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I. INTRODUCTION

Various studies have shown that anywhere from 70%, to as high as 90%, of faults on most overhead lines are transient [1, 2, 6]. A transient fault, such as an insulator flashover, is a fault which is cleared by the immediate tripping of one or more circuit breakers to isolate the fault, and which does not recur when the line is re-energized. Faults tend to be less transient (near the 80% range) at lower, distribution voltages and more transient (near the 90% range) at higher, subtransmission and transmission voltages. [2]

Lightning is the most common cause of transient faults, partially resulting from insulator flashover from the high transient voltages induced by the lightning. Other possible causes are swinging wires and temporary contact with foreign objects. Thus, transient faults can be cleared by momentarily de-energizing the line, in order to allow the fault to clear. Autoreclosing can then restore service to the line. [6]

The remaining 10 - 30% of faults are semi-permanent or permanent in nature. A small branch falling onto the line can cause a semi-permanent fault. In this case, however, an immediate de-energizing of the line and subsequent autoreclosing does not clear the fault. Instead, a coordinated time-delayed trip would allow the branch to be burned away without damage to the system. Semi-permanent faults of this type are likely to be most prevalent in highly wooded areas and can be substantially controlled by aggressive line clearance programs.

Permanent faults are those that will not clear upon tripping and reclosing. An example of a permanent fault on an overhead line is a broken wire causing a phase to open, or a broken pole causing the phases to short together. Faults on underground cables should be considered permanent. Cable faults should be cleared without autoreclosing and the damaged cable repaired before service is restored. There may be exceptions to this, as in the case of circuits composed of both underground cables and overhead lines, as we will explore later.

Although autoreclosing success rates vary from one company to another [1], it is clear that the majority of faults can be successfully cleared by the proper use of tripping and autoreclosing. This de-energizes the line long enough for the fault source to pass and the fault arc to de-energize, then automatically recloses the line to restore service. Thus, autoreclosing can significantly reduce the outage time due to faults and provide a higher level of service continuity to the customer. Furthermore, successful high-speed reclosing on transmission circuits can be a major factor when attempting to maintain system stability during fault clearing, as we will see later in this paper.

For those faults that are permanent, autoreclosing will reclose the circuit into a fault that has not been cleared, which may have adverse affects on system stability (particularly at transmission levels). However, knowledge of the issues to consider for proper selection and application of autoreclosing will help to determine when and where to use autoreclosing. The remainder of this paper covers the use of autoreclosing, primarily on transmission lines, and the issues to consider for proper application of autoreclosing. The application of autoreclosing on distribution lines, while similar in many respects, is not covered.

A. Purpose

The purpose of this paper is to collect the various topics of protection that are associated with reclosing and present them here for use in applying autoreclosing to transmission circuits.

B. History

According to a report written by the IEEE PSRC in 1984 [1], automatic reclosing was first applied in the early 1900's on radial feeders protected by instantaneous relays and fuses. These schemes reclosed the circuit two or three times prior to lockout, with a 73% to 88% success rate on the first reclose actions, and covered both radial and looped circuits, predominantly at distribution voltages, but also including 154kV.

Jackson, et al [8], reported that high-speed reclosing (HSR) was first used by American Electric Power System (then known as American Gas & Electric) in 1935 as a means to defer construction of redundant transmission lines. System continuity was maintained on these radial lines by rapidly reclosing a single line rather than providing a second, redundant path for power to flow. Modern systems with single radial lines to transmit power from one point to another are commonplace. It is more common to have a network with parallel transmission lines. HSR is used more for maintaining system stability and synchronism than for point-to-point continuity.

The development of high-speed breakers for transmission lines by the late 1930's led to the application of high-speed reclosing (HSR) on these lines, resulting in improved system stability. Probability studies of the insulator flashover were initiated to determine minimum reclosing times that still permitted enough time for arc de-ionization. Early applications of HSR on multi-terminal lines tripped all terminals and then reclosed the circuit breaker at high-speed at one terminal. If this high-speed reclosure was successful, the remaining terminals were reclosed with time delay to complete the through circuit. [1]

The preceding historical information touches on a number or reasons for using autoreclosing on both distribution and transmission systems. Following is a summary of reasons for using autoreclosing. This list may not be complete, and each engineer needs to consider any additional reasoning when applying autoreclosing in any given application.

1. Minimizing the interruption of the supply to the customer
2. Maintenance of system stability and synchronism (high-speed tripping/autoreclosing on OH transmission lines)
3. Restoration of system capacity and reliability with minimum outage and least expenditure of manpower
4. Restoration of critical system interconnections

5. Restoration of service to critical loads
6. Higher probability of some recovery from multiple contingency outages
7. Reduction of fault duration, resulting in less fault damage and fewer permanent faults
8. The use of high-speed tripping and autoreclosing schemes in fuse saving schemes to prevent permanent outages for transient faults beyond tap fuses
9. The use of delayed tripping and autoreclosing schemes in fuse blowing schemes to allow time delayed tripping to clear semi-permanent faults.
10. Ability to run substations unattended, resulting in saved wages
11. Relief for system operators in restoration during system outages

Reasons 8 and 9 above apply to distribution systems. Reasons 10 and 11 may require remote tripping and closing capability and/or automatic restoration ability, such as those schemes used with autosectionalizers.

C. Fundamentals

The application of autoreclosing requires the evaluation of many factors. These factors may vary considerably depending upon the system configuration, the system components, and the reclosing philosophy utilized by the protection engineer or company. The following factors are of fundamental concern:

1. The benefits and possible problems associated with reclosing
2. The choice of dead time
3. The choice of reset time
4. The decision to use single- or multiple-shot reclosing

Some of the benefits associated with autoreclosing were noted earlier in this paper. These benefits must be weighed against any potential problems that may arise when applying autoreclosing.

The dead time of a circuit breaker on a reclosing operation is defined in IEEE Std. C37.100-1992 as the interval between interruption in all poles on the opening stroke and reestablishment of the circuit on the reclosing stroke. The choice of high-speed versus delayed autoreclosing has a direct effect on the amount of dead time, as will be seen later in this paper.

The dead time of a reclosing relay is similar to the dead time of a circuit breaker. It is the amount of time between the autoreclose scheme being initiated (e.g., by the operation of a protective element) and the operation of the ‘reclose’ contacts, which energize the circuit breaker closing coil.

Reset or reclaim time of an automatic circuit recloser or automatic sectionalizer is defined in IEEE Std. C37.100-1992 as the time required, after one or more counting operations, for the counting mechanism to return to the starting position. In an autoreclosing relay, the reset time is the time following a successful closing operation, measured from the instant the auto-reclose relay closing contacts make, which must elapse before the auto-reclose relay will initiate a new reclosing sequence in the event of a further fault incident.

Figure 1 depicts circuit breaker dead time, reclosing relay dead time, and reclosing relay reclaim or reset time.

The factors noted above are fundamental when evaluating autoreclosing applications. Decisions when choosing these in autoreclosing applications are influenced by the type of protection and switchgear used, the nature of the system, and the possibility of stability problems, and the effects on various consumer loads.

Distribution networks and transmission systems present some similar and some different problems in respect to the application of autoreclosing.

II. DEFINITIONS

Before discussing the issues involved in the application of autoreclosing schemes, it is useful to define some of the terms in common usage. The majority of these definitions are taken from reference [3], IEEE Standard Definitions for Power Switchgear, IEEE Std. C37.100-1992.

