NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Technical Reference Document

# Advantages and Disadvantages of EHV Automatic Reclosing

NERC System Protection and Control Subcommittee

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# 1. Introduction

Automatic reclosing (autoreclosing) is utilized on transmission systems to restore transmission elements to service following automatic circuit breaker tripping. The autoreclosing scheme may be high-speed or time-delayed, supervised or unsupervised. It can consist of one shot or multiple shots (reclosing attempts) depending on attributes of the transmission system in the local area and the criticality of the line for transferring power across the system and/or supplying load. Supervision may include measurement of system voltages to determine whether adjacent elements are live (energized) or dead (de-energized), and to assess the phase relationship when both adjacent elements are live.

Logic may disable the autoreclosing scheme if acceptable autoreclosing conditions are not met within a defined time duration or the logic may wait indefinitely for acceptable conditions. The latter practice may be useful for restoration following a major disturbance during which several transmission elements have been tripped, although this practice may lead to unpredictable and potentially undesired autoreclosing. When this practice is used it should be based on analysis of the potential system conditions for which autoreclosing may occur in order to manage risk to equipment.

IEEE Standard C37.104, "IEEE Guide for Automatic Reclosing of Line Circuit Breakers for AC Distribution and Transmission Lines," provides detailed information on the considerations that should be evaluated in establishing parameters for autoreclosing schemes. This paper is not intended to replicate the information in the guide, but rather to highlight some of the considerations based on observations of the August 14, 2003 Northeast Blackout.

The Blackout Recommendation Review Task Force (BRRTF) observations focused primarily on the unsuccessful reclosure of the Argenta – Battle Creek 345 kV line in south-central Michigan, which attempted to reconnect two systems that were rapidly moving apart. Recognizing the trade-offs between the risks of unsuccessful autoreclosure and the operational benefits of restoring elements to service, the BRRTF Recommendation TR-20 states that:

> "NERC should review and report on the advantages and disadvantages of autoreclosing methods on the EHV system including:
> High-speed automatic reclosing for multi-phase and single phase operation
> Synchronism check reclosing"

While the BRRTF recommendation specifically references "the EHV system," the SPCS notes in developing this white paper that several of the interesting events that occurred on August14, 2003 involved autoreclosing of 230 kV transmission lines. The SPCS also notes that autoreclosing practices on 230 kV transmission lines typically are similar to those utilized on the EHV system. Therefore, the observations and recommendations contained in this white paper are applicable to all transmission lines operated at 200 kV and above. This paper does not address reclosing practices associated with sectionalizing transmission lines to restore service to tapped loads.

This paper assesses the Argenta – Battle Creek and Argenta – Tompkins autoreclosing events in south-central Michigan as well as autoreclosing events between western New York and Ontario, New York and PJM, and reconnecting the Toledo, Ohio area to the Eastern Interconnection on August 14, 2003. The conditions under which these autoreclosing events occurred are compared against the autoreclosing logic. For each case IEEE Standard C37.104 is reviewed to assess what industry guidance is provided presently and where appropriate, considerations for additional guidance are presented.

This report discusses single-phase tripping and autoreclosing, but the SPCS has not included any specific recommendations on this subject as no events on August 14, 2003 involved single-phase operation. Furthermore, no events of the August 14 disturbance point to potential issues with installations where single-phase tripping and reclosing is used.

# 2. Significant Autoreclosing Events from the August 14, 2003 Northeast Blackout

## 2.1. Argenta – Battle Creek and Argenta – Tompkins 345 kV line Autoreclosing

The Argenta – Battle Creek and Argenta – Tompkins 345 kV lines were initially tripped at 16:10:36.203 and 16:10:36.310 respectively, by directional comparison phase relays at the Argenta terminals only. Each line then autoreclosed (high-speed) 0.5 seconds after it tripped. These lines are located in south-central Michigan as shown in Figure 2.1.1.

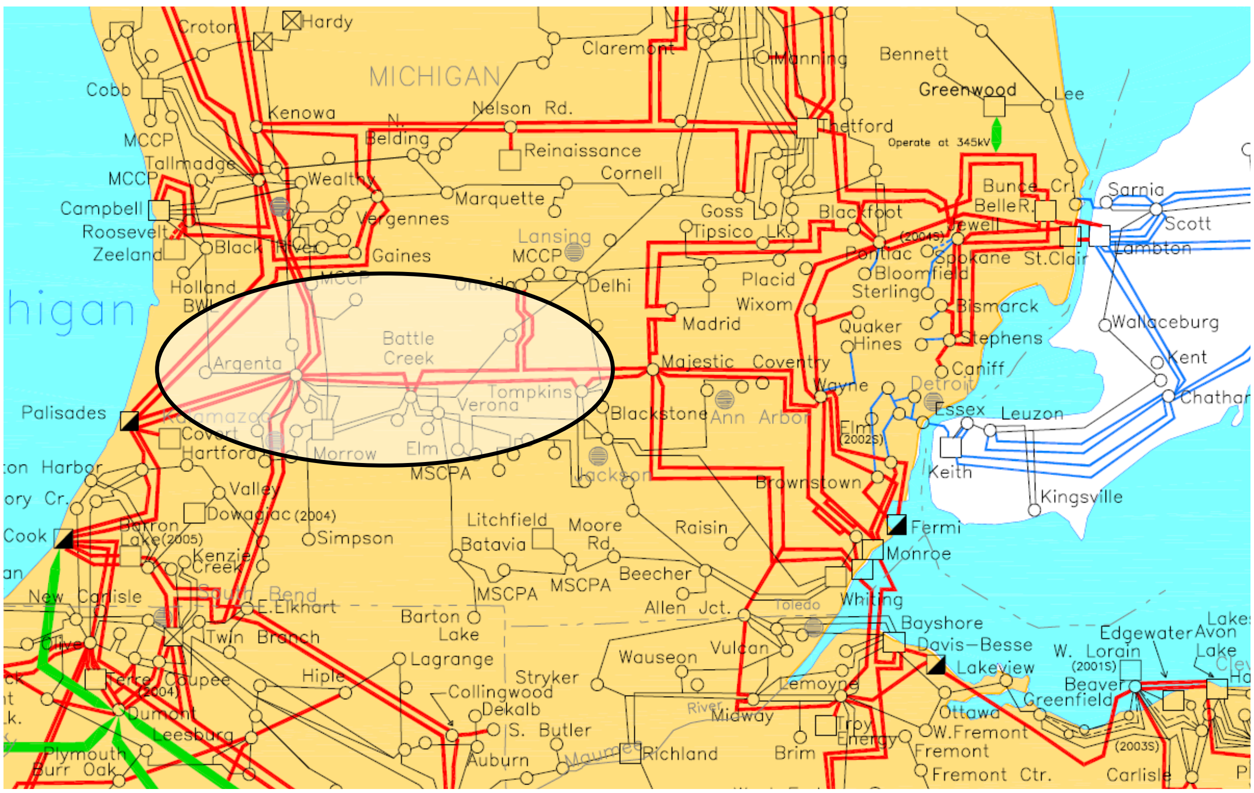


Figure 2.1.1 — Transmission System in South-Central Michigan

After the initial trips of the two Argenta lines and before the reclose attempts, western and eastern Michigan began to slip out of synchronization with respect to each other, with the angles between the voltages at Argenta in western Michigan and Battle Creek and Tompkins in eastern Michigan increasing steadily. The angle between Argenta and Battle Creek was about 15 degrees prior to the line tripping. After tripping, the angle increased to 80 degrees just prior to the Argenta high-speed autoreclosing attempt on the Argenta – Battle Creek line. The angle between Argenta and Tompkins reached 120 degrees just prior to the Argenta high-speed autoreclosing attempt on the Argenta – Tompkins line. Both of these autoreclosing attempts utilized unsupervised high-speed autoreclosing and were unsuccessful due to the large angle across the lines. The resulting apparent impedance at the Argenta terminal was within the transmission line protection high-speed tripping relay characteristic.

