
Considerations for **Transmission Reclosing Practices** In the MRO Area

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Introduction

Many faults that occur on overhead electrical systems are temporary in nature. As such, auto-reclosing can be used to effectively restore the system. This paper will address transmission reclosing practices only. Distribution reclosing will not be addressed. (Transmission designated voltage levels will vary in different electrical Utilities.)

There are various reasons for reclosing a line. It is imperative to have input and guidance from Planning and Operational groups to determine the appropriate reclosing practices for a particular Utility and Region. The following are some of the major considerations for transmission level reclosing:

- System Stability.
- System Security.
- Continuity of service.

Reclosing can be either unsupervised high speed or time-delayed, supervised by voltage/sync elements. The decision as to which to apply must weigh the benefit and consequences of each to determine the acceptability of the risk in the particular application.

Reclosing on non-critical lines, as previously determined by the Planning groups, may vary depending on protection philosophy and equipment applied.

According to a paper presented by Gerard Gustafson of Basler Electric Company at the 27th WPRC, October 23 -26, 2000, ^[1] automatic reclosing was first applied in the early 1900s on radial feeders protected by instantaneous relays and fuses. (IEEE PRSC 1984 ^[2]). This application was similar to the actions provided from various types of reclosers used on the lower voltage feeders of today. The paper also states Jackson et al ^[3] reported that the first high speed automatic reclosing (HS A/R) was used by America Electric Power System (formerly known as American Gas & Electric at the time this was applied.) This was implemented to reduce the necessity to construct additional transmission lines. HS A/R was required mainly to maintain system stability rather than the continuity of the power supply. (High speed auto-reclose is defined as unsupervised reclose within 1.0 second of tripping.)

Present Practices

Practices vary among utilities in the MRO. Reclosing practices also vary depending on voltage levels and the type of line considered. Some companies auto-reclose for all faults and only block on loss of communications. Some utilities reclose if the speed of clearing is fast enough, independent of the fault configuration. Some allow high speed auto-reclose (HS A/R) only for l-g faults and block reclose for any multi-phase faults. Others allow HS A/R for phase to phase and l-g faults but not three phase faults. Still others allow reclosure for all types of faults. In many instances the later is a legacy design from when the relays were only designed to allow or not allow HS A/R for all fault configurations.

System stability is a determining factor on whether high speed auto-reclose is attempted. This includes concerns with reclosing too slowly and concerns that the system will enter instability if reclosed back onto a faulted line. In situations where reclosing onto a faulted line does not

impact the stability of the system, multi-shot reclose attempts may be possible. In this case, the restoration of the line is required more for load continuity to the customers. However, the breaker duty cycle must be considered when high speed multi shot reclosing is applied. The breaker should be de-rated if the multiple recloses do not have sufficient time between. If the interval is less than the required time, the breaker needs to be de-rated.

Breaker Duty Cycle and Interrupting Capability:

The standard duty cycle for a circuit breaker is a close-open operation, a dead time of 15 seconds or 0.3 seconds; and another close-open operation. This is defined in IEEE Std. C37.04-1999 clause 5.8.

Breaker Duty Cycles Wait Times			
	Post 1st Open	Post 1st Close/Open	Post 2nd Close/Open
Breaker Speed	(Seconds)	(Minutes)	(Final State)
Slow Reclosing	15	3	Open
Rapid Reclosing	0.3	3	Open

Table 1.0

-Effect of autoreclosing on interrupting rating

Autoreclosing duty cycle	Duty cycle characteristic applied	Reclosing relay delay settings	Modified interrupting rating (kA)
CO + 5 s + CO	b	R _{T1} = 5	37.31
CO + 20 s + CO	None	R _{T1} = 20	39
CO + 5 s + CO + 15 s + CO	a and b	R _{T1} = 5	34.78
		R _{T2} = 15	
CO + 5 s + CO + 15 s + CO + 30 s + CO	a and b	R _{T1} = 5	32.24
		R _{T2} = 15	
		R _{T3} = 30	
CO + 0 s + CO + 10 s + CO + 30 s + CO	a and b	R _{T1} = 0	30.55
		R _{T2} = 10	
		R _{T3} = 30	
CO + 15 s + CO + 15 s + CO + 30 s + CO	a	R _{T1} = 15	33.93
		R _{T2} = 15	
		R _{T3} = 30	

Table 2.0

Where: For a typical 39 kA interrupting capability rated breaker

“CO” – Close Open

“a” - is set for more than 2 operations.