Several of the terms defined below are illustrated in Figure 1, which shows the sequence of events in a typical autoreclosing operation, where the circuit breaker makes one attempt at reclosure after tripping to clear a fault. Two conditions are shown: a successful reclosure in the event of the fault is transient, and an unsuccessful reclosure followed by lockout of the circuit breaker if the fault is permanent. [2]

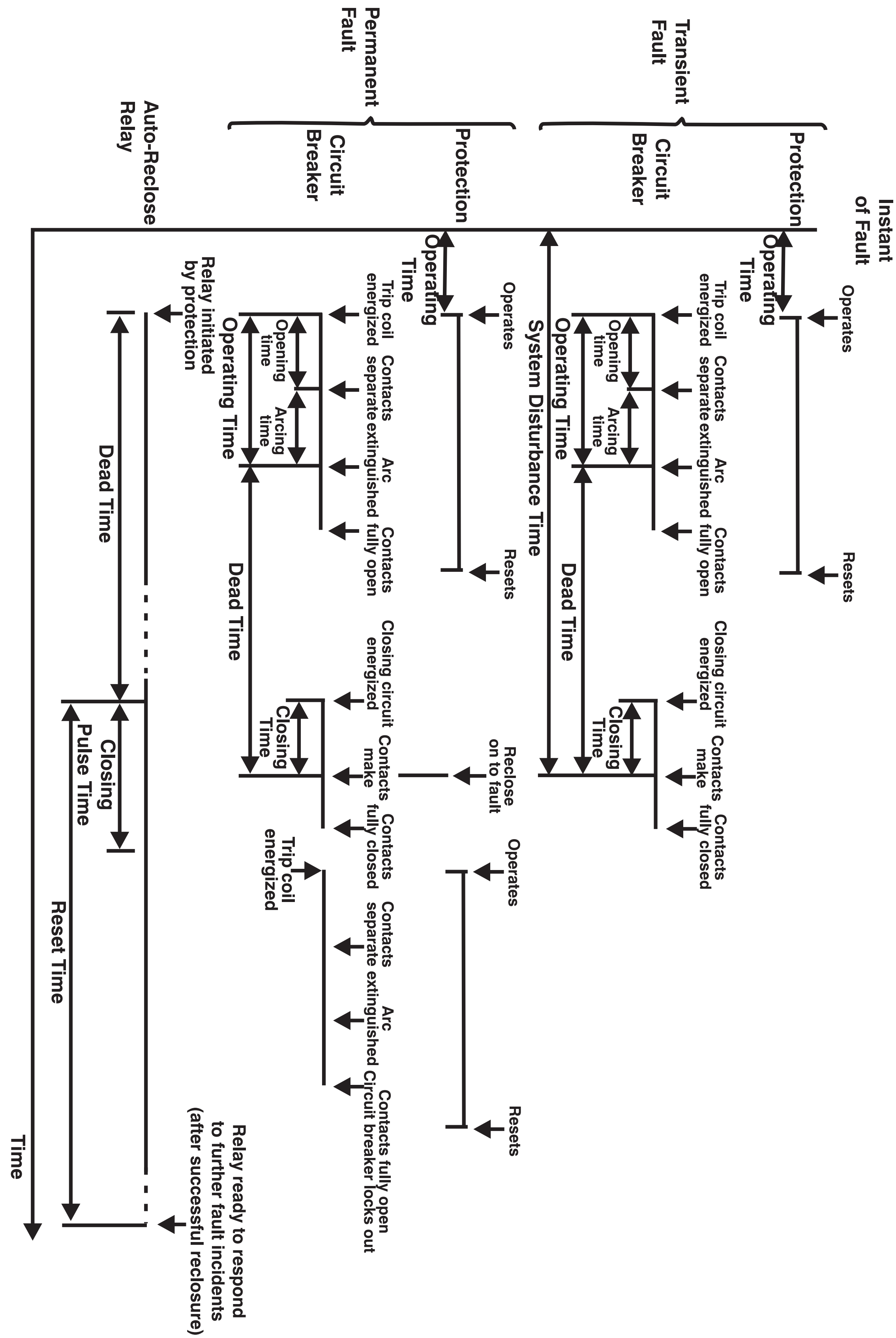

Figure 1: Operation of Single Shot Auto-Reclose Scheme for Transient and Permanent Faults [2]

Arcing time (of a mechanical switching device)
The interval of time between the instant of the first initiation of the arc and the instant of final arc extinction in all poles.

See Figure 1 on previous page and Figure 2 below.

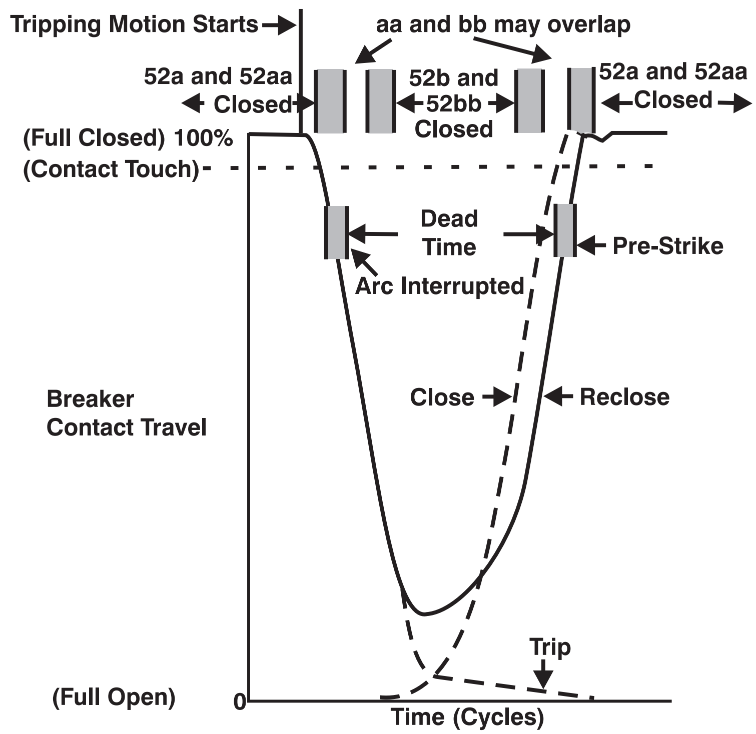

Figure 2: Typical Circuit Breaker Instantaneous Reclosing Cycle [10]

Breaker reclosing time
The elapsed time between the energizing of the breaker trip coil and the closing of the breaker contacts to reestablish the circuit by the breaker primary contacts on the reclose stroke. (i.e., breaker operating time plus breaker dead time).

Closing time (of a mechanical switching device)
The interval of time between the initiation of the closing operation and the instant when metallic continuity is established in all poles.

Dead time (of a circuit breaker on a reclosing operation)
The interval between interruption in all poles on the opening stroke and reestablishment of the circuit on the reclosing stroke.

Note: The dead time of an arcing fault on a reclosing operation is not necessarily the same as the dead time of the circuit breakers involved, since the dead time of the fault is the interval during which the faulted line is de-energized from **all** terminals.

De-ionizing time
The time following the extinction of an overhead line fault arc necessary to ensure dispersion of ionized air so that the arc will not re-strike when the line is re-energized.

Delayed autoreclosing
The autoreclosing of a circuit breaker after a time delay that is intentionally longer than for high-speed autoreclosing.