Dynamic simulations of the blackout suggested that the sequence of events subsequent to the Argenta 345 kV line trips is not sensitive to whether autoreclosure was attempted on these lines; the system would have separated and blacked-out either way. However, the potential for equipment damage or significant adverse impacts to system performance under other conditions warrants a review of how autoreclosing might be modified to prevent autoreclosing to reconnect two systems that are out of synchronism.

## 2.2. Ontario – Western New York Reconnection

The Ontario and western New York islands separated from each other at 16:10:50. The separation occurred interior to Ontario on the lines to the west of the Beck and Saunders generating stations. Following separation the frequency continued to decline in the under-generated Ontario island and frequency increased dramatically in the over-generated western New York island. The western New York frequency accelerated quickly to 63 Hz before being arrested by a combination of unit trips and governor actions in the local island. Five of the six nuclear units in this island tripped on this over-frequency excursion. The reconnection of the two islands occurred at 16:10:56 when three of the five 230 kV lines at Beck reclosed.

Subsequent to reconnection of the two islands, the common frequency fell below 58.8 Hz and the second stage of underfrequency load shedding was initiated in Ontario and New York. Most of the 4500 MW of load in this stage was shed at that time. With this load reduction and further governor action from the connected hydro units, the frequency recovered quickly to 60 Hz and it appeared that the frequency in the combined Ontario and western New York island system was about to settle out. During this time, however, capacitor banks in Ontario and generating units in both Ontario and New York continued to trip. The generating units in New York were tripped due to the impact of the 63 Hz excursion on internal plant control systems. The capacitors were tripped as the interior Ontario voltages peaked above 120 percent after the load shedding.

The reconnection at Beck only lasted 14 seconds before the multiple unit trips and oscillating system conditions caused the three Beck connections to trip again at 16:11:10. At this time the interior Ontario system was again generation deficient and the frequency declined. By 16:11:20, frequency was again 58.8 Hz and the remainder of the second stage of underfrequency load shedding in Ontario took place. A comparable rise in voltage was detected and more capacitor banks were tripped in Ontario to lower the voltage on the unloaded system. The amount of remaining generation was insufficient to arrest the continuing frequency decline and at 16:11:56 both frequency and voltage collapsed on the majority of the Ontario system. Beck and Saunders generation remained connected to the western New York island.

### 2.2.1. Reconnection Sequence at Beck

The five 230 kV transmission lines west from Beck utilize dead-line autoreclosing at the lead terminal after five seconds followed by a voltage-plus-time live-line autoreclose without synchronism check at the other terminal of each line. The lead terminal is at Beck for some lines and at the remote terminal for others. Synchronism check is not employed for this autoreclosing scheme. These five lines extend west from Beck toward the Middleport, Beach, and Burlington substations as shown in Figure 2.2.1.

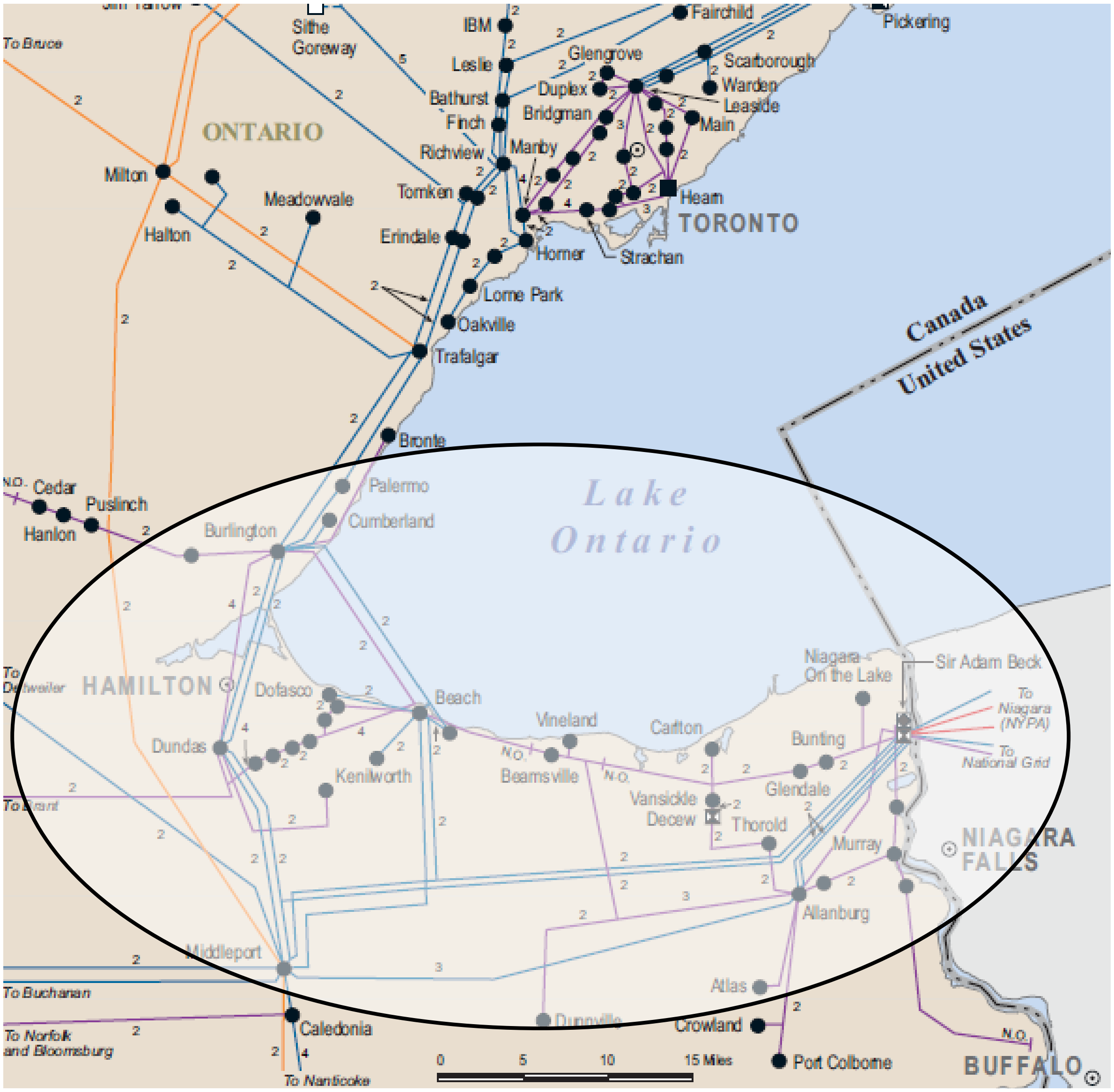


**Figure 2.2.1 — Transmission System near Beck**

The Q23BM, Q25BM, and Q29HM 230 kV lines reclosed successfully reconnecting the two islands. The remaining two lines did not reclose due to circuit breaker equipment problems that prevented the lead breaker from reclosing. The two systems were close enough to being in synchronism that the resulting apparent impedance did not cause the lines to re-trip and the two islands remained connected for 14 seconds with the resulting conditions as noted above.

