-to-phase protection operates when the zone 4 time expires.

The resistive reach of zone 4 for 3-phase events is "blinded" by "AND-ing" with the outer OOS element, M4P*X6ABC. This logic allows both zones 1 and 2 to operate normally, including the ground elements (not shown) that reflect the user's normal application.

The logic format may be extended to time-delayed zone 2 or instantaneous elements, including communication-aided schemes:

SV2 = M2P*(50Q2 + X5ABC)
SV2PU = Zone 2 time delay, e.g. 20 cycles
SV2DO = 0.00
TR = M1P*(50Q1+X5ABC)+SV2T+SV4T+ . . .
TRCOMM = SV2 + . . .
PT1 = SV2 + . . .

Out-of-Step Trip Security

Secure out-of-step tripping applications may require additional logic supervision when the manufacturer's OOS algorithm is based only on positive sequence impedance calculations. Three-phase, phase-to-phase, or phase-to-ground faults at a specific location have roughly similar positive sequence impedances, but very different negative and zero sequence impedances. A secure minimum OST timer (above) will help, but may still not protect against evolving faults. Secure trip supervision can usually by be provided by requiring a low level of negative sequence current, below which out-of-step tripping is allowed,

TR = OST*!50Q4 + . . .

Out-of-step trip applications using trip on the way out (TOWO) may require supervision of the relay trip signal so that transient recovery voltage (TRV) will be within circuit breaker rating. Some relays provide this function with a timer. However, since the timer setting should depend on the actual rather than maximum (target) system swing rate, an alternate (or additional) method[4] delays the trip until positive sequence voltage recovers to a near-normal level (e.g. ≈ 0.80-0.85 per unit) after slipping a pole:

59V1P = 0.8 per unit (e.g. 96 volts on a 120 volt base)
TR = OST*!50Q4*59V1 + . . .

General Out-of-Step Conclusions

1. The static OOS solution technique described includes maximum variations in system configuration to provide substantial margins to compare with stability or RTDS results.
2. No reliable shortcut to stability analysis is available to determine OST locations, but this paper's techniques allow calculation of OST settings with improved confidence over other static methods once locations are determined.
3. PSB locations are usually electrically near the OST locations. Further evaluation and preliminary settings can be developed using the static approach described in this paper.
4. OOS relay settings based on the calculated "swing band" can be determined using a spreadsheet relatively easily for an experienced protection engineer. The results are more complete and improve confidence in the solution compared to static methods described in relay instruction manuals or other literature.
5. The spreadsheet calculated settings provide improved guidance for stability or RTDS work as necessary to confirm OOS relay settings.
6. Specific spreadsheet warnings identify areas of potential concern.

Loadability and Coordination Conclusions

1. The outer OOS characteristic must be set inside the reach of the NERC loadability characteristic and the measured impedance immediately after fault clearing (when a nearby fault initiates the system disturbance).
2. Either protection characteristic shapes other than the traditional mho circle and/or custom logic may be used to avoid OOS encroachment on protection elements.
3. Some OST relays require custom logic to avoid out-of-step trips during unbalanced or evolving faults.
4. Some relays require custom logic to avoid excessive transient recovery voltage for trip-on-the-way-out applications.