High-speed autoreclosing
The autoreclosing of a circuit breaker after a necessary time delay (typically less than one second) to permit fault arc de-ionization with due regard to coordination with all relay protective systems. This type of autoreclosing is generally not supervised by voltage magnitude or phase angle.

Operating time (circuit breaker)
The time from the energizing of the trip coil until the fault arc is extinguished.

Operating time (protection)
The time from the inception of the fault to the closing of the tripping contacts. Where a separate auxiliary tripping relay is employed, its operating time is included.

Reset time (of an automatic circuit recloser or automatic line sectionalizer)
The time required, after one or more counting operations, for the counting mechanism to return to the starting position.

System disturbance time
The time between the inception of the fault and the circuit breaker contacts making on successful reclosing.

Single-shot reclosing
An operation sequence providing only one reclosing operation, lockout of the circuit occurring on subsequent tripping.

III. AUTOMATIC RECLOSING ON TRANSMISSION AND SUBTRANSMISSION SYSTEMS

The voltage classes considered as transmission and subtransmission levels are:

Subtransmission	34.5 kV - 138 kV
Transmission	115 kV and higher

with transmission divided into:

High Voltage (HV)	115 - 230 kV
Extra High Voltage (EHV)	345 - 765 kV
Ultrahigh Voltage (UHV)	1000 kV and higher

The voltage values indicated represent the nominal and typical rms system voltages (line-to-line) in common use today [12]. These classes are general and may vary from one system to another, as well as overlap from one class to another.

A. Transmission and Subtransmission Overview

Referring to the voltage classifications above, the subtransmission and transmission systems are generally accepted as those circuits with voltages of 34.5 kV and higher, although the lines between distribution and subtransmission/transmission are not always clear.

Transmission and subtransmission lines are more likely to be looped interconnected systems, meaning that the line has a positive-sequence source at two or more ends. Fault current to line faults is supplied by the source terminals, and all source terminals must be tripped to clear both phase and ground faults.

B. Application of Autoreclosing on Transmission Systems

A primary concern in the application of autoreclosing, especially on EHV-rated lines and higher, is the maintenance of system stability and synchronism. This is normally done through the application of high-speed tripping and autoreclosing. The problems involved with maintaining stability on these lines when autoreclosing during a fault on the line depend on the characteristics of the system - whether it is loosely connected, for example, with two power systems connected by a single tie line, or, conversely, highly interconnected, in which case maintaining synchronism during autoreclosing is much easier.

The intent of autoreclosing on transmission and subtransmission systems, other than the maintenance of stability, is to return the system to its normal configuration with minimum outage of the line with the least expenditure of manpower. System restoration becomes increasingly important when applied to lines that interconnect systems and are critical for reliable power exchange between the systems. Individual utility policy and system requirements dictate the complexity and variety of automatic reclosing schemes in service today.

IV. HIGH-SPEED AUTORECLOSING ON TRANSMISSION AND SUBTRANSMISSION SYSTEMS

High-speed autoreclosing, used in conjunction with high-speed clearing of faults, is used on transmission and subtransmission for improving stability. Factors to consider when using high-speed autoreclosing include:

1. The maximum time available for opening and reclosing the system without loss of synchronism (maximum dead time). This time is a function of the system configuration and the transmitted power.
2. The time required for de-ionization of the arc path so that the arc will not restrike when the breaker is reclosed. This time can be estimated by the use of a formula developed from empirical data gathered from laboratory tests and field experience.
3. The protection characteristics
4. The circuit breaker characteristics and limitations.
5. Choice of reclose reset time
6. Number of reclose attempts

These factors will be considered next.

A. System Stability and Synchronism

Any unbalance between generation and its load initiates a transient that causes the rotors of the synchronous machine to “swing” because net accelerating (or decelerating) torques are exerted on the rotors. If these torques are large enough to cause some of the rotors to swing far enough, one or more machines may “slip a pole” and synchronism is lost. In order to ensure stability, a new state of equilibrium must be reached before this can happen.

Loss of stability can be caused by a severe generation unbalance (e.g., excess generation due to loss of load). Figure 3 shows how the rotor angle of the machines will increase. If the angle differences between the machines do not change significantly, synchronism will be maintained and the machines will eventually settle to a new angle (a). If the machines are separated by large angles, they will continue to drift apart and the system will become unstable (b).

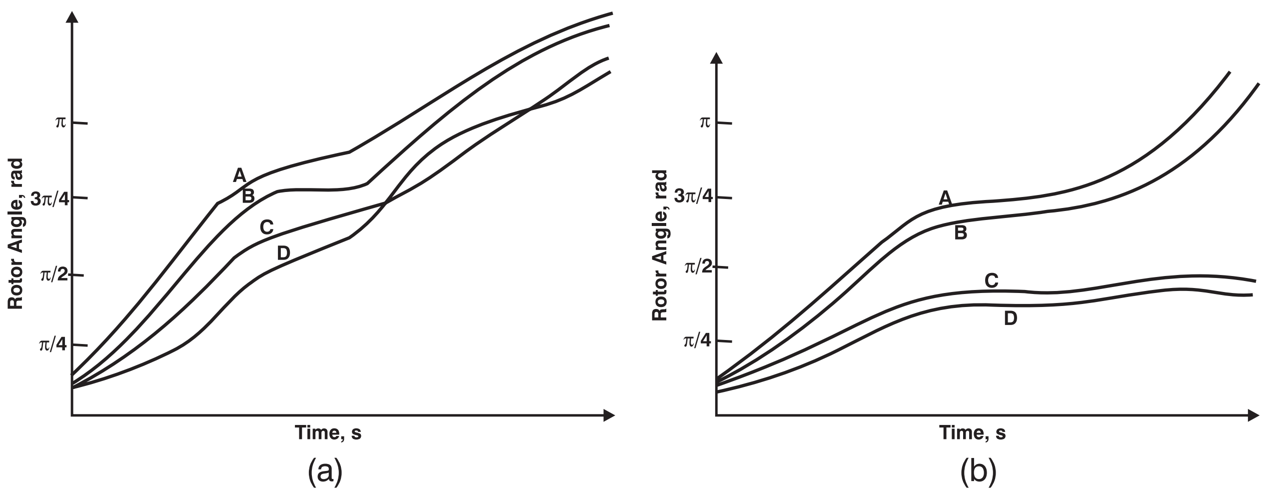

Figure 3: Response of a Four-Machine System During a Transient [16]

The problem of stability is concerned with the behavior of synchronous machines after they have been perturbed. If the perturbation does not involve any net change in power, the machines should return to their original state. If an unbalance between the supply and demand is created by a change in load, in generation, or in network conditions, a new operation state is necessary. In any case, if the system is stable, all interconnected synchronous machines should remain in synchronism (i.e., operating in parallel and at the same speed).

The transient following the perturbation on the system is oscillatory and dampens to a new quiescent condition if the system is stable. The oscillations are reflected as power fluctuations over the power line and can be represented graphically using the equal area criterion and the power-angle curve [16].

The power-angle curve of a synchronous machine relates the power output of the machine to the angle of its rotor. For a two-machine system this can be represented as:

$$P = (V_S V_R / X) \sin \delta \qquad \text{(Eq. 1)}$$

Where:

- P= the power transmitted between the machines during the transient condition
- V_S= the voltage at the sending end
- V_R= the voltage at the receiving end
- δ= the angle by which V_S leads V_R

The maximum power occurs when the angle between the two machines is 90 degrees and the minimum power occurs when the angle is 0 or 180 degrees.