Subsequent to the second separation between Ontario and western New York the Q25BM line reclosed again with the two systems operating at significantly different frequencies, resulting in a significant voltage depression and tripping of the transmission line. The process was repeated on the Q29HM transmission line 1.5 seconds later with the same result.

## 2.2.2. Reconnection Sequence at St. Lawrence

Four 230 kV transmission lines connect St. Lawrence to the transmission system in eastern Ontario; one line terminates at Hawthorne and three lines terminate at Hinchinbrooke as shown in Figure 2.2.2. All four of these lines tripped at 16:10:50.

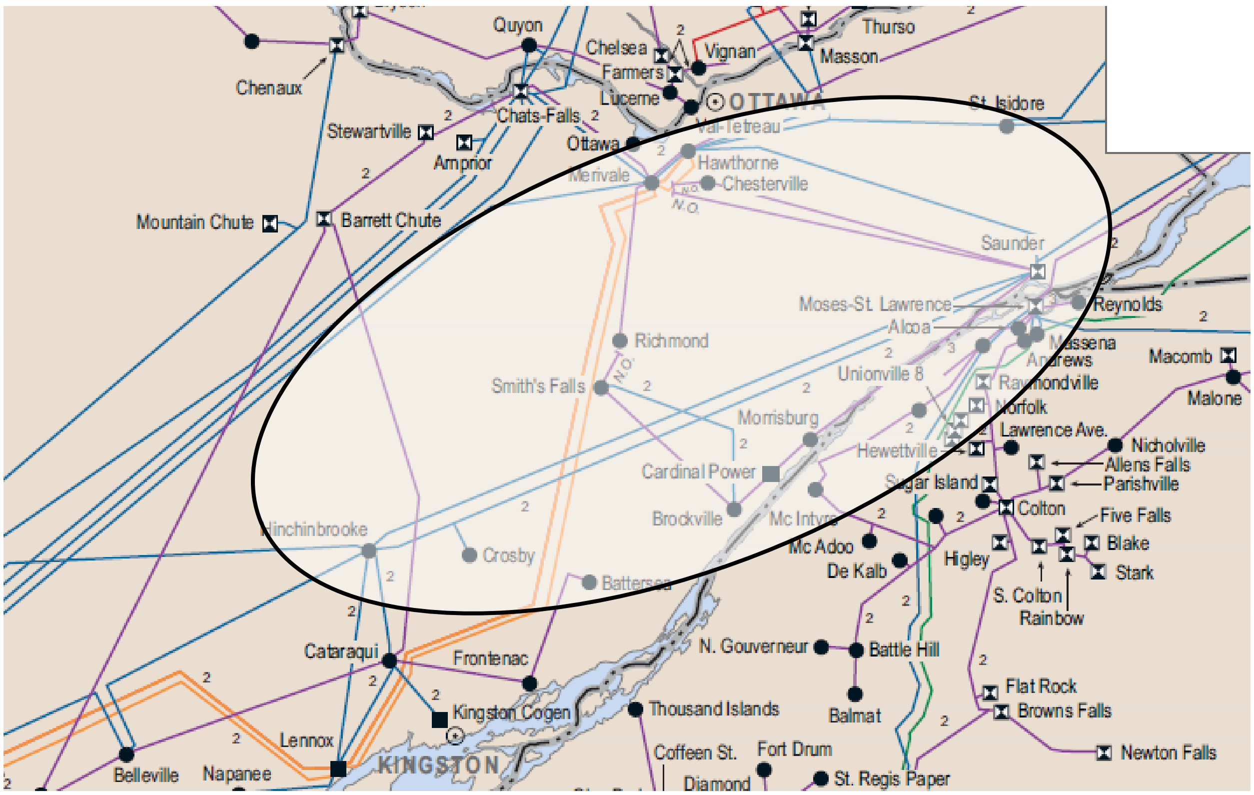


**Figure 2.2.2 — Transmission System near St. Lawrence (Saunders)**

The St. Lawrence to Hawthorne 230 kV transmission line (L24A) utilizes dead-line autoreclosing at Hawthorne after 0.5 second followed by a voltage-plus-time (0.1 second) live-line autoreclose without synchronism check at St. Lawrence. The L24A line reclosed with approximately an 80 degree angle difference between the two line terminals resulting in an apparent impedance within the zone 1 relay reach at both terminals. The line retripped instantaneously resulting in an additional disturbance to the system.

The three St. Lawrence to Hinchinbrooke 230 kV transmission lines (L20H, L21H, and L22H) utilize dead-line autoreclosing at Hinchinbrooke after 5 seconds followed by a live-line reclose with synchronism check at St. Lawrence. The L20H, L21H, and L22H 230 kV transmission lines reclosed at Hinchinbrooke at 16:10:55, but did not reclose at St. Lawrence because the angle difference exceeded the 60 degree setting of the synchronism check acceptance angle.

## 2.3. Toledo Reconnection

The Toledo area formed an island upon separation from the Cleveland area at approximately 16:10:42. The island was reenergized about 1.5 seconds later when two 345 kV circuit breakers closed at the Majestic substation in southeast Michigan, connecting transmission lines between the Toledo island at Lemoyne and Allen Junction and the southeast Michigan peninsula at Coventry. The frequency in the combined area was about 57 Hz when Toledo reconnected and continued to decline at about 2 Hz/second. About two seconds later, the combined Toledo and Lansing areas separated from Detroit as frequency began stabilizing in the western part of the peninsula but continued to fall in Detroit. The transmission system between the Toledo, Ohio area and southeast Michigan is shown in Figure 2.3.1

DFR recordings show Toledo oscillating against southeast Michigan from 16:10:46 to 16:10:53. Over that period, the frequency appeared to be recovering as load tripped on extreme low voltage and started to rebalance with resources within the Lansing/Toledo island. Voltage oscillated around 0.30 per unit at the Lemoyne station in Toledo for four seconds until Toledo reconnected to the Eastern Interconnection via Fostoria Central and East Lima in Ohio at 16:10:50. This connection was completed following autoreclosing of the Fostoria Central – Lemoyne 345 kV line at Fostoria Central at 16:10:46 and autoreclosing of the East Lima – Fostoria Central 345 kV line at East Lima at 16:10:50. At the time East Lima autoreclosed the voltage at East Lima was 350 kV and the voltage on the Fostoria Central side of the open breaker was 68 kV with a 24 degree angle difference. After the autoreclosing at East Lima the Fostoria Central voltage returned to 320 kV; however, two seconds later the Fostoria Central – Lemoyne line tripped again, severing the path to East Lima and blacking out Toledo.