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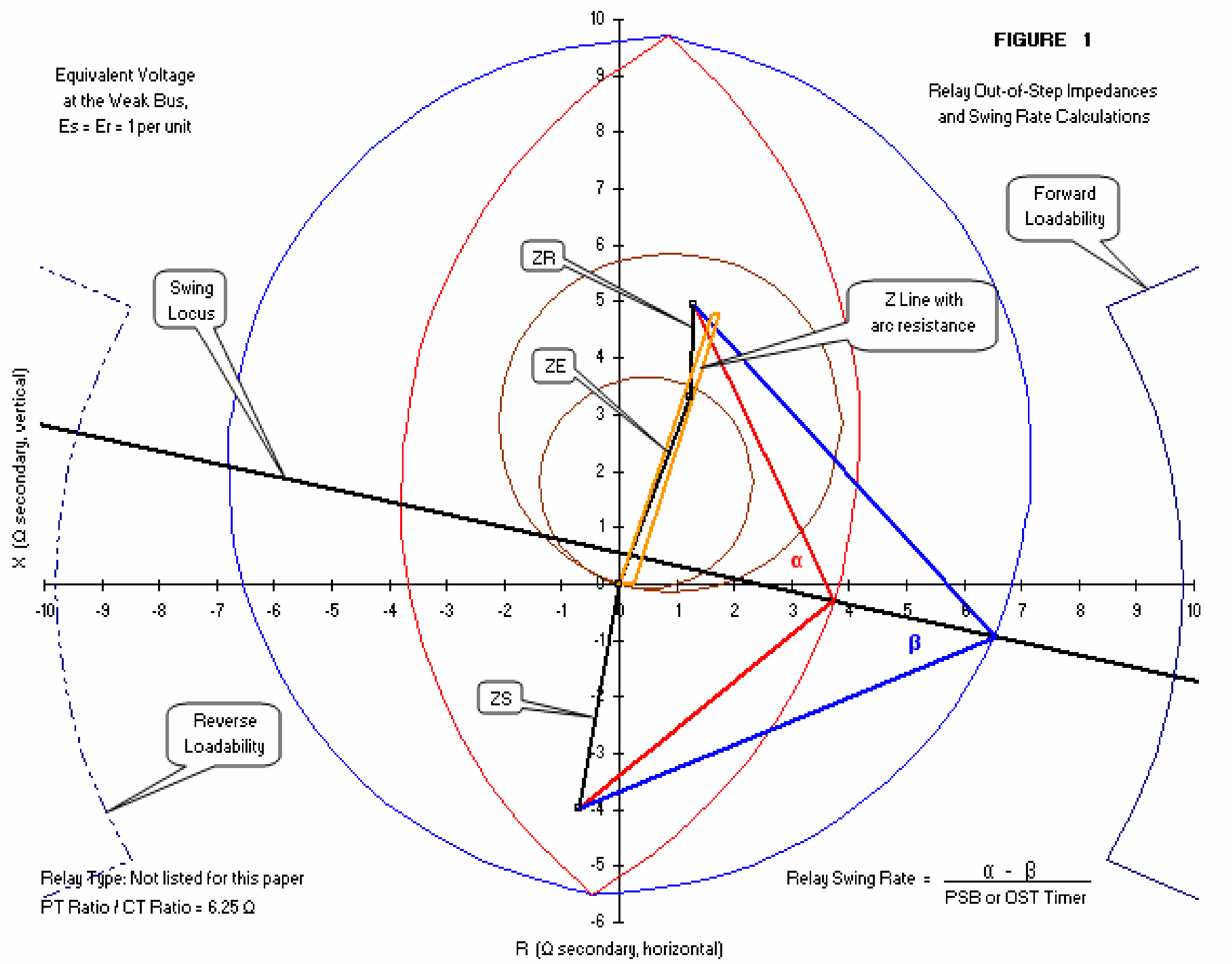