Figure 4 shows a power-angle curve for a simple two-machine system with a single transmission line connecting the two sources, *A* and *B*. The curve for normal conditions is the one with the greatest height and with a maximum of:

$$P_M = (V_A V_B / X) = \frac{(1.1)\ (1.0)}{0.6} = 1.83 \text{ pu} \qquad \text{(Eq. 2)}$$

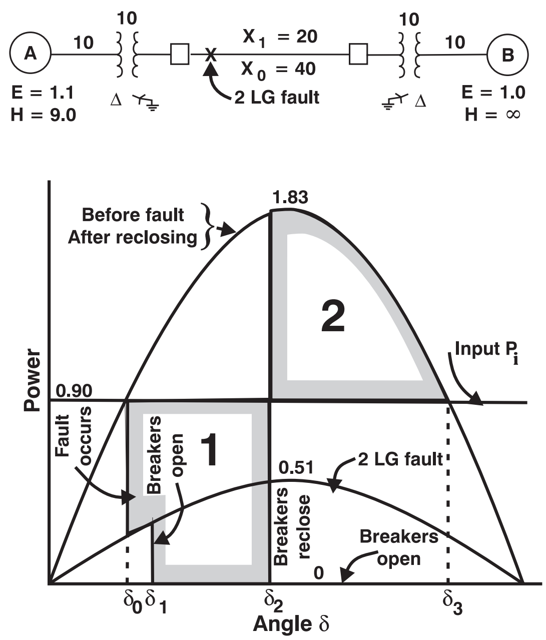

Figure 4: Application of the Equal-Area Criterion for Stability to the Reclosing of a Single-Circuit Tie Between Systems A and B [6]

During the fault (2LG) the power-angle curve is reduced as shown, and during the opening of the breakers, the amplitude of the curve is zero. For a complete development of 2LG fault level, refer to [6].

The height of the horizontal line labeled 'Input', P_i, represents the electrical and mechanical power transmitted prior to the fault. The initial angular separation of machines *A* and *B* is δ_0, the clearing angle is δ_1, the reclosing angle is δ_2, and the angle of maximum swing without loss of synchronism is δ_3. The equal area criterion requires that for stability, area 2 must exceed area 1. Without reclosure, synchronism would be lost regardless of the amount of power transmitted. Hence, the stability limit without reclosure is zero. With rapid enough clearing and reclosure, however, the stability limit can be made to approach the amplitude of the normal power-angle curve.

To determine whether the system in Figure 4 is stable, we must calculate the areas 1 and 2. If area 2 is greater than area 1, then the system is stable. If area 2 equals area 1, then the input power of 0.9 per unit, P_i, is the stability limit. Any higher input power would cause area 2 to increase and area 1 to decrease, thus causing instability (assuming they are equal prior to increasing the input power). If area 1 is greater than area 2, then the system is unstable.

$$Pi := 0.9 \qquad Pm := 0.51 \qquad PM := 1.83$$

$$\delta_0 := 29.4\,deg \qquad \delta_2 := 82.3\,deg$$

$$\delta_1 := 38.1\cdot deg \qquad \delta_3 := 150.6\,deg$$

$$A1 := Pi\cdot(\delta_2 - \delta_0) - \int_{\delta_0}^{\delta_1} Pm\cdot\sin(\delta)\,d\delta \qquad A2 := \int_{\delta_2}^{\delta_3} PM\cdot\sin(\delta)\,d\delta - Pi\cdot(\delta_3 - \delta_2)$$

$$A1 = 0.788 \qquad A2 = 0.767$$

Area 2 is slightly less than area 1, thus the system is unstable. In order to ensure stability for the 2LG fault, area 1 must be decreased and/or area 2 must be increased. This can be done by reducing the input power, P_i, or by clearing the fault faster (i.e., reclosing faster).

Figure 5 shows the application of the equal area criterion to a two-machine system connected by a double-circuit line. A 2LG fault is applied. When one line is opened to clear the fault, the resulting power-angle curve is almost as high as the curve for the normal conditions. In order for stability to be maintained during the disturbance, the sum of the areas 2 and 3 must be greater than that of area 1.

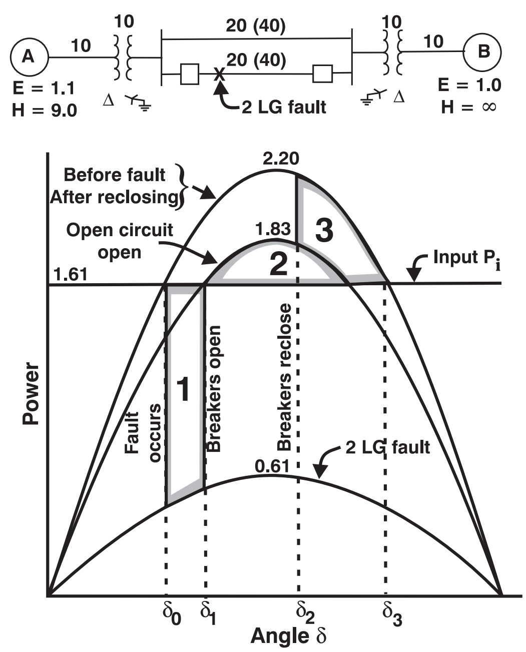

Figure 5: Application of the Equal-Area Criterion for Stability to the Reclosing of a Single-Circuit Tie Between Systems A and B [6]

B. De-ionization of Arc Path

When applying high-speed reclosing to transmission and subtransmission systems in order to maintain system stability, it is important to know how long the line must be de-energized in order to allow enough time for de-ionization of the arc so that it will not re-strike and reestablish the fault when voltage is reapplied. The de-ionization time required depends on the circuit voltage, conductor spacing, fault current magnitude, and weather conditions. Results obtained from laboratory testing and field experience can be seen in Figure 6. An equation for the de-ionization time based on voltage level that closely follows this empirical data can be used as a minimum de-ionization time estimate: [13]

$$t = 10.5 + kV/34.5 \text{ cycles} \qquad \text{(Eq. 3)}$$

Where:
kV is the rated line-to-line voltage.