“b” – the time interval between operations is less than 15 seconds.

The interrupting capabilities of oil and air magnetic circuit breakers are de-rated for other duty cycles. The breaker de-rate is defined in IEEE Std. C37.010-1999 clause 5.9.

The following chart shows the success rate of the 1st, 2nd and 3rd reclose attempts. As this chart shows, the first attempt has the best success rate by far. ^[4]

Reclose Success Rate for Successive Multiple Reclosures	
Reclose Attempts	Success Rate
1st	90%
2nd	4%
3rd	1%

Table 3.0

The practices within the MRO groups are so varied that it is not possible to select one or two particular methods that would meet every need of all the groups. This paper proposes the following based on technical system criteria that will best fit the application anywhere in the MRO.

Transmission Lines:

- For 500 kV lines, only lines to ground faults are candidates to allow high speed auto-reclose.
- High Speed Auto Reclosing (unsupervised) should be applied where it supports System Stability or if load continuity is a concern.
- Reclosing on a non critical transmission line should be performed at one end first by Live Bus/Dead Line. The other end(s) should be reclosed through synchronizing equipment.
- Reclosing on transmission lines near generation must consider the impact on machine shaft torque as well as system stability. If possible, utilize 10 second or longer delayed reclosing at the remote terminal to limit interaction with shaft oscillations and only reclose through sync check at the generation terminal. ^[11]
- Where system stability is a concern, the line may be tripped single phase and high speed auto-reclosed. (Unbalance affects on zero sequence protection may require some evaluation by the applicant.) All multi phase faults should trip three phase and consideration should be given to blocking auto-reclosing.
- High speed auto-reclose should only be applied for high speed trips in communications aided zone two trips for stability critical and load sensitive lines. High speed auto-reclosing should be disabled or blocked for loss of communications. Lines that do not use communications schemes should be reclosed through synchronizing or voltage supervision. (The speed of clearing has a significant affect on the rotor angle of the generators). The faster that the fault

is cleared the more time is available to provide more retarding torque to bring the rotor angle back into synchronism when the line is reclosed. (See the following Power Transfer curves that show the affects of a fault, clearing successful reclosing. Figures 1, 2 and 3.)

- The equal area criteria is used here to determine the impact to the system based on the speed of fault clearing and the duration before successfully reclosing or the impact of an unsuccessful reclosure. Figure 1^[5] shows the affects of a three phase high speed trip and auto reclose on the system. The power stability curve represents a single line between two systems where a double line to ground (2LG) fault occurred. The figure shows that the mechanical power and electrical power are operating at 0.9 p.u. at angle δ_0 when a 2LG fault occurs and the power output drops to the 2LG curve. The rotor angle between the generator and the system pull apart due to the mechanical input power exceeding the electrical output power. The breaker opens at δ_1 . All the power now goes to accelerating the generator rotor and the system slows down from the loss of generation versus load. From δ_1 to δ_2 the circuit is open and there is zero power transfer across the line. The line recloses at δ_2 and the power transfer theoretically goes back to the higher power transfer curve. The inertia of the generator continues to increase the rotor angle and hopefully slows down from the retarding torque before the critical angle at δ_3 . If the area in the shaded region 2 is equal or greater than the area in region 1, the system will return to a stable operation.