FIGURE 1

Relay Out-of-Step Impedances and Swing Rate Calculations

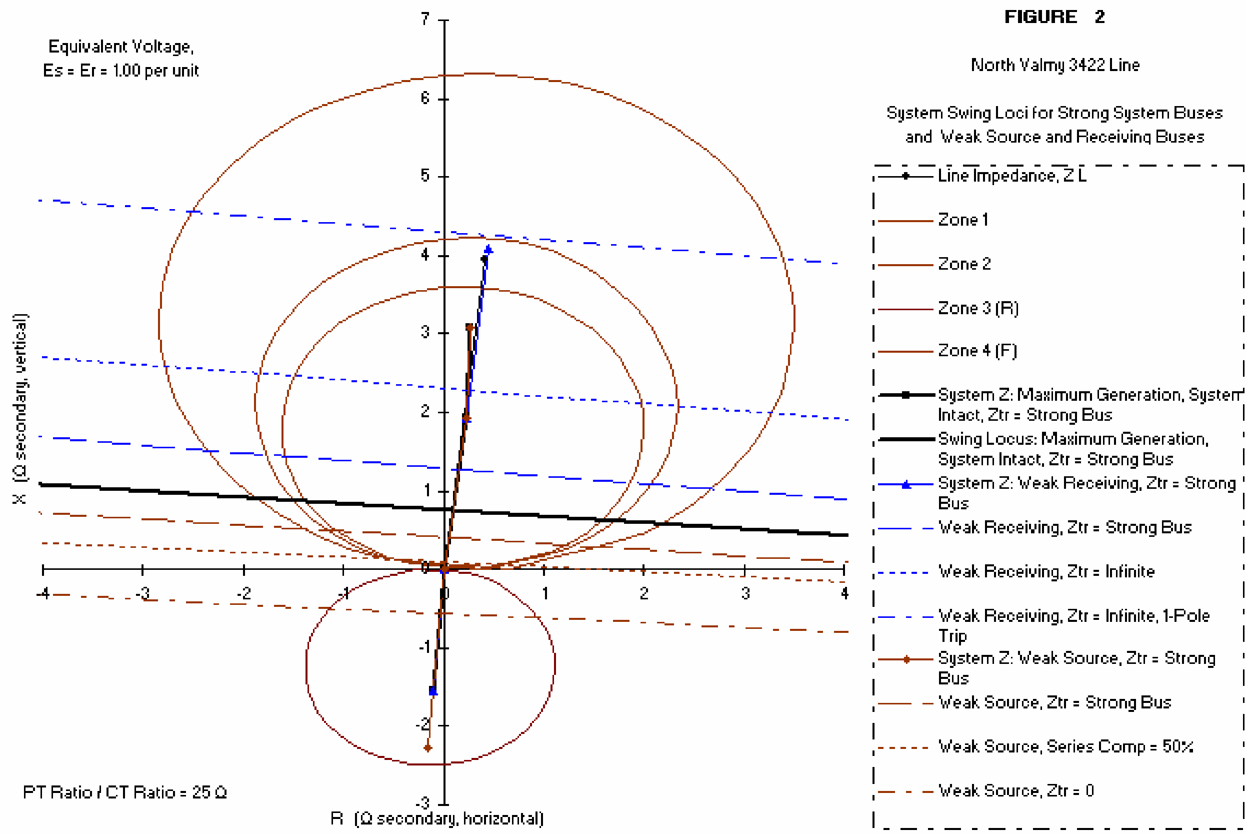

FIGURE 2

North Valmy 3422 Line

System Swing Loci for Strong System Buses and Weak Source and Receiving Buses

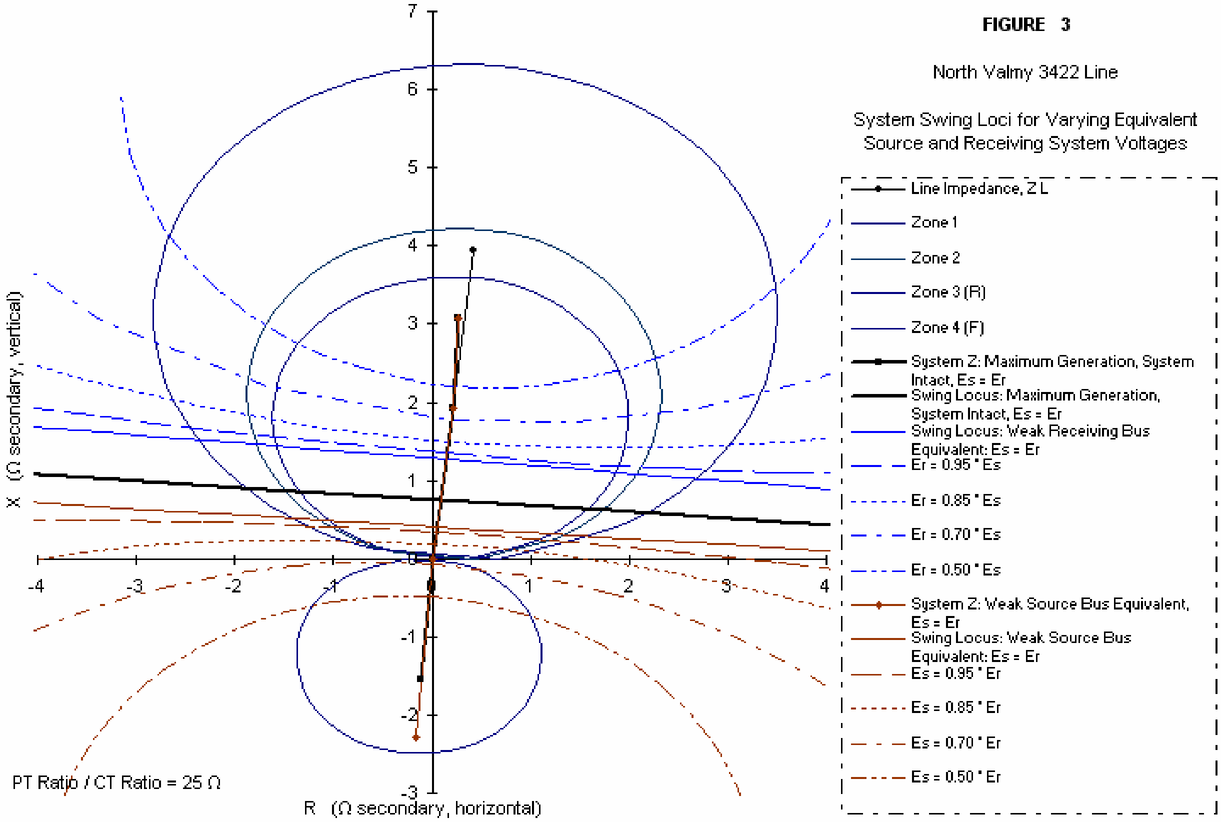

FIGURE 3

North Valmy 3422 Line

System Swing Loci for Varying Equivalent Source and Receiving System Voltages

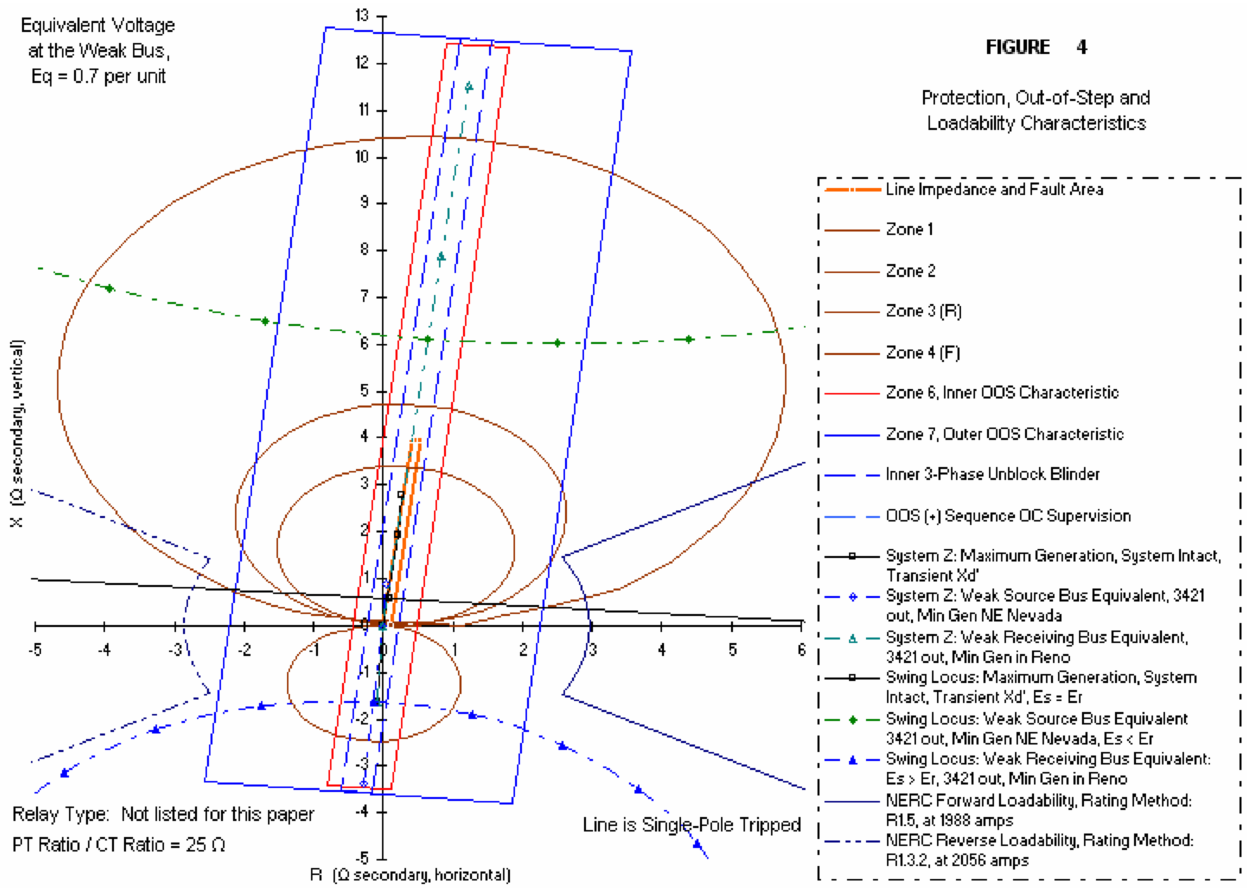

FIGURE 4

Protection, Out-of-Step and Loadability Characteristics

Appendix A
Out-of-Step Calculation Spreadsheets

Each spreadsheet version includes the relay type(s) as part of the name and three tabs:

- **[NOTES]** provides detailed descriptions of the input data and expected results for the spreadsheet calculations.
- **[System & Relay OOS Data]** includes all user-entered data and performs all calculations.
- **[Out of Step and Loadability]** graphically presents the calculation results, including descriptors for the specific application.