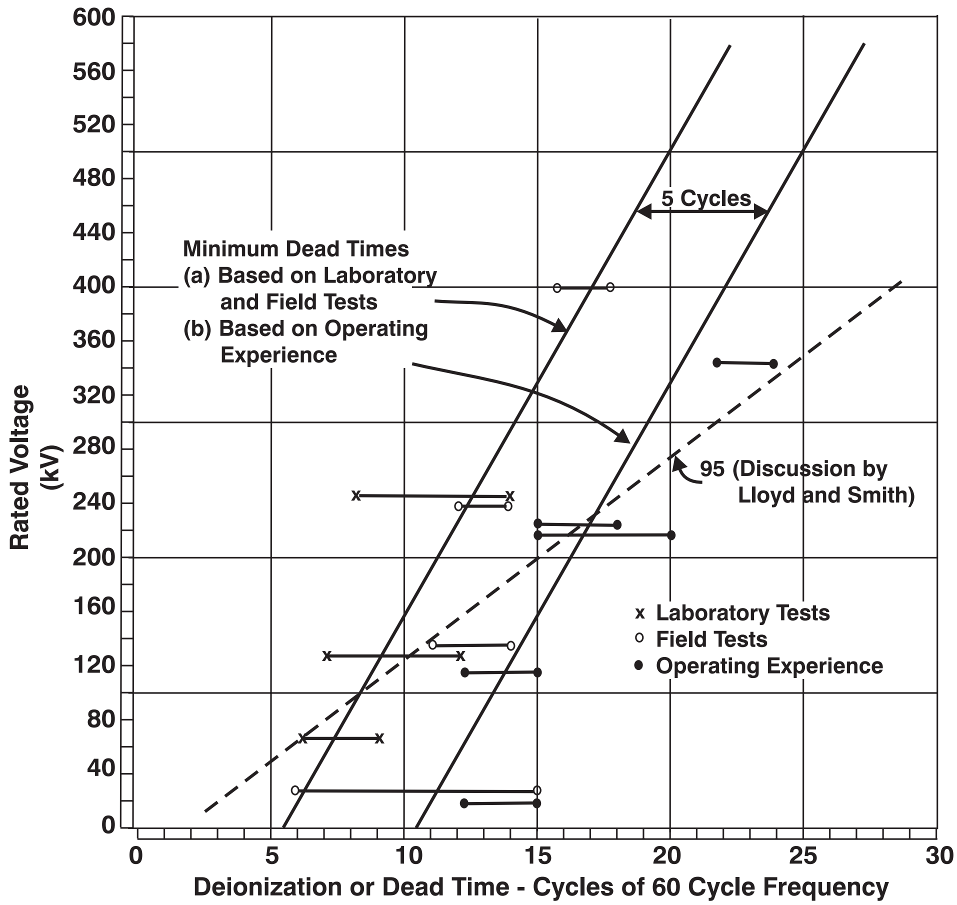

Figure 6: Dead Time for Arc Path Deionization [13]

Thus, the higher the voltage, the more time is required for de-ionization. The time will slightly increase with an increase in the arc current or arc duration or in the presence of rain. The time will decrease as the wind speed increases.

Table 1 shows some commonly used voltages and the corresponding de-ionization time estimate using Equation 3 above.

Voltage (KV L-L)	De-ionization Time (Cycles)
34.5	11.5
115	13.8
345	20.5

Table 1: Minimum De-ionzation Time Of Common Voltage Levels Using Equation 3

Comparing these times with Figure 6 shows that the formula used to calculate the times corresponds to the 'Operating Experience' line (see Figure 7 below).

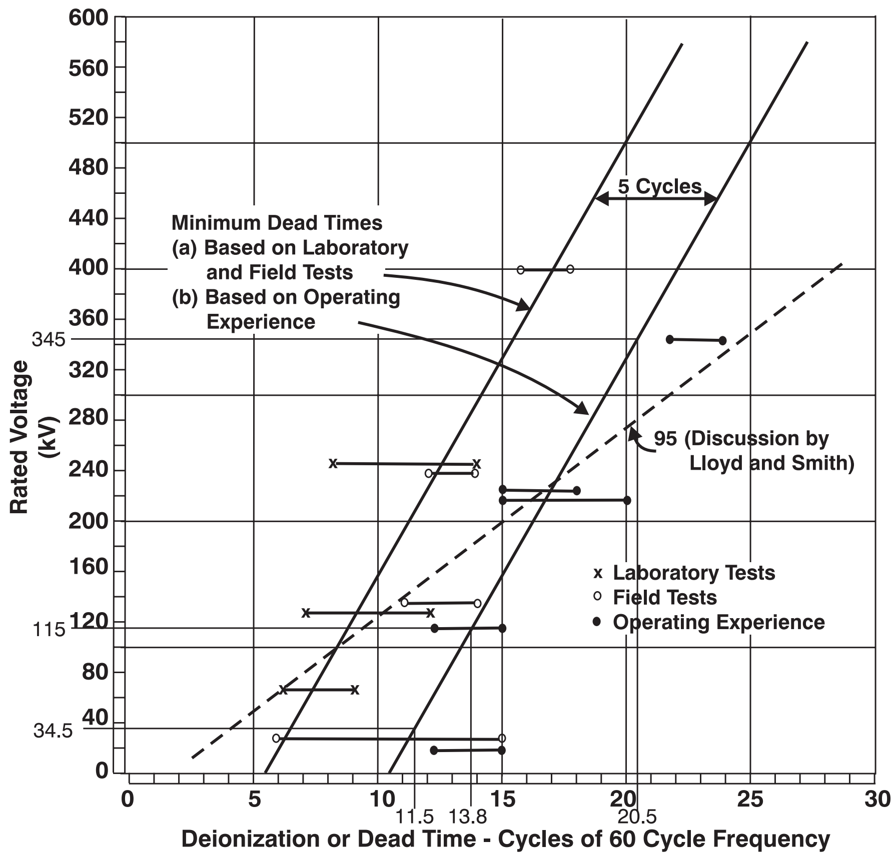

Figure 7: Dead Time for Arc Path De-ionization, with Operating Experience Line

The use of single-pole switching requires the faulted conductor to be disconnected for a longer period than if three-pole switching were used. This is due to the capacitive coupling between the unfaulted phases, which tends to maintain the arc. Single-pole switching is addressed in more detail later in this paper.

C. Protection Characteristics

On transmission lines where stability is a concern, simultaneous tripping of both circuit breakers ensures the quickest arc de-ionization of the fault. Any time during which one circuit breaker is open in advance of the other represents an effective reduction in the dead time, and may jeopardize the chances of a successful reclosure (see Figure 8 on next page). Simultaneous tripping, in conjunction with high-speed reclosing, keeps the system disturbance time to a minimum.

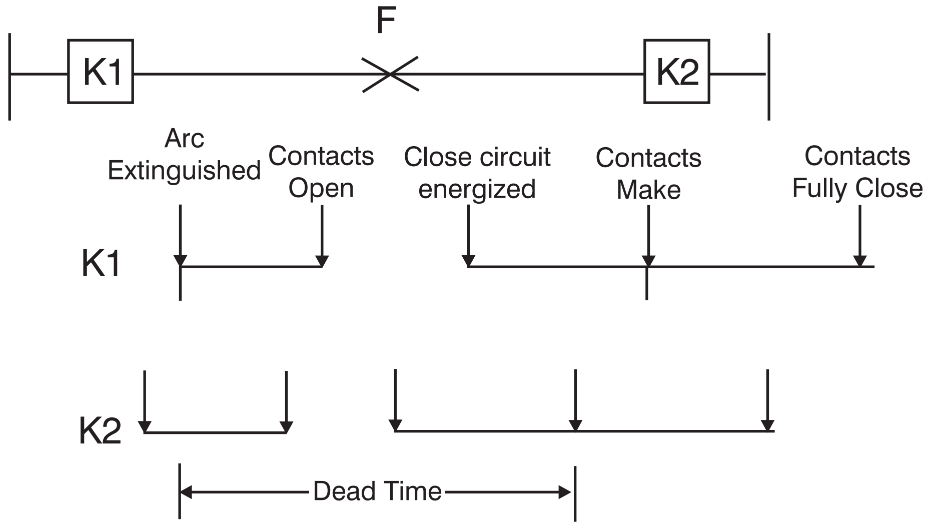

Figure 8: Non-Simultaneous Tripping Reduces Dead Time

Simultaneous tripping can be accomplished by use of high-speed distance relays. When distance relays are used and the fault is near one end of the line, special measures need to be taken to ensure simultaneous tripping of each end. These are described later in this paper. Where distance relaying of this type is not feasible, some form of pilot relaying can be used.