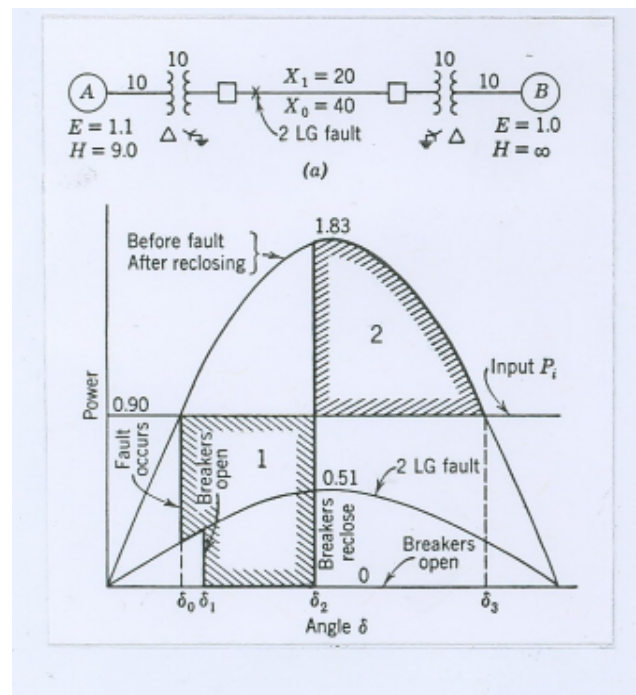


Figure 1

- The second graph, Figure 2,^[5] shows the affect when there are two lines in parallel with the faulted line trips high speed and recloses. The mechanical power into the system can be higher due to the capabilities of the system to handle the extra power produced. In this case the mechanical power is balanced by the electrical power produced at 1.61 p.u. At the point of fault and angle δ_0 the 2LG faults and the power output drops to the lower 2LG 0.61 p.u.

curve. The angle moves to δ_1 due to the mechanical power exceeding the power transferred across the system. At angle δ_1 the breakers open and the power is now transferred through the parallel line and moves up to the 1.83 curve. The rotor angle continues to increase to angle δ_2 when the line recloses and the power transfer overshoots to curve 2.20 p.u. Again the rotor angle continues to increase until the retarding torque slows the rotor before it reaches the critical angle at δ_3 . In this case if the combined region of 2 and 3 are equal to or greater than region 1 the system will remain stable.

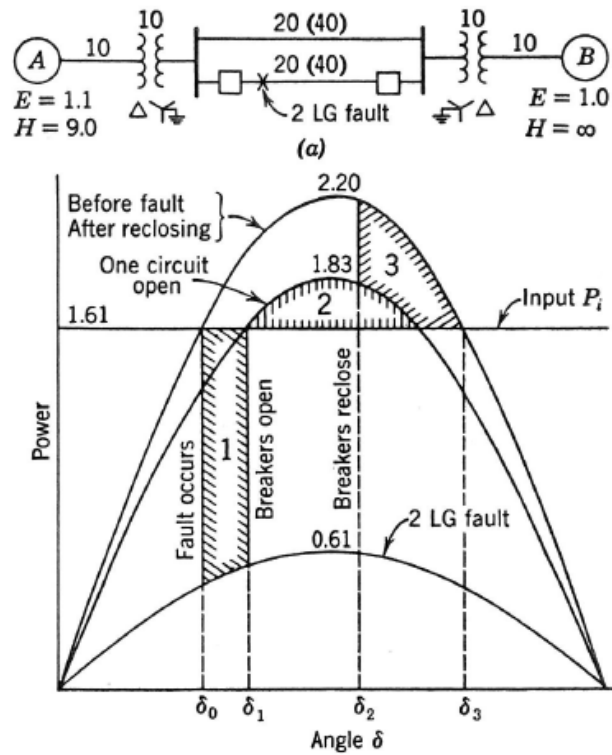


Figure 2

This above Figure 2 ^[5] demonstrates the affects of high speed auto reclosure for a two line configuration. The same analysis can be performed for single phase high speed tripping and auto reclosure.

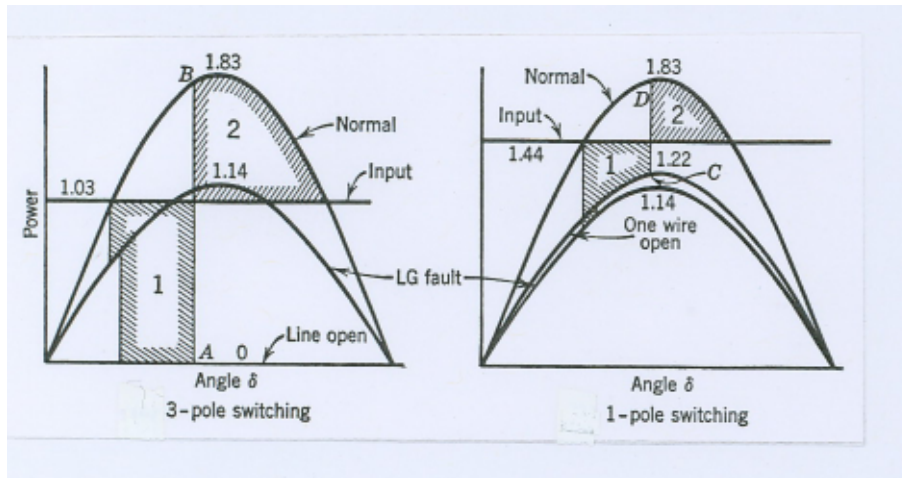


Figure 3

Figure 3 ^[5] illustrates the affects of single phase (1 – pole) to three phase (3 - pole) switching. As can be seen the single phase switching scheme allows a significantly greater power transfer capability as shown by the 1.03 p.u. for three phase switching compared to the 1.44 p.u. for the single phase switched line. The system is more stable as the fault on the single phase switched line only drops the power transfer to the 1.14 curve during the fault and recovers to the 1.22 p.u. curve when the single phase opens. The overall system angular change is much less than seen in the three phase switched case.