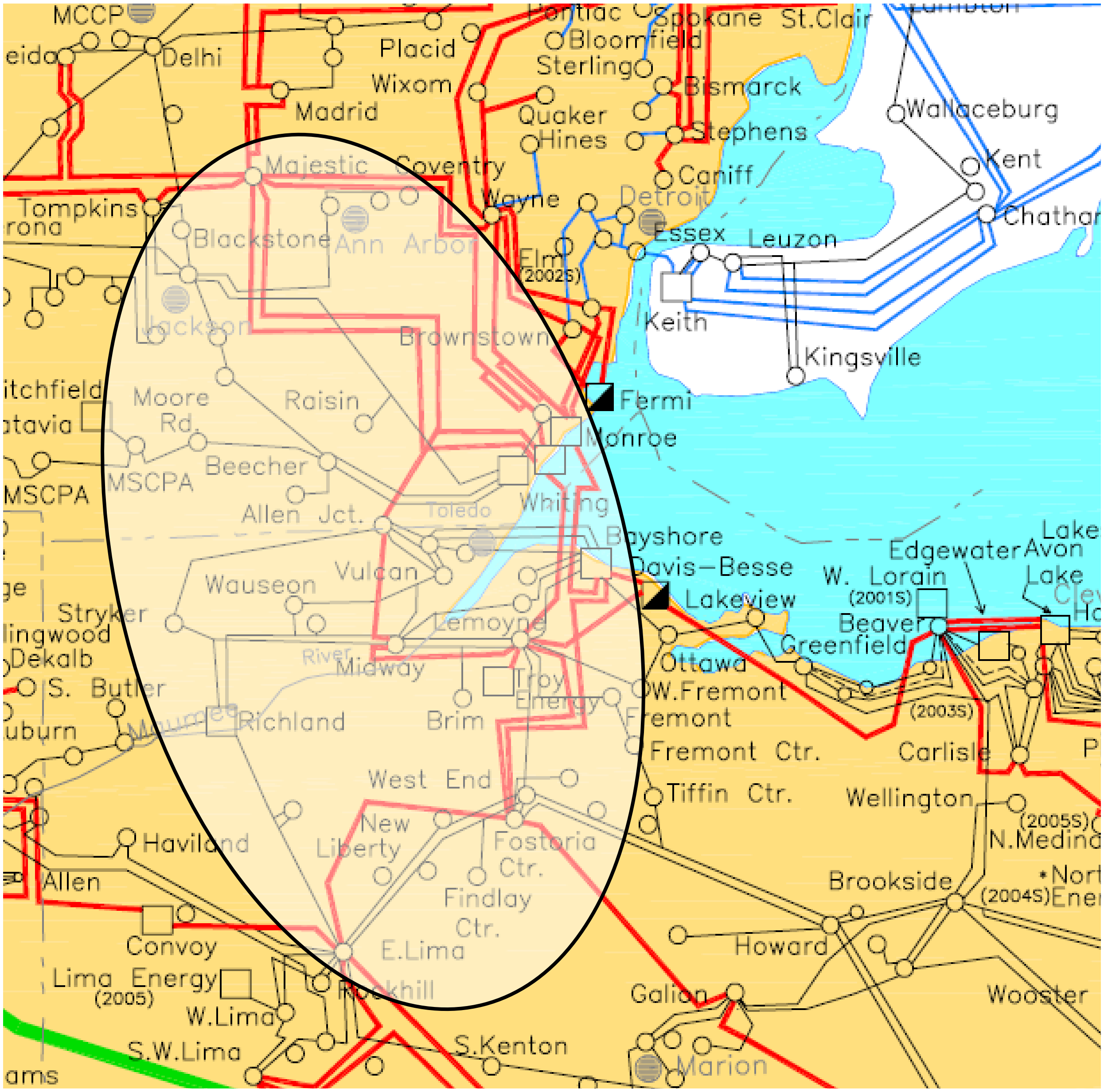


**Figure 2.3.1 — Transmission System near Toledo, Ohio and Southeast Michigan**

Finally, at 16:10:59, Toledo was again reenergized and reconnected to the Eastern Interconnection, this time via western Michigan as Argenta – Tompkins reclosed. This autoreclosing permanently energized Toledo and the Majestic Substation, connecting Toledo to Western Michigan and the rest of the Eastern Interconnection. At 16:11:08 the Fostoria Central – Lemoyne 345 kV line reclosed and at 16:11:15 Lemoyne circuit breaker 06 reclosed, connecting Toledo to northern Ohio in addition to western Michigan.

While the Toledo island was eventually restored through autoreclosing, several unsuccessful attempts were made to reenergize the island which potentially could have resulted in equipment damage or subjected additional portions of the system to unacceptable operating conditions. The sequence of events above raises questions as to whether the autoreclosing logic utilized on these transmission lines was adequate to prevent autoreclosing under undesirable conditions. While the actual autoreclosing logic in use at that time is not available it appears the East Lima – Fostoria Central autoreclose occurred through live bus-dead line logic that assumed the Fostoria Central end of the line was open; i.e. because 68 kV on a 345 kV line was below the threshold for detecting a dead line. It also is noteworthy that the southeast Michigan area was operating at 57 Hz when it attempted to re-energize the Toledo island, potentially exacerbating the system condition in this area.

## 2.4. Homer City – Watercure

Subsequent to separation between PJM and New York the Homer City – Watercure 345 kV line was closed at the Watercure terminal in New York but open at Homer City. This line had tripped at the Homer City terminal during the system separation at 16:10:39. The line reclosed at Homer City at 16:11:10 attempting to reconnect the western New York island to the Eastern Interconnection and immediately tripped at Watercure. During the time the line was closed the 345 kV bus voltage dropped to 255 kV due to the significant power flow across the line.