While it is important to autoreclose on lines using distance or pilot relaying, it is desirable that reclosing should be blocked and the breaker should remain open for out-of-step conditions. An out-of-step condition is generally an indication that the power swing is too great to maintain synchronism of the two separated systems; therefore, autoreclosing will not be effective and should be blocked.

If single-pole switching is used, there must be a method for the relays to properly detect the faulted phase and trip the proper poles accordingly.

D. Circuit Breaker Characteristics

In order to interrupt faults that are permanent, circuit breakers used with high-speed reclosing must have an interrupting duty capable of interrupting faults twice or more in rapid succession. This requires evaluation, and possible derating, of the breaker from the standard duty of two operations 15 seconds apart. (This is examined in detail later.)

Circuit breakers used for high-speed reclosing are fitted with operating mechanisms and control circuits that will automatically reclose at high speed and, if necessary, trip a second time. These breakers are often designed with special mechanisms that give higher speeds than are attainable with standard closing solenoids.

Special control circuits on breakers are used for high-speed autoreclosing. After the breaker has been tripped by the protective relays, the trip coil is de-energized and the closing coil is energized well before the end of the opening stroke, thus reversing the motion of the piston and breaker contacts. Typical travel-time curves for an oil circuit breaker with a pneumatic operating mechanism are shown in Figure 9.

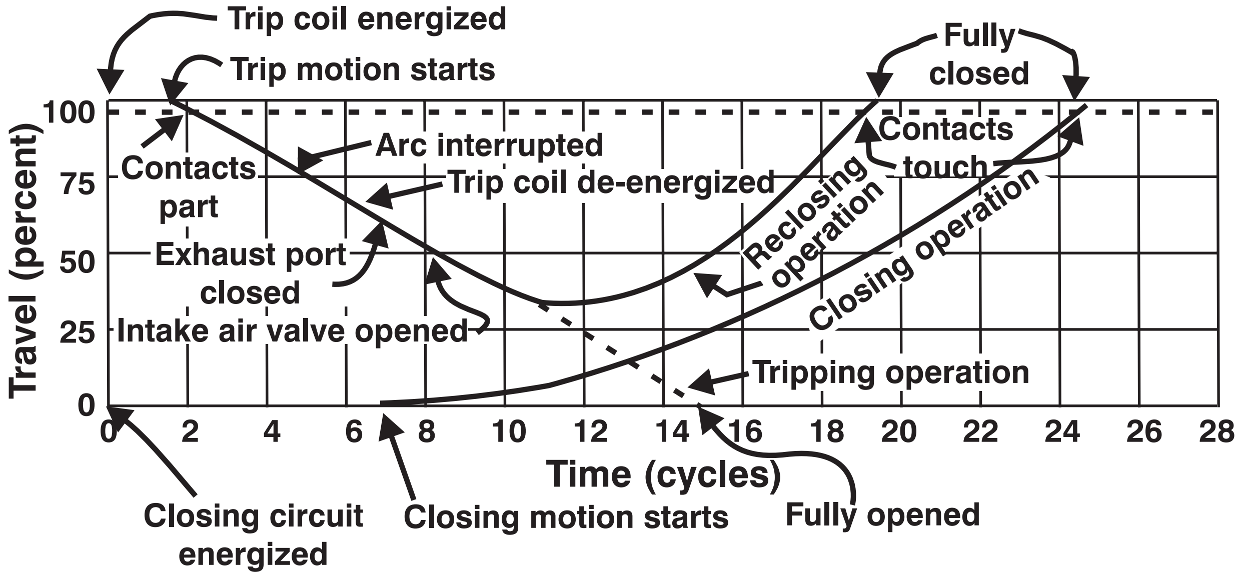

Figure 9: Typical Travel-Time Curves of Oil Circuit Breaker Operated by Pneumatic Mechanism [6]

E. Choice of Dead Time

The dead time setting on a high-speed autoreclosing relay used on transmission lines should be long enough to allow complete arc de-ionization. When using high-speed reclosing with modern fast circuit breakers, it is important to know that at some point the de-ionization time requirement will be longer than the dead time imposed by the circuit breaker. (See Figure 10.) Times shown are typical for high-speed HV breakers. Arc de-ionizing time is shown as variable and depends primarily on the voltage level. At the point where arc-deionizing time is longer than the dead time imposed by the circuit breaker, dead time must be introduced outside of the breaker. This is done with a dead time or reclose time setting in the autoreclosing relay. (See Figure 11.)