- High speed (≤ 1.0 seconds, unchecked) auto reclose should be blocked for loss of communications and timed trips. Loss of potential (fuse failure) to distance relays , switch onto fault trip, power swing trip, breaker failure transfer trip received from remote and multi-phase faults are other conditions when auto reclose should be blocked for either supervised or unchecked auto reclose. Auto reclose should always be blocked for manual trips and transfer trips.
- The most common practice is to provide single shot auto-reclose at transmission voltages 100 kV and above. Some companies perform multiple shot reclosure between 100 kV and 200 kV.
- The surge impedance or characteristic impedance of a transmission line is independent of the line length. Surge Impedance Loading is the point where the power flow balances the shunt capacitive reactive power flow down any line balances the shunt capacitive reactive power produced with the series inductive power consumed. At Surge Impedance Loading, the voltage profile across the entire line is constant (flat). The loading on short EHV and UHV lines can be up to 3 times the Surge Impedance Loading (SIL). The St. Claire curve (Figure 4) ^[6] derived from empirical studies illustrate a non linear relationship between maximum loading of a transmission line and the length of the line. It shows that the line will carry 3 times Surge Impedance Loading (SIL) at 50 mi (80 km) and 1 times SIL at 300 mi (480 km). The St. Claire curve is dependent on the voltage level which is defined by the Surge Impedance of the line.

- The following is the expression for surge impedance SI or characteristic impedance of a line.

$$SI = \frac{V}{I} = \sqrt{\frac{L}{C}}$$

- When transmission lines are loaded above surge impedance loading, the remaining system should be studied extensively to determine if it can handle this loss of the heavily loaded line. Consideration should be given to the underlying subsystem to ensure that the relays will not trip due to the “Skip Loading” from the loss of the EHV or UHV transmission lines. As table 4.0, “Typical Transmission Line Characteristics” shows, the Surge Impedance Loading capabilities of a line are proportional to the square of the voltage and inversely proportional to the surge impedance of the line. Therefore, the higher the system voltage, the greater the impact due to “Skip Loading” will be on the subsystem. Loss of a 345 kV, 500 kV and 765 kV line will result in increasingly larger amounts of power flow in the subsystem. High speed reclosing on a heavily loaded line with high reactive losses may help maintain voltage stability and system stability.
- Lines that end in a transformer shall not reclose for transformer faults. These lines should trip three phase at both ends. Unsupervised reclosing should only be permitted if no transformer protection has operated or the transformer has been isolated.
- High speed or unsupervised auto-reclosure should not be applied on radial lines with generators connected. Cumulative torsional stresses on the generator rotor shaft may result in premature rotor failure.

- On 500 kV and higher voltage lines, phase and neutral reactors should be considered to reduce fault levels and provide arc quenching to assure a higher probability of successful auto-reclosure.

St. Clair Curve:

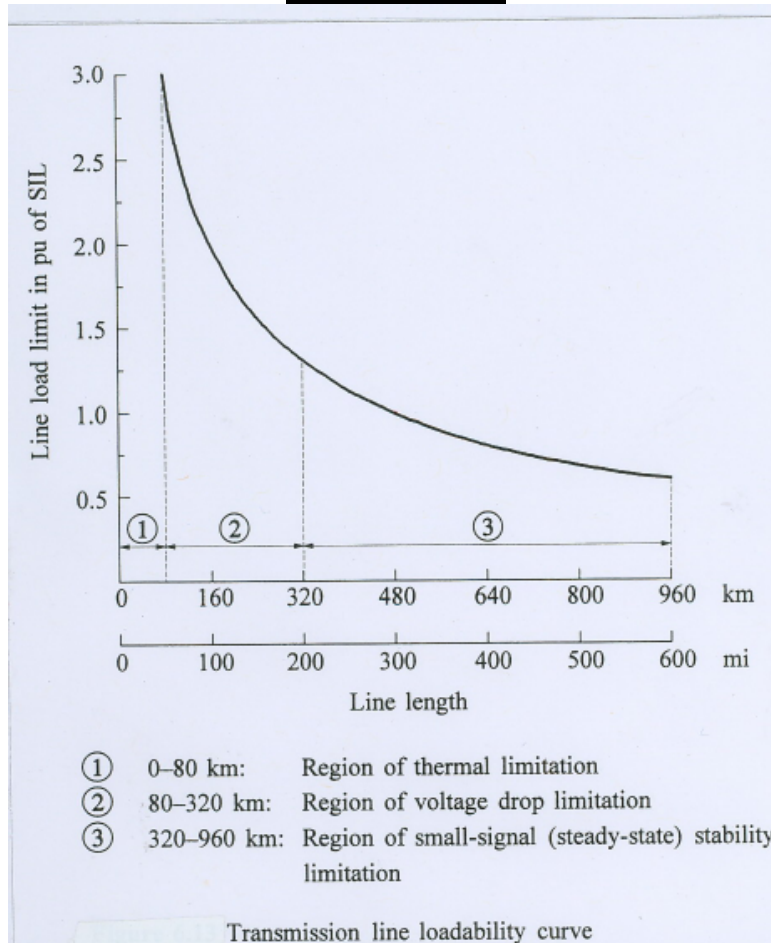
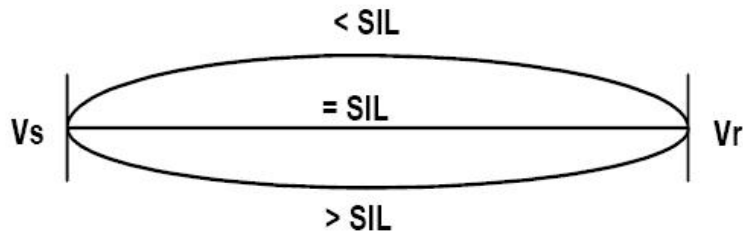


Figure 4

The following is a drawing illustrating voltage profile across transmission lines for SIL, < SIL and > SIL values chart defining the Surge Impedance for various voltage levels along with a chart showing the Transmission Line Characteristic for various voltage levels.



Typical Transmission Line Characteristics						
Voltage	SI	R	X	Charging	SIL	X/R
(kV)	(Ohms)	(Ohms/km)	(Ohms/km)	(kVAr/km)	(MW)	
69/72	370	0.4	0.5	15	13/14	1.2
138/144	370	0.2	0.5	70	50/55	2.5
230/240	340	0.07	0.45	225	170	6
230/240 bundled	300	0.07	0.4	290	180/195	6
345 bundled	285	0.026	0.365	525	415	14
500 bundled	250	0.018	0.345	1340	990	20

Table 4.0

Line Dead Times on Transmission Lines:

Line dead times should be determined by the System Planning Studies. For three phase trips, the line dead time should be from 20 to 30 cycles depending on the system capabilities of the system. For single phase trips, the line dead time should be 45 to 60 cycles depending on system capabilities. High speed automatic reclosing (HS A/R) or unchecked reclosing should be applied only where system stability or critical load continuity is a priority. The duration depends on the amount of time for the ionized air in the fault path to recover the insulation value to prevent re-strike on re-energization of the line. The deionization time is dependent on voltage, conductor spacing, magnitude of the fault current and the atmospheric conditions. (Westinghouse Electric Corporation^[9]). (This longer line dead time is required to allow the air to recover the dielectric insulation strength which is sustained by the secondary arc from the zero sequence coupling from the other two connected phases. If the ratios of the power (or primary) arc current to secondary arc current ≥ 50 , the arc extinction should be successful. (However, there have been cases where ratios of 25 and even 15 were successful.) This time could be less, depending on the ground return impedance values.^[8])

The following empirical formula can be used to determine the minimum time to de-ionize the air at the location of the fault:

$$t = 10.5 + \frac{V_{LL}}{34.5}$$

Where: t = time in cycles
 V_{LL} = rated Line to Line voltage in kV

This equation is a straight line approximation of the measured values.

kV	De-ionization Time (Cycles)	De-ionization Time (msec.)
34.5	11.5	191.67
115	13.8	230.00
138	14.5	241.67
230	17.16	286.11
345	20.5	341.67
500	24.99	416.55
765	32.67	544.57

Table 5.0

See Figure 5 below for the empirical formula was derived from.