Data entry cells in [System & Relay OOS Data] use a yellow highlighted background. System data includes fault duties, line and system equivalent impedances, loadability ratings, descriptions, and other information in primary system quantities (amps, ohms, etc). Arc resistance calculations are based on the weak bus fault input data.

Relay input data includes relay type (when the spread sheet accommodates more than one), distance protection element and out-of-step resistance settings in relay (secondary) quantities (ohms, amps, etc).

Calculated OOS relay settings are in violet background cells. These settings are primarily "top" and "bottom" reach and OOS characteristic timer(s). The default top and bottom reach calculations may be modified by user-entered multipliers. User-entered OOS timers can override the calculated OOS values within the relay's available range.

The spreadsheet calculates the relay swing rates across the swing band (green background cells) for the left and right sides of the OOS characteristic for the strong and both weak bus system models. These six calculated relay swing rates are often close to each other, but may differ by up to a factor of approximately two or more when at least one of the weak bus models is substantially weaker than the strong bus model. The user must "tweak" the OOS resistance settings to match the minimum calculated relay swing rate to the target system swing rate.

The spreadsheet imposes the calculated minimum secure PSB or OST timer as the minimum setting value. This value is usually larger than the minimum available relay setting. Since the target system swing rate is constant, the OOS timer increases automatically as the user increases separation between the inner and outer OOS resistive characteristics.

The spreadsheet provides several "sanity checks." Each check highlights a calculated result (green cells) and provides a message that indicates an acceptable result or a warning that further analysis may be needed. Checks for most transmission relays include:

- Margin between the outer OOS and loadability characteristics is required. A warning is provided if encroachment occurs.
- The minimum fault swing rate should be greater than the maximum calculated relay swing rate across the swing band for all six calculated swing rates to ensure OOS settings dependability.
- The minimum inner (middle, if used) OOS characteristic resistive reach should be larger than the line resistance plus fault arc resistance.

The following checks are included for relays that may be applied for out-of-step tripping:

- For OST security, the minimum calculated OOS inner characteristic (power) angle for all six calculated swing loci intersections should be at least 120º. A 120º angle may not always be enough, but a larger angle will always increase OST security.
- For trip-on-the-way-out (TOWO) applications, the maximum calculated separation angle when the trip decision is made should not exceed 90º. This angle will often exceed 90º for transmission relays. Additional delay or other supervision may be needed to avoid excessive breaker TRV.

Additional checks and warnings are provided for functions pertinent to specific relays within individual spread sheets.

All the data plotted on the chart at [Out of Step & Loadability] is calculated by the spreadsheet in blue background cells. The data is scaled in relay (secondary) ohms.

The chart includes appropriate title block information entered by the user. The legend block identifies the specific plotted data, including user-entered information describing the weak bus cases and line loadability. Separate notes identify weak bus voltage level, relay type, ratio of primary to secondary impedances (PT/CT ratio), and single-pole tripping and series compensation (when used). The user may change resistance (R) and reactance (X) scales to get an appropriate "look" for the chart.

Appendix B

PSRC “Power Swing and Out-of-Step Considerations on Transmission Lines”

The Power System Relaying Committee (PSRC) of the IEEE Power Engineering Society published an example of OOS setting calculations in reference (5), Appendix B. PSRC illustrated the system as two 230 kV lines connecting a generating station (KCL, 4 units, 147 MVA each) to a major switching station (SEK). The methods developed in this paper were applied to the stable and unstable power swing cases modeled in this PSRC example.

The example included results of "full loop" dynamic simulations for faults on one line close to the KCL station with loss of that line upon fault clearing. Fault clearing times were increased until the system could no longer maintain stability. The swing center of an unstable power swing passed close to the KCL terminal or through the unit transformers. The line relays were set to trip for an unstable swing using trip on the way in (TOWI) because the breakers are rated to withstand the expected TRV.

The system was initially loaded at a point off-scale to the right on Figure B-1. At fault inception, the stable impedance trajectory quickly moved to the origin, then upon fault clearing quickly moved right, outside the outer OOS characteristic, then left (more slowly) in the direction of the origin. The impedance trajectory entered the right side of the outer OOS characteristic before reversing direction and moving back to the right into the load region. Only zone 1 protection is shown.