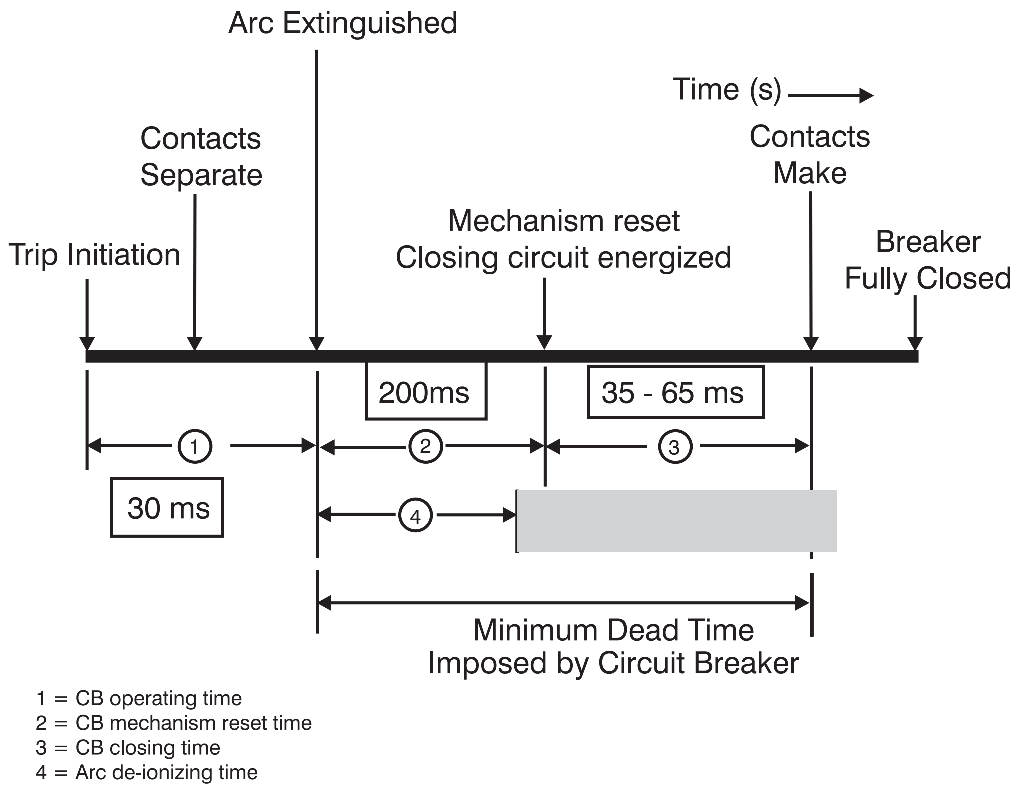

Figure 10: Arc De-ionization Time Longer Than Breaker Dead Time

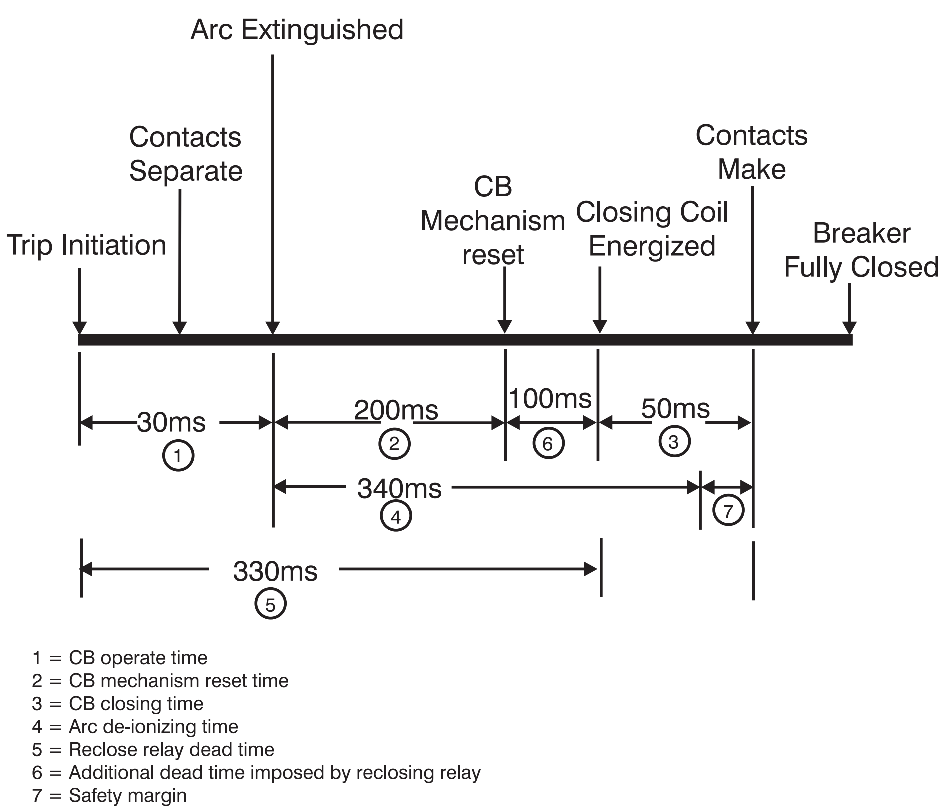

Figure 11: Addition of Dead Time by Reclosing Relay

F. Choice of Reset Time

The reset time of autoreclosing relays on transmission lines must be long enough to allow the protective relays to operate when reclosing onto a permanent fault. Times from 3 to 10 seconds are common [2]. Also, note that the reset time of the protective relay should be short enough so it is completely reset prior to the circuit breaker closing on a reclose operation. In this way, the protective relay will be prepared to operate if the reclose operation is not successful.

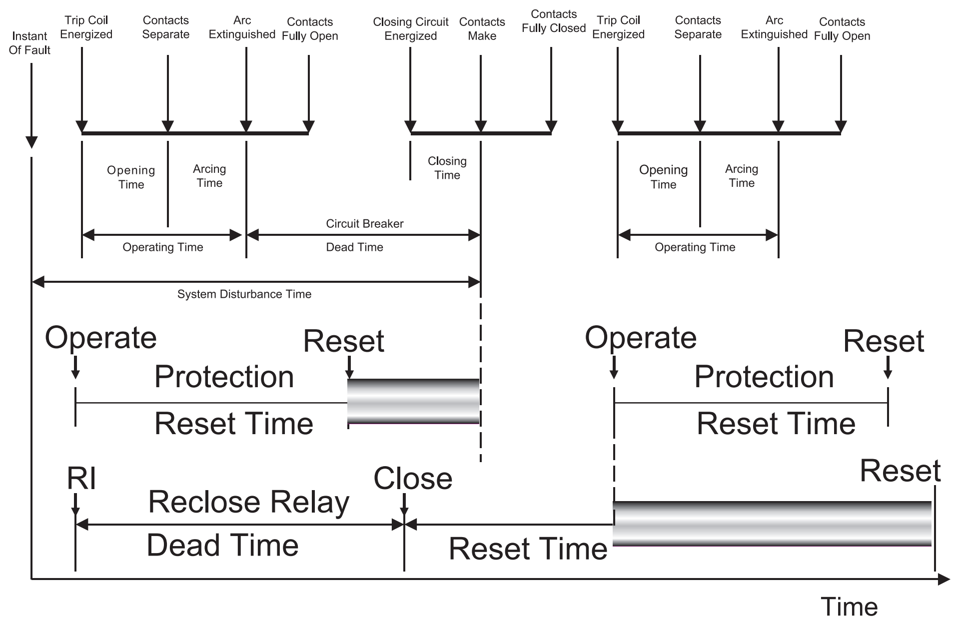

Figure 12: HSR - Reset Times

G. Number of Reclose Attempts

High-speed reclosing on transmission and subtransmission systems where stability is a concern is invariably single shot. Repeated attempts of reclosing with high fault levels would have serious effects on system stability. Furthermore, the incidence of semi-permanent faults that could be cleared by repeated reclosures is to be less likely than on distribution systems.

V. HIGH-SPEED AUTORECLOSING ON LINES WITH DISTANCE SCHEMES

When using step distance relaying on lines with high-speed reclosing, attempting to perform simultaneous tripping presents some difficulties.

Because of the errors involved in determining the ohmic setting of distance relays, it is difficult, if not impossible, to accurately set a distance relay to cover 100% of the line with high-speed relaying. It is common to allow for these errors by setting the relay to cover 80-90% of the line length in the first or instantaneous zone. Figure 13 illustrates a typical three-zone distance scheme covering two transmission lines. Thus, there is a zone near the end of each line in which the faults are cleared by sequential tripping. These end zones represent 20-40% of the line length. The remaining 60-80% between the end zones is cleared simultaneously by the breakers at both ends.

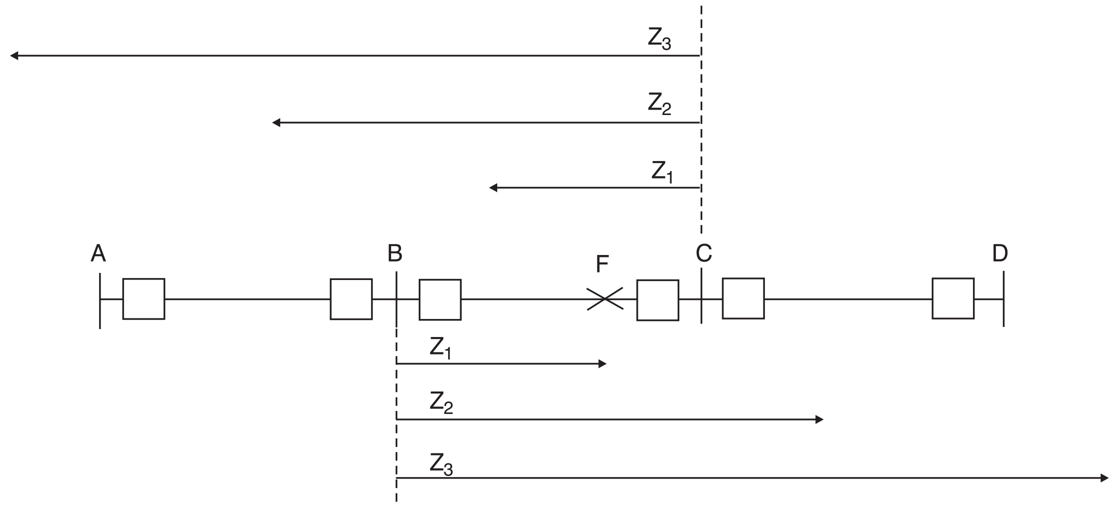

Figure 13: Typical Step Distance Scheme

Therefore, a fault occurring in an end zone would be cleared in the zone 1 time, or instantaneously, by the protection at one end of the line, and in the zone 2 time (0.3-0.4 seconds) by the protection at the other end. High-speed reclosing used on the circuit breakers at each end of the line could result in a dead time insufficient to allow for de-ionization of the fault arc. A transient fault could, therefore, be reclosed on and seen as a permanent fault, resulting in the locking out of both breakers.