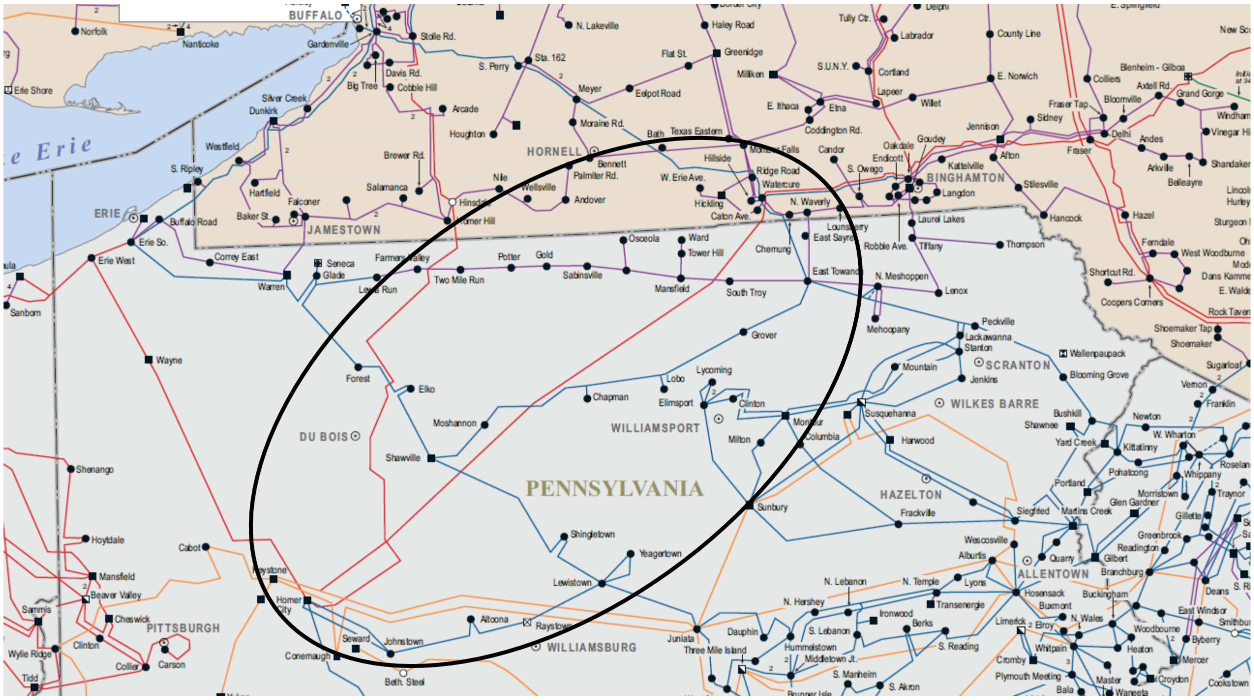


**Figure 2.4.1 — Transmission System in the Homer City – Watercure Area**

At 16:14:45, the Homer City – Watercure 345 kV line reclosed and held for about 20 seconds. The line most likely re-tripped due to power swings through the area. The Watercure – Oakdale 345 kV line interior to New York tripped concurrently with the Homer City – Watercure re-trip. The two systems had thus been tied back together briefly, but voltages pulled 180 degrees apart almost immediately after the Watercure and Oakdale breakers tripped.

Although conditions were satisfied to permit autoreclosing on this line, the system conditions would not support synchronized operation. While the actual autoreclosing logic in use at that time is not available, these events may have similar issues as the Toledo area reconnection with regard to detection of whether equipment is energized or de-energized.

# 3. Summary of Issues

The events described above exhibit a number of common attributes with regard to the conditions under which autoreclosing occurred and the potential for adverse impacts. This section discusses these attributes and potential impacts on an application basis rather than an event-by-event basis. The following applications are discussed:

- High-speed autoreclosing
- Synchronism check supervision
- Voltage supervision
- Single-phase tripping and autoreclosing

## 3.1. High-Speed Autoreclosing

### 3.1.1. Review of Issues Related to High-Speed Autoreclosing

For the purposes of this document, high-speed autoreclosing is defined the same as in IEEE C37.104: "High-Speed autoreclosing is the automatic autoreclosing of a circuit breaker with no intentional time delay beyond an allowance for arc deionization."

Advantages and Disadvantages

High-speed autoreclosing provides a number of potential benefits following temporary faults including fast restoration of system capacity and service to customers, improvement in system stability, and minimizing angular separation which, in turn, minimizes system impact upon autoreclosing. The primary disadvantages of high-speed autoreclosing are the increased impact associated with autoreclosing into a permanent fault, in particular when this occurs in proximity to generating plants, and the increased impact that may occur when reclosing between systems that are not in synchronism or are in synchronism but are far apart in phase angle.

When high-speed reclosing is used on non-radial transmission lines, standard industry practice documented in IEEE C37.104 is to apply high-speed reclosing only when high-speed tripping is installed to initiate tripping at all line terminals; and to allow its operation only when such a high-speed trip actually occurs. Typically the high-speed tripping is accomplished using some form of communication-aided scheme or line differential scheme. Utilizing high-speed autoreclosing only after high-speed tripping provides two benefits for typical system conditions:

(1) The fault protective relays clear the fault fast enough that system dynamics are minimally impacted. This ensures that the autoreclose can be carried out fast enough that the synchronizing angle changes very little and can be ignored.

(2) It ensures simultaneous initiation of the timers of the autoreclosing functions at each line terminal, and thus minimizes the probability of non-simultaneous autoreclosing that would lead to failure to clear the fault, retripping, and additional system disturbance.

As observed in the examples cited below from August 14, 2003, these benefits may not be realized under severely stressed system conditions.

Special Considerations for Series Compensated Lines

Special precaution must be taken if high-speed reclosing is used for a system with series capacitors and particularly if the line being closed has series capacitors in it. The presence of series capacitors can greatly amplify the impact of transients on nearby turbine-generators and can cause excessive loss-of-life on turbine generator shafts. Special studies such as electromagnetic transients (EMTP) are needed to evaluate such impacts and require detailed turbine generator modeling. Reclosing into a permanent fault before the original transients have decayed could be very damaging to turbine-generators. For this reason high-speed reclosing is not commonly used in series capacitor compensated systems.

Observations from August 14, 2003

IEEE C37.104 does advise that high-speed autoreclosing should not be used where the synchronizing angle may become too great. However, no guidance is given regarding the conditions under which the potential angle should be evaluated. Typically analysis of the potential angle is limited to conditions considered to be credible when applying planning or operating reliability criteria. Such conditions typically are limited to opening and reclosing the line being evaluated, with one or two other lines open. The conditions observed on August 14, 2003 exceed the worst conditions typically evaluated when establishing autoreclosing schemes.

Reclosing under such large angular separation is a major risk. Even though for this event the US-Canada Joint Task Force Report states that generators apparently suffered no damage and the NERC Major System Disturbance Task Force (MSDTF) determined that the subsequent events of August 14, 2003 would have been the same regardless of whether these high-speed reclosures occurred, autoreclosing under such system conditions would certainly not be expected to be helpful and does pose a significant risk of damage:

- Generators may be subjected to excessive shaft torques and winding stresses and resultant loss of life of the turbine generator system.
- Transmission circuit breakers may be subjected to conditions that exceed the breaker capability to interrupt current due to resultant transient recovery voltage. When a system is reclosed with excessive angular separation the apparent impedance subsequent to reclosing can be expected to fall within the tripping characteristic of the transmission line protection, resulting in initiation of a trip signal while the system is out-of-step. In the worst case, the circuit breaker may be subjected to opening while the system is 180 degrees out of phase, resulting in a 2.0 per unit voltage across the opening breaker contacts which they cannot sustain, leading to destruction of the breaker.

These events also highlight that following a line trip, a significant increase in angle between line terminals can occur in a very short time when the parallel transmission path is weak. The transient flow present after autoreclosing may be much higher than the line loading prior to opening the line, resulting in an apparent impedance that falls within the tripping characteristics of distance relays, switch–on-to-fault relay elements, and other relay elements. It may not be possible nor desirable for relay elements, even those set to the NERC loadability criteria, to avoid tripping during these transient conditions. Thus, assuring that relays do not trip due to load during stressed, but sustainable, system conditions is an important defense to avoid system separation and transient conditions that challenge the logic of autoreclosing schemes. Conversely, when system conditions are not sustainable tripping may be desirable. When tripping occurs under unsustainable or unstable system conditions it is desirable to provide logic to the autoreclosing scheme, such as using an out-of-step function to block autoreclosing following a zone 1 trip.

### 3.1.2. Recommendations

The guidance in C37.104 regarding application of high-speed autoreclosing is sound. However, the SPCS recommends that this guidance be expanded to provide additional advice regarding application of high-speed autoreclosing on lines subject to tripping during system separation. Note that the recommendations in C37.104 and in this paper apply when high-speed autoreclosing is utilized; the SPCS supports the recommendation in C37.104 that consideration of high-speed autoreclosing must recognize the risks associated with its application. These recommendations are not meant to imply a blanket endorsement for the use of high-speed autoreclosing.