Fault clearing was about one cycle longer for the unstable than for the stable case. The unstable trajectory (Figure B-2) behaved similarly to the stable case during and at fault clearing. After fault clearing, the trajectory entered the outer, then the inner OOS characteristics from the right before exiting on the left.

These Figures show that power swings for both stable and unstable cases stay well within the calculated swing band. The “swing impedance” at fault clearing was well outside the outer characteristic. The spreadsheet calculated a minimum inner characteristic (power) angle of only about 103º. This angle and the outer characteristic settings are acceptable since the stability cases confirmed the security of the blinder settings.

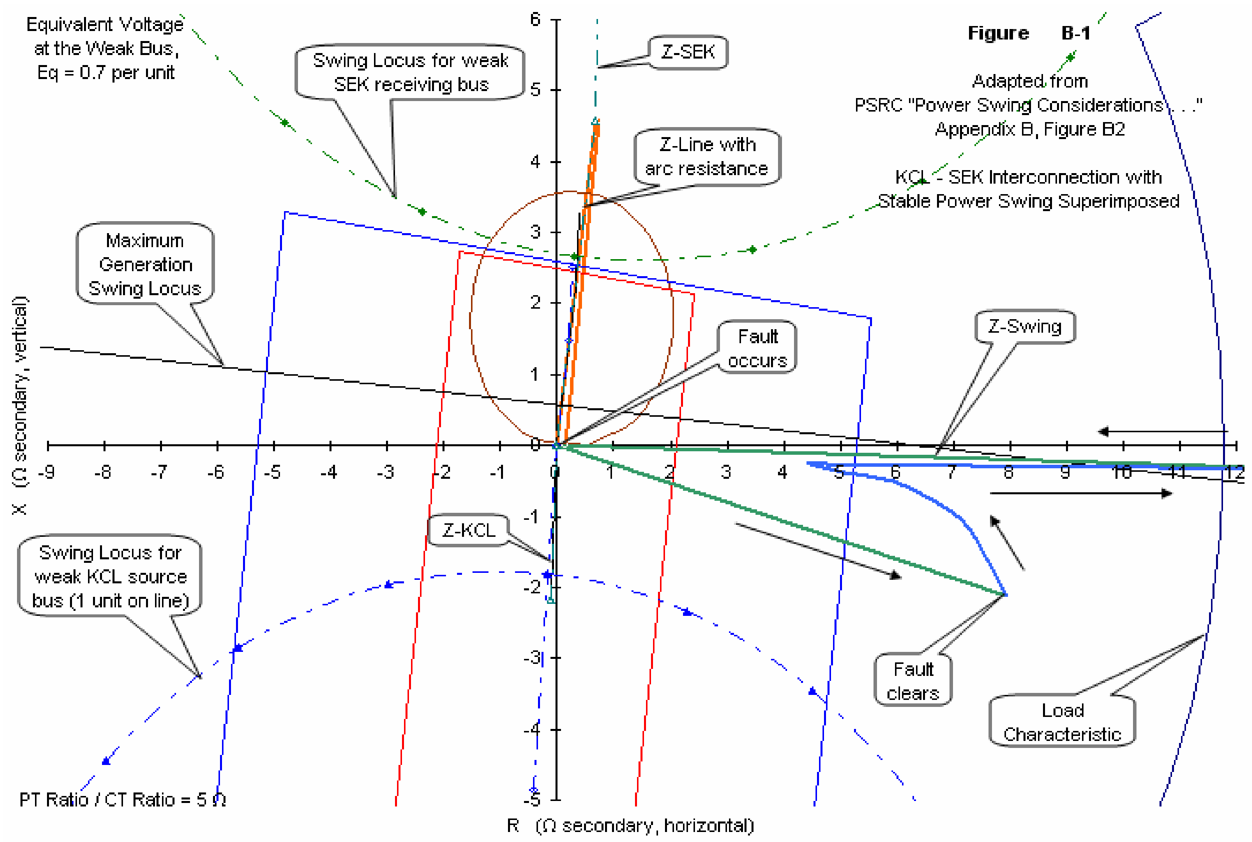

Figure B-1

Adapted from PSRC "Power Swing Considerations . . ." Appendix B, Figure B2

KCL - SEK Interconnection with Stable Power Swing Superimposed

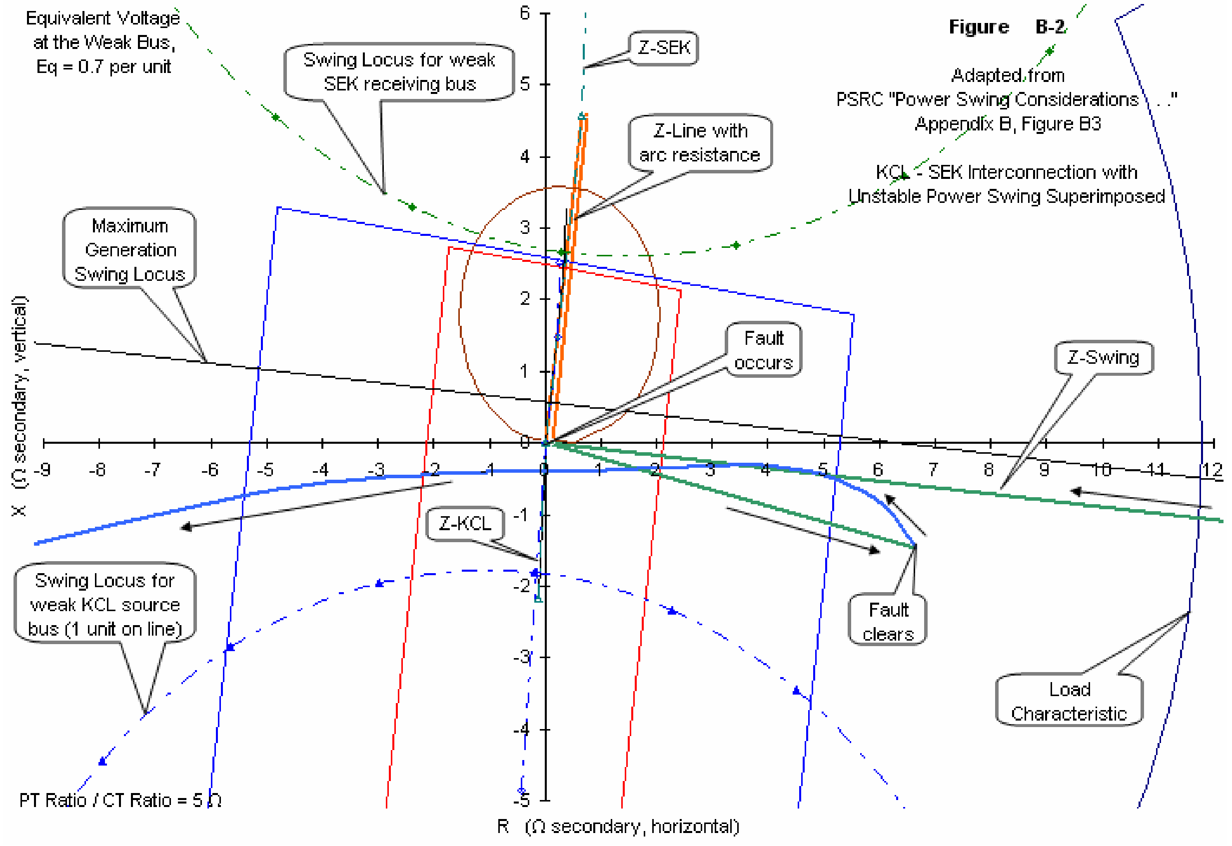

Figure B-2

Adapted from PSRC "Power Swing Considerations . . ." Appendix B, Figure B3

KCL - SEK Interconnection with Unstable Power Swing Superimposed

Appendix C
Add a New Separation Location to an Existing Remedial Action Scheme

Utility A built a new 230 kV line tied in near the end of a radial 115 kV system to improve reliability and add transmission capacity to the lower voltage system. The new tie is completed through a 230/115 kV transformer at station GLD. The new line is part of an intertie with Utility B and is subject to operation of an existing remedial action scheme (RAS).

The RAS separates utilities A and B (and others) for loss of certain facilities within the BES. When the critical outage is detected, communication signals are sent to all locations where the electric systems should be separated. Utility A added communication facilities to carry the RAS “islanding” signal to the new GLD 230 kV line terminal. Utility A also installed out-of-step tripping relays at GLD 115 to ensure that the systems will dependably separate.

Utility A performed dynamic simulations to model OOS relay performance. The critical system fault that triggers RAS operation was modeled and all other islanding locations controlled by the RAS operated as designed. The new GLD 230 kV islanding location was assumed not to operate so that separation depended on the 115 kV OST relays.

Prior to RAS operation, power flow was modeled from the new 230 kV line through the GLD 115 kV (source) terminal toward the SPG 115 kV (receiving) terminal.