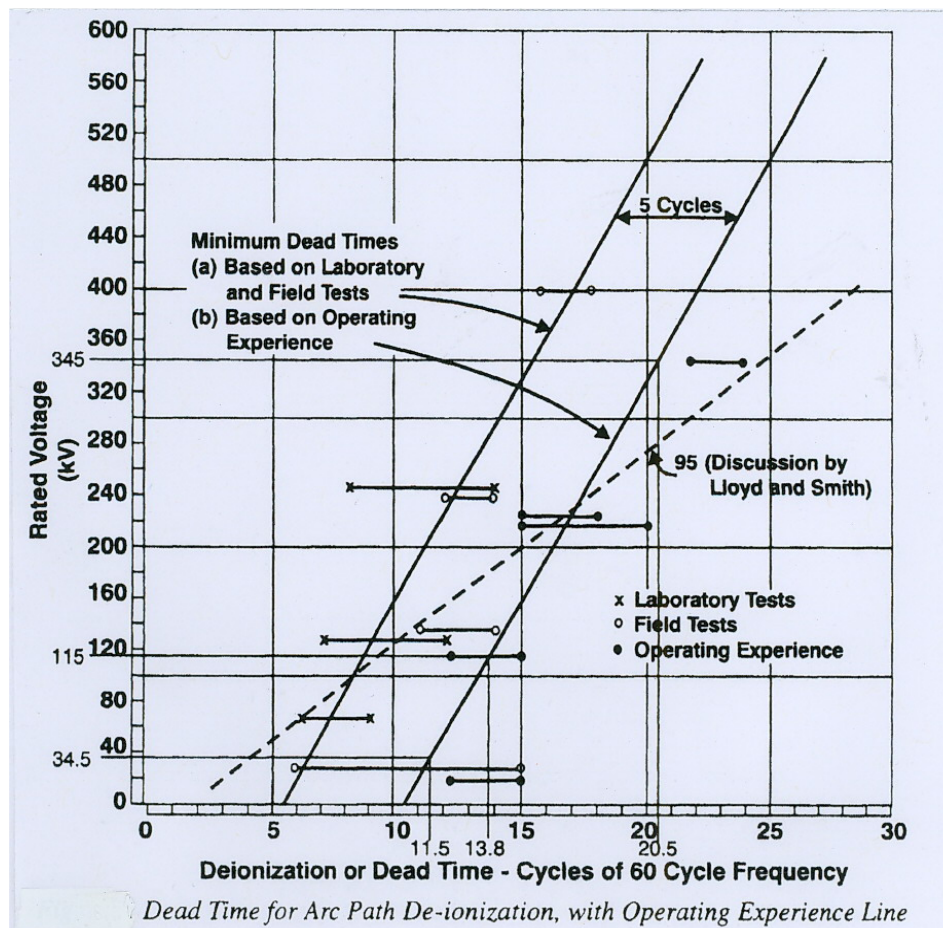


Figure 5

The above equation is depicted by the (b) regression line based on operating experience

These values may be longer where mutual coupling from adjacent lines or zero sequence coupling from the two remaining phases for a single phase trip. In addition, this dead time should be as long as possible, within stability limits of the system where high speed reclosing is applied. If a fault occur during this dead time, the line should trip three phase and block reclose.

During reclose after an initial fault, zone 1 extension may be used, to ensure fast clearing of a fault occurring anywhere along the line up to 100 % of the line from either end during the high speed reclose attempt. This can be achieved by extending the zone 1 reach to zone 2 reach (or ≥ 120 %) of the protected line during the high speed auto-reclose attempt. (Even on communications assisted line protection applications, the zone extension scheme facilitates high speed clearing from either end independent of detection from the opposite end.)

Conversely, a Zone 1 extension scheme can be applied, in lieu of communications, to allow fast clearing of faults occurring over 100% of the line. This is achieved by the Zone 1 at each end normally extending beyond the remote terminal. Following a trip for a line fault, an output from the reclosing relay causes the Zone 1 to be pulled back in reach (typically to 80 – 90% of the line impedance). Reclosing for subsequent trips, if used, must be delayed because the status of the remote breaker(s) is (are) unknown.^[12] This is the European method and may not be acceptable where the loss of two adjacent line segments cannot be tolerated.

Slow speed reclosing with Synchronism Check (Synch Check) relays is acceptable where stability or critical processes are not concerns. Synch Check is normally applied when the systems are interconnected through other parts of the system.

In setting the Synch Check relay, the following should be considered:

1. The voltage magnitudes on either side of the breaker should be well matched and above a minimum magnitude.
2. The frequency on either side of the open breaker. (In most cases, the frequencies are the same.)
3. The separation across the open breaker is at an acceptable angle. (Normally between 20° to 60° .)