The SPCS recommends that when high-speed autoreclosing is used, consideration be given to application on lines subject to tripping during out-of-step conditions that would result in system separation. Consideration should include weighing the benefits of high-speed reclosing for the typical trip and reclose sequences that occur for normal system events against the risks associated with high-speed reclosing during unusual system events, which typically are rare in comparison. When studies or actual system events identify lines that are subject to tripping during system separation, consideration should be given to adding supervision to the high-speed autoreclosing scheme. Preventing undesired high-speed autoreclosing during out-of-step conditions may prevent damage to generating and substation equipment necessary for prompt system restoration.

### 3.1.3. Potential Implementation of Recommendations

Synchronism checking relays, whether they are electromechanical induction disc types, or newer electronic or microprocessor-based reclosing relays or multifunction relays, all track the movement of voltage phasors over time. Such relays require a second or longer to determine that the voltage relationship is suitable for circuit breaker closing. They cannot measure quickly enough to supervise a high-speed autoreclosing shot.

There is a technique, not widely used in existing installations, to check voltage for a high-speed autoreclosing shot. A high-speed voltage element can be connected to measure the difference voltage between a phase conductor of the line to be reclosed and a corresponding voltage from the bus that supplies it.

When a line breaker trips, the voltage magnitude measurement across the open breaker contacts depends on the combination of voltage magnitude difference and phase angle difference between the local bus and remote source energizing the line. For a nominal system voltage of 1 per unit, an angular difference of 30 degrees, and voltage magnitudes the same on either side of the breaker, the corresponding voltage difference magnitude is slightly above 0.5 per unit.

As stated above, the allowable angle setting (actually a voltage difference setting) of this type of relay is calculated using a nominal system voltage. However, during actual operation the voltage difference (angle) measured by the relay depends on the actual voltages applied to the relay. If the actual voltages are higher or lower than the nominal voltage used to calculate the angle setting, the angle that will be deemed within the allowable synchronism-check window will be lower or higher than the calculated angle setting. For instance, at 69V and 30 degrees, the voltage difference measured by the relay is 36V. However, if both voltages measure by the relay are at 0.85x69V = 58.6V and the actual angle is 36 degrees, the voltage difference is also 36V. The allowable synchronism-check angle is widened due to lower than nominal voltages. Since picking an angle setting for synchronism check to cover any contingency is not an exact science and since this variance in angle is not too great, using voltage difference to provide a measure of the angle between two voltages provides acceptable performance for a synchronism-check application. Relay programming can be used to block reclosing with such low voltages, or to scale the difference limit to maintain the acceptance angle with low voltages.

Figure 3.1.1 below shows the polar plot of the operating characteristic for a voltage difference relay connected across the open breaker as just described, and set for 0.5 per unit. This is sometimes called a lollipop characteristic. The center of the characteristic is defined by the reference voltage phasor with a magnitude of 1.0 per unit at zero degrees. Autoreclosing would be allowed if the voltage phasor being compared to the reference voltage is anywhere within the operating characteristic. The voltage measurement function in a relatively new relay can pick up or drop out in 20 to 50 milliseconds. High-speed autoreclosing is normally performed with a line-dead time of 250 to 600 milliseconds. Thus, the voltage measuring element has time to block high-speed autoreclosing if the voltage across the open breaker is larger than 0.5 per unit. This will not inhibit high-speed autoreclosing under normal system conditions. After a high-speed trip, one end must autoreclose at high-speed; the other end performs the fast voltage check and decides whether to close.

Despite its simplicity, this measurement provides a good discriminant for supervising any autoreclosing scheme, high-speed or time-delayed. Regardless of what combination of phase angle and magnitude difference produce the total apparent voltage difference across the open breaker, the magnitude of the current that flows when the breaker closes is proportional to this net voltage difference divided by the fixed system impedance.

While the particular combination of watt and var flow after closing may vary from case to case, the net shock to the system on autoreclosing is proportional to this voltage difference.

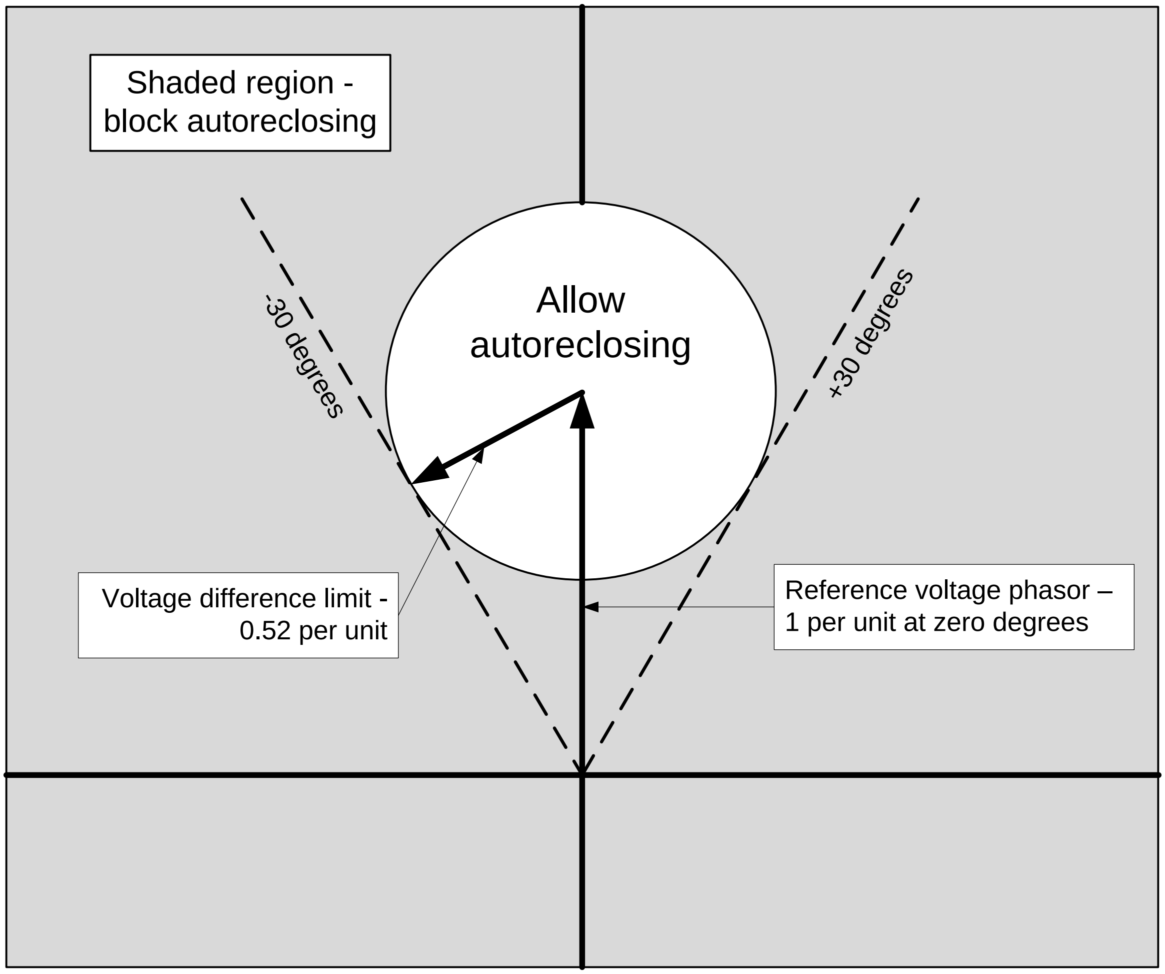


**Figure 3.1.1 — Voltage Difference Check Characteristic for High-Speed Autoreclosing Supervision**

In electromechanical or solid state line protection schemes with separate relay(s) for autoreclosing, the supervision requires an added voltage relay at one end of the line that can pick up or drop out in about 20 to 50 milliseconds. The voltage relay is connected between the voltage transformers on either side of the breaker. In applying this method, the engineer must ensure that the autoreclosing relay skips the high-speed autoreclosing shot if the closing path is blocked by the supervising relay at the moment that this shot is attempted (as opposed to allowing the autoreclosing relay to wait for acceptable voltage conditions to appear).