There are two methods available for overcoming this problem. The first, where there is no pilot channel, is an extension of the zone 1 reach to apply instantaneous tripping over the entire line. The second is the use of a signaling channel to send a tripping signal to the remote end when a local zone 1 trip occurs.

A. Zone 1 Extension

Simultaneous tripping of both ends of a transmission line can be accomplished by setting the zone 1 relays to cover 120% of the line length so that all faults on the line fall within zone 1 and would be cleared instantaneously. The problem with this is that for faults near the end on the adjacent section (within the 120% Zone 1 reach), the unfaulted section will trip.

The zone 1 extension scheme uses zone 1 relays set in the usual way to see 80-90% of the line and then have the zone 1 reach extended to include 20% of the next line by way of a range control relay. Thus, the zone 1 extension reach includes the line plus 20% beyond the end of the line.

When a fault occurs within the zone 1 extension reach, a distance relay operates in the zone 1 time, trips the breaker and energizes the reclosing relay. As the breaker starts to reclose, the zone 1 reach is restored to the normal 80-90% range. If the fault is transient, the breakers will reclose successfully. If the fault is permanent, normal zone 2 and zone 3 timers will coordinate with the zone timers on the next section. Autoreclosing is blocked by zone 2 and zone 3 operation.

The problem with zone 1 extension schemes is the tripping of the breaker on the adjacent section for faults outside the section, but within the zone 1 extension reach (see Figure 14, fault F_2). This tripping of breakers outside the faulted section can be eliminated with the use of signaling channels.

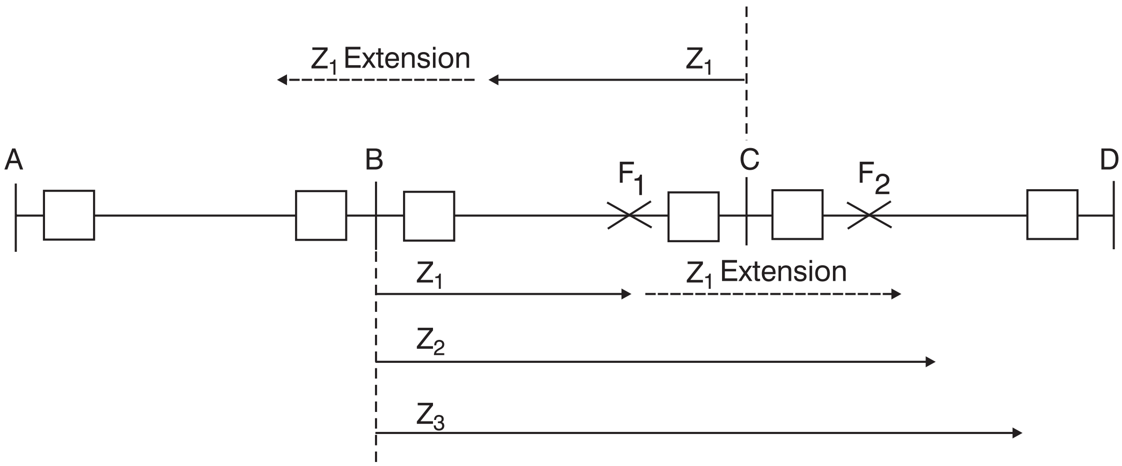

Figure 14: Zone 1 Extension

B. Signaling Channels – Pilot Protection

Another way to obtain instantaneous tripping over the entire length of the line is by using a signaling channel between the two ends. Communication is accomplished using various mediums such as pilot wires or even the overhead conductors. High-speed relaying schemes such as direct transfer trip (DTT), permissive overreaching transfer trip (POTT), permissive underreaching transfer trip (PUTT), blocking and unblocking are used to effect simultaneous tripping of both ends.

Figure 15 shows a typical step distance scheme employing direct transfer trip over phone lines, microwave, or power line carrier. High-speed reclosing is initiated by a pilot trip (PI), thus ensuring simultaneous reclosing.

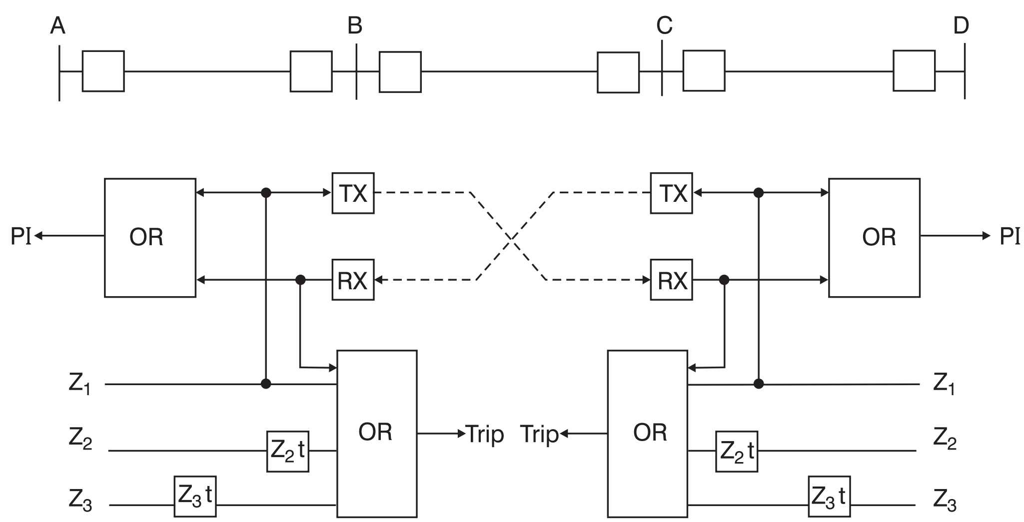

Figure 15: DTT Scheme

VI. DELAYED AUTORECLOSING ON TRANSMISSION AND SUBTRANSMISSION SYSTEMS

On highly interconnected transmission and subtransmission systems, where the loss of a single line is unlikely to cause loss of synchronism between the two ends, delayed autoreclosing can be used. In this case, the dead time is allowed to be long enough for any power swings on the system to settle down before reclosing. Thus, the problems of fault arc de-ionization times and circuit breaker operating characteristics are eliminated.

Where delayed autoreclosing is used on transmission systems, it is usual practice to use a synchronism check relay in the reclosing scheme. Even though the tripping of the line is unlikely to cause a loss of synchronism, there may be a voltage and/or phase difference developed between the two ends of the tripped line, which might cause problems if reclosed out of phase. Synchronism check relays generally check for phase angle, voltage and frequency difference when employed in autoreclosing schemes.

On a line of this type, it is common practice to reclose the breaker at one end first, a process known as ‘dead line charging’. Reclosing on the other end is then under the control of the synchronism check relay for ‘live line reclosing’. See Figure 16. Thus, any tapped load is restored during the reclosure of the first breaker.