Figure 6^[13] illustrates the area where the two sides of the breaker are within the values to allow the breaker to close. The shaded area inside the circle is the region that meets some of the criteria for closing. The arrow head at the centre of the circle is the reference voltage that is set on the synch check relay. The radius of the circle is the difference allowable between the two voltage phasors where reclosure is allowed. If the voltage magnitude difference is too large, the amount of reactive current to balance the voltage magnitudes can be large on closing. If the frequency and or angular separation across the breaker are too large, the amount of MW flow on closure of the breaker can be significant. Too large of an angle or frequency may result in damage to rotor shafts due to the large torsional stress to realign the two angle across the breaker.

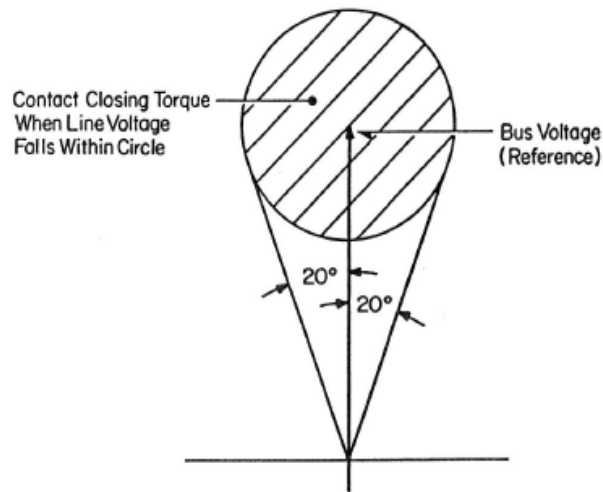


Figure 6
Typical Synchro-Verifier Relay Closing Characteristics

Figure 7 ^[13] shows the characteristics on the Synch Check relays. The first circle (solid) represents the 20° tolerance setting. The second and third dotted circles represent the 40° and 60° characteristics.

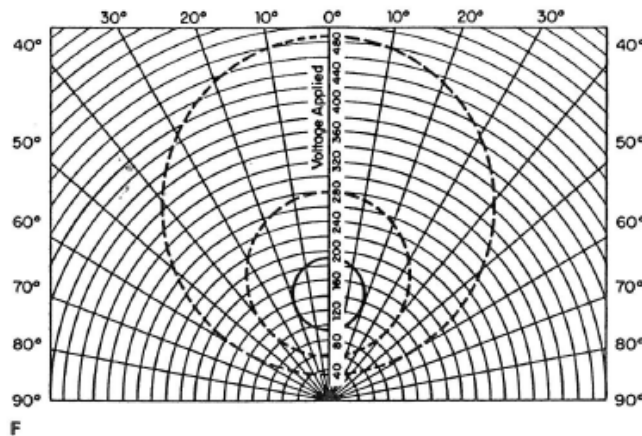


Figure 7
Typical Voltage - Angle Characteristics for Various Angle Settings

The graph in Figure 8 ^[13] illustrates a reclosing characteristic of a certain synch check relay. Some microprocessor relays calculate the actual voltage between the two voltages. The inverse characteristics show three angle settings of the relay at 20°, 40° and 60°. To set this relay, the maximum system slip frequency is required. (Normally there is no slip or a very small change in the slip.) Depending on the allowable reclosing angle, the time dial must be set in relation with the allowable angle and the maximum system slip frequency. The synch check relay must also be time delayed depending in the durations that it takes the two systems to come into this characteristic. However, there also is a window time that if exceeded will not allow reclosure. At

that time, Synch Override may be necessary where the operator will choose to reclose the breaker despite the inability of the two systems to come into the Synch Check characteristics.

This information is required to be provided by the System Planning groups depending on the inertia of the system and other control information.