For newer microprocessor line relays, the implementation might be achieved with new settings. Most such relays will have some internal logic programming capability that allows the external voltage relay input to supervise the high-speed autoreclosing shot. The latest generations of multifunction microprocessor relays have analog computational capability with measurement speed suitable for this application

## 3.2. Synchronism Check Supervision

### 3.2.1. Review of Issues Related to Synchronism Check Supervision

Synchronism check is used to supervise autoreclosing between two portions of a system that are connected through ties in parallel with the path being closed. Synchronism check supervision limits the impact associated with autoreclosing under such "live-bus/live-line" conditions. The system impact resulting from live-bus/live-line autoreclosing is proportional to the angle across the breaker, the voltage magnitude difference across the breaker, and inversely proportional to the impedance in the path that is being closed. Synchronism check relay settings are based on the static angular difference as well as the magnitude difference that will be measured between the voltages on each side of an open breaker. This check is intended to ensure suitable connection and power flow through parallel system paths before the supervised breaker is allowed to close.

Synchronism check typically is utilized on EHV systems and on lower voltage systems in proximity to generation. Under some conditions it is permissible to autoreclose under live-bus/live-line conditions without a synchronism check relay because the maximum expected angle is not excessive or there is sufficient impedance in the path being closed to prevent a significant system impact.

Synchronism check is not intended to supervise autoreclosing between portions of systems that are not synchronized; i.e. when there are no parallel paths and a slip frequency exists between the systems on each side of the open breaker.

Advantages and Disadvantages

Synchronism check supervision provides the advantage that adverse system impacts can be limited by preventing reclosing when a large enough angular separation exists between two parts of the system that autoreclosing may result in equipment damage or system instability. The disadvantage of utilizing synchronism check supervision is that system restoration by autoreclosing and manual closing may be unnecessarily restricted if the synchronism check settings are too conservative.

Observations from August 14, 2003

IEEE C37.104 recommends using synchronism check relays when analysis demonstrates that for credible conditions there could be harmful effects on the system, generators, or customers due to excessive differences in frequency, voltage magnitude, or phase angles across the breaker being closed. However, no guidance is given regarding the extent to which conditions may be deemed credible. Typically the conditions evaluated are limited to application of planning or operating reliability criteria. Such conditions typically are limited to opening and reclosing the line being evaluated, with one or two other lines open. The conditions observed on August 14, 2003 exceed the worst conditions typically evaluated when establishing autoreclosing schemes.

The autoreclosing at Beck and St. Lawrence occurred between two portions of the system that were not in synchronism and the live-bus/live-line reclosing on these lines did not utilize synchronism check supervision. Reclosing under such conditions presents a significant system risk if the autoreclosing occurs when the systems are out-of-step. Even though the autoreclosing of these lines did not exacerbate the events of August 14, 2003, autoreclosing under such system conditions generally would not be expected be successful and does pose a significant risk of equipment damage and further system disturbance. It should be noted that the Beck breakers and protections were installed in the late 1950’s/early 1960’s and synchronism check supervision subsequently has been added to the autoreclosing on these lines.

### 3.2.2. Recommendations

The guidance in C37.104 regarding application of synchronism check supervision is sound; however, the SPCS recommends that this guidance be expanded to provide additional advice regarding application of synchronism check supervision on lines subject to tripping during system separation.

The SPCS recommends that when studies or actual system events identify lines that are subject to tripping during system separation, consideration should be given to adding synchronism check supervision to the live-bus/live-line autoreclosing scheme. Preventing undesired live-bus/live-line autoreclosing during out-of-step conditions may prevent damage to generating and substation equipment necessary for prompt system restoration.

Consideration should be given to assess the advantages and disadvantages of supervising live-bus/live-line autoreclosing with synchronism check for the typical trip and reclose sequences that occur for normal system events against the risks associated with unsupervised autoreclosing during unusual system events, which typically are rare in comparison.

### 3.2.3. Potential Implementation of Recommendations

Typically when two islands are separated under out-of-step conditions, the voltage and angle will not satisfy the synchronism check conditions for a sufficient period of time due to the slip frequency between the two islands. In cases for which the slip frequency is small, the synchronism check conditions may be satisfied. When this occurs it is possible that during the time between closure of the synchronism check contact and breaker closure the systems may slip enough to result in an angle across the breaker that could result in equipment damage and/or an additional disturbance to the two systems being connected.

Some modern relays measure the slip frequency between two islands and provide conventional synchronism check for static conditions when the slip frequency is below a user-defined threshold setting, and also prevents autoreclosing when the slip frequency exceeds a user-defined setting.

## 3.3. Voltage Supervision

### 3.3.1. Review of Issues

Voltage measurements typically are used to determine the status (live or dead) of the system on each side of a breaker to supervise autoreclosing. This supervision can be used to facilitate lead/follow autoreclosing in which one (lead) terminal energizes a dead transmission line and the other (follower) terminal(s) autoreclose after the line remains re-energized, to minimize the impact of reclosing into a permanent fault. It also can be used to protect against equipment damage resulting from autoreclosing in the presence of trapped charge or large motors on a disconnected line or portion of the system.

Voltage supervision may be based on single-phase or multi-phase measurements. Three-phase measurement provides the highest level of reliability and is recommended when potential devices are available on each phase.

Advantages and Disadvantages

The primary advantage of voltage supervision is to supervise lead/follow reclosing to protect the system or specific equipment from the impacts of reclosing into a permanent fault. Autoreclosing into a permanent fault may result in significant shaft torque on generating units or subject large power transformers to heavy through fault current. When autoreclosing is utilized near such equipment voltage supervision may be utilized to prevent autoreclosing into a dead line, instead establishing a remote line terminal as the lead terminal.

The primary disadvantage of voltage supervision is the time required to determine the status on each side of the breaker. The time required to determine the status on each side of the breaker to be reclosed is not a concern with time delayed reclosing (typically 1 second or more) and as discussed above in Section 3.1.3 it is possible with modern protective relay systems to utilize voltage supervision even with high-speed autoreclosing. A secondary concern is the possibility of incorrect status determination due to a blown fuse or unusual conditions in which a line is energized at abnormally low voltage. However, this concern can be managed in cases where voltage supervision is desirable. The risk associated with an incorrect status typically is less than the risk of not using voltage supervision.

Observations from August 14, 2003

On August 14, 2003, several lines autoreclosed under abnormal system conditions for which both line terminals were live, yet live-bus/dead-line reclosing logic saw the line as dead and initiated autoreclosing. In the worst case condition the East Lima – Fostoria Central 345 kV line autoreclosed with 68 kV at the Fostoria Central terminal. Similar conditions may have resulted in undesirable autoreclosing between the New York and PJM systems on the Homer City – Watercure 345 kV line. Autoreclosing under such undesirable conditions can contribute to propagating a major disturbance or impeding system restoration by collapsing a healthy portion of the system by tying it to a weakened or collapsing portion of the system.