Figure C-1 models the predicted results. Zone 3 encroaches on line loadability, so that the logic supervision described under Relay Element Modifications should be considered. The inner OOS characteristic does not encroach on zone 2, so this logic only has to be applied to zone 3, which also "blinds" zone 3 to load encroachment.

Figure C-1 includes dynamic modeling results for the first two out-of-step swings (separation should occur on the first swing). Both swings enter the Figure on the right side and exit on the left, but stay within the swing band calculated by the spreadsheet. The minimum inner OOS characteristic (power) angle is 123º, which provides added confidence that OST decisions for other conditions will also be secure.

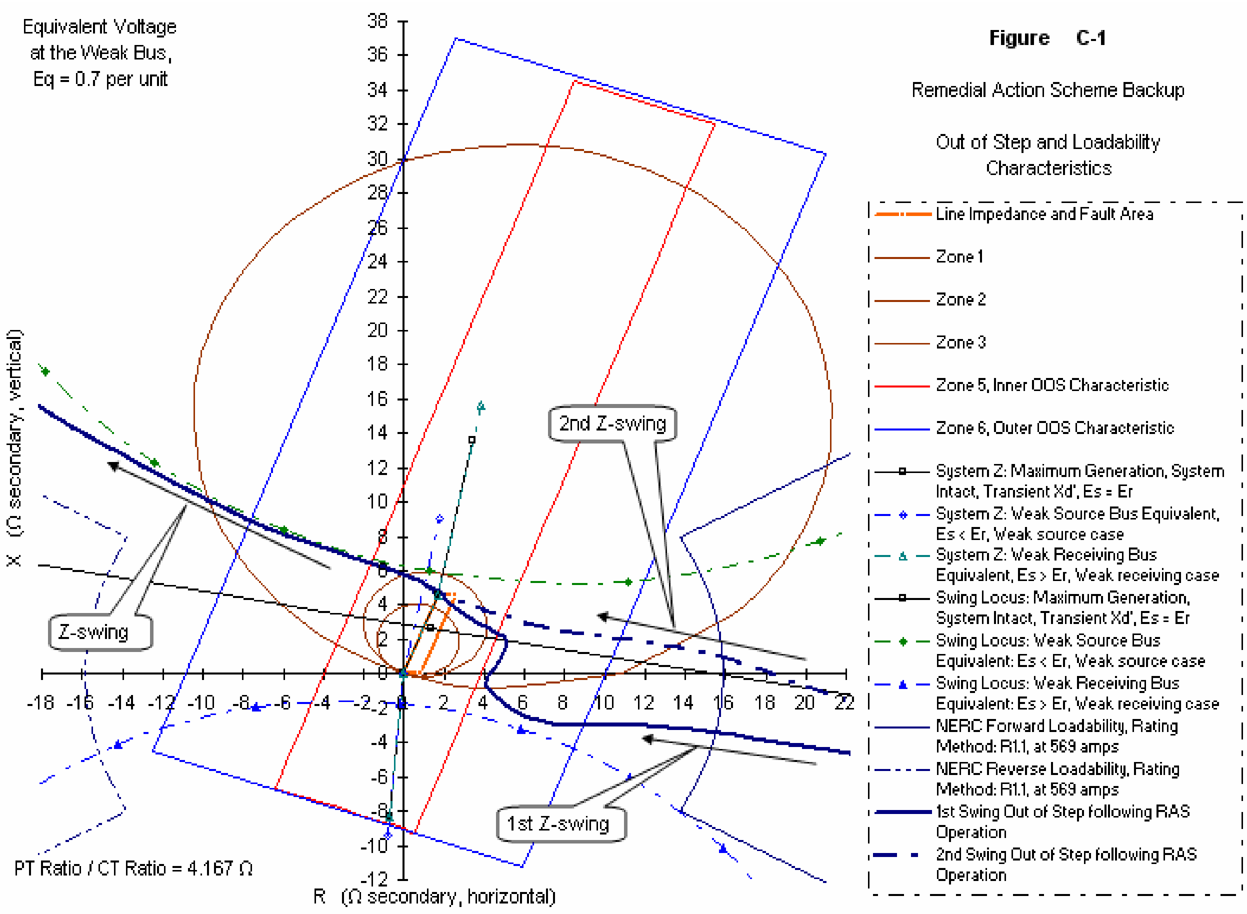

Figure C-1

Remedial Action Scheme Backup

Out of Step and Loadability Characteristics