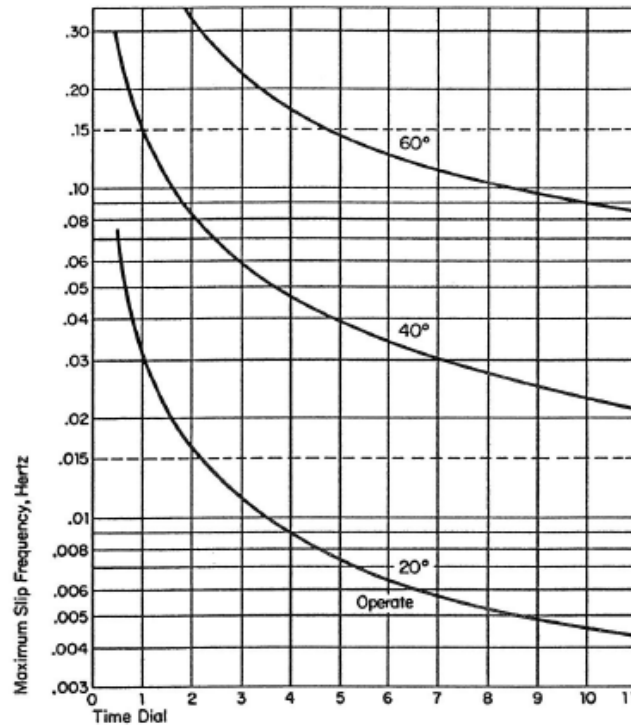


Figure 8
Approximate Maximum Slip Frequency for Which Operation Occurs (Rated Voltage on Both Sides.)

Reclosing is normally initiated by protection operations or by operator action either locally or remotely via the SCADA system. Automatic high speed reclosing should only be allowed if the protective relay determines it meets the predetermined conditions to allow high speed auto reclosure to occur.

Manual local or operator remote closures should not allow an automatic reclose again if it is reclosed onto a fault.

Cables:

- Cable faults are usually permanent. As such, these faults should require testing before re-energization is allowed.
- Where the line consists of an overhead line with a small portion of cable in series, unchecked reclosure may be acceptable based on the risk the owner is willing to take. Another option is to separately protect the overhead and cable portions and only allow reclosure if the fault is on the overhead part of the line.

Bus Bar:

- Auto-reclose is not generally applied on bus bar trips. In some instances, where continuity of service is the primary concern and stability is not an issue, reclosing has been applied.

Transformer & Wound Devices:

- The transformer and wound equipment (submerged in oil) shall be blocked from reclose for insulation indicative trips such as differential or sudden pressure operations until the transformer is tested.
- Air core reactors, shall be allowed to reclose at the Utility's discretion where voltage control is a concern. (Normally only used in Special Protection Schemes.)

Radial Lines (Connected to Grid Stations):

Radial lines connected to the grid level voltage can also have a significant impact on the system performance. The grid positive sequence voltage may drop significantly enough to curtail the transfer of power across the system.

The power transfer equation listed below, shows that the drop in the positive sequence voltage will curtail the power transferred across the system. The change in positive sequence voltage is directly proportional to the power transfer. The change in positive sequence voltage (power) will accelerate the generator and decelerate the load causing the system to pull apart. Depending on the inertia of the system "H", the system stability may be jeopardized.

The equations for power transfer:

$$P = \frac{E_s \cdot E_r}{X} \cdot \sin\delta$$

E_s - Sending End Thevenin Voltage
 E_r - Receiving End Thevenin Voltage
 X - Reactance between E_s and E_r
 δ - Angle between E_s and E_r

- Radial lines may be reclose-enabled depending on the operating criteria of the Utility.
 - Reclosing should not be applied on transformer ended lines without confirming the condition of the transformer.
 - Fuse coordination:
 - Consideration should be given to whether reclosing is applied on a line that has fused laterals for fuse clearing or fuse saving schemes.
 - Fuses are not adequate protection for delta connected transformers. As such they do not protect the transformer for internal faults nor do they protect for
-

HV or LV side faults on the transformer side of the fuse cut-out after the fuse blows on the faulted phase. (The fault will continue to be supplied from the interconnected transformer windings.)

- Transformers greater than 10 MVA should be provided with fault clearing isolating equipment (line breaker or circuit switcher) along with differential and other protective relays. Transformers below 10MVA may be fused.

Series Compensated Lines:

- Depending on the design of the series capacitor, the auto reclose design may be different. If the series capacitor bank only uses gapped protection without any non linear arresters, the reclose of the line should be delayed to allow the trapped charge to dissipate to prevent the possibility of having the line trip on reclose. For series capacitors that use MOVs, a time delay may not be required. Reclosing on series Compensated Lines may be designed to close the by-pass breaker across the capacitor. This removes the capacitor bank from the line during the line dead time until the last breaker is closed to speed up the reclose. This is used to reduce the mutually coupled zero sequence currents on single phase trip & reclosed lines and to reduce the impact on the series capacitors if the line is reclosed back onto a permanent fault.

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