### 3.3.2. Recommendations

Modern reclosing relays provide voltage threshold settings to determine if system elements are live or dead. Separate settings are available for minimum voltage of a live element, versus a lower maximum voltage setting for a dead element. If a voltage on either side of the breaker should fall between these two thresholds, the power system condition is indeterminate and autoreclosing is not allowed.

In general it is advantageous to select a live voltage detector threshold that is high enough to ensure that a disconnected element is not assumed to be live due to trapped charge on a cable or capacitor bank or induced voltage from a parallel transmission line in the same right-of-way, but low enough to ensure that an energized element is determined to be live for any abnormal, but sustainable system conditions for which reclosing would be advantageous. The SPCS has previously considered appropriate voltage thresholds for relay loadability and for applying switch-on-to-fault (SOTF) protection in coordination with autoreclosing live and dead voltage detector settings.

Live-bus and live-line voltage detectors should be set at or below the lowest system voltage for which automatic reclosing is deemed desirable on a stressed system. As with PRC-023-1, the standard for transmission relay loadability, this white paper will define a stressed system condition as a bus voltage of 0.85 per unit. This is not a worst case voltage, but a voltage that was observed on August 14, 2003 at many buses before the cascade portion of the blackout. It appeared in a time frame during which automatic action to return the power system to within limits was quite possible. Thus a setting in the vicinity of 0.8 per unit is appropriate and not unusual.

Dead-bus and dead-line detectors should be set as low as possible, but also should be set high enough to ensure that a disconnected element is determined to be dead even in the presence of trapped charge on a cable or capacitor bank or induced voltage from parallel transmission line in the same right-of-way. Dead-line reclosing voltage supervision is often set as low as 0.2 or 0.3 per unit, but in some cases may need to be set significantly higher.

It is important to note that considerations for setting live and dead voltage detectors, including personnel safety, equipment protection, reclosing under desirable conditions, and preventing reclosing under undesirable conditions, may lead to conflicting criteria. When this occurs it should be clear that protecting personnel and equipment have the highest priority.

# 3.4. Single-phase Tripping and Autoreclosing

## 3.4.1. Review of Issues

Single-phase tripping (also known as single-pole tripping) and autoreclosing may be utilized on transmission lines to improve system stability for single-phase-to-ground faults. By tripping only the faulted phase, approximately half the power transmitted prior to the fault can be transmitted on the two remaining phases, reducing the angular separation between portions of the system and the torque impact on generating unit shafts upon reclosing. Single-phase tripping in North America is mostly used in long EHV transmission corridors where circuit breakers with independent tripping and closing mechanisms are available and phase spacing reduces the probability of multi-phase faults. For some longer lines, special system grounding schemes are needed to control induced voltage on the tripped phase and allow the fault arc to extinguish. In any case, if one shot of single-phase tripping and reclosing is unsuccessful, all three phases are tripped to avoid sustained unbalanced current flows in the system.

Advantages and Disadvantages

The primary advantage of single-phase tripping and autoreclosing is to improve system stability and mitigate impact on system equipment upon reclosing following transient single-phase-to-ground faults.

The primary disadvantage of single-phase tripping and autoreclosing is the additional cost and complexity associated with such a scheme. While the complexities are not overwhelming, a large number of issues must be considered to ensure that utilization of single-phase tripping and autoreclosing does not result in a negative impact on system reliability. These considerations include:

- The protection system must be capable of differentiating between single-phase and multi-phase faults and be capable of detecting faults on the two in-service phases during the interval between tripping and reclosing the faulted phase.
- The protection system must be able to reliably identify the faulted phase for a single-phase-to ground fault. Modern current differential relays handle this need well. With all other line protection schemes high fault resistance, source impedance variations, and fault location can conspire to confuse one line terminal and lead to three-pole tripping.

- The reclosing scheme should include longer autoreclosing dead time intervals for single-phase faults with single pole tripping versus multi-phase faults with three-pole tripping to account for the longer arc deionization time resulting from induced voltage from the two energized phases.
- Protection systems on adjacent elements must be coordinated to prevent tripping on unbalanced currents observed during the interval between tripping and reclosing the faulted phase.
- Studies must be performed to ensure acceptable transient overvoltages and negative sequence current with one pole open.
- Studies may show that additional equipment, such as a set of grounding reactors, be installed at a terminal of a long line to control open-phase conductor voltage.
- The circuit breaker must have three independent poles.

The first three protection requirements are handled by features included in contemporary microprocessor multifunction transmission line relays.

Observations from August 14, 2003

There were no events on August 14, 2003 that involved circuits on which single-phase reclosing is utilized. Only the first few 345 kV line trips in Ohio involved transmission line faults. These faults involved tree contact and the autoreclosing would have tripped to lockout regardless of whether three-phase or single-phase tripping and reclosing was utilized. The remaining line protection operations were a result of protection systems tripping under load or power swing conditions. These conditions are positive sequence phenomena and would have resulted in tripping all three phases regardless of whether single-phase tripping was utilized. Thus, for the conditions observed on August 14, 2003, single-phase tripping and autoreclosing did not contribute to the sequence of events nor would single-phase tripping have provided any system benefit in stopping or limiting the cascade.

### 3.4.2. Recommendations

The SPCS believes the industry guidance and expertise within entities that utilize single-phase tripping and autoreclosing is sound. No action is required in consideration of blackout experience.

# 4. Conclusions

Autoreclosing schemes are an important element of transmission system protection. Most industry guidance on the application of autoreclosing schemes has focused on normal system conditions and stressed operating conditions for which the power system is designed. Performance of autoreclosing schemes during abnormal operating conditions observed during major system disturbances such as the August 14, 2003 Northeast Blackout provide reason to review the extent to which abnormal conditions should be considered in applying autoreclosing schemes. The SPCS believes the industry guidance for application of autoreclosing in IEEE C37.104 is sound, but has highlighted a number of areas for further consideration. Specifically, the SPCS has focused on three primary recommendations:

- Evaluate high-speed autoreclosing applications when applied on lines subject to tripping during out-of-step conditions that would result in system separation. When studies or actual system events identify lines that are subject to tripping during system separation, consideration should be given to adding supervision to the high-speed autoreclosing scheme.
- When studies or actual system events identify lines that are subject to tripping during system separation, consideration should be given to adding synchronism check supervision to the live-bus/live-line autoreclosing scheme. Preventing undesired live-bus/live-line autoreclosing during out-of-step conditions may prevent damage to generating and substation equipment necessary for prompt system restoration.
- Live-bus and live-line voltage detectors should be set at or below the lowest system voltage for which automatic reclosing is deemed acceptable on a stressed system. This paper recommends a setting in the vicinity of 0.8 per unit, and not greater than 0.85 per unit. Dead-bus and dead-line detectors should be set as low as possible – often at 0.2 to 0.3 per unit, but also should be set high enough to ensure that a disconnected element is determined to be dead even in the presence of trapped charge or induced voltage from a parallel transmission line in the same right-of-way.

Consideration of the recommendations should include weighing the benefits for the typical trip and autoreclose sequences that occur for normal system events against the risks associated with unusual system events, which typically are rare in comparison.

# APPENDIX A – System Protection and Control Subcommittee Roster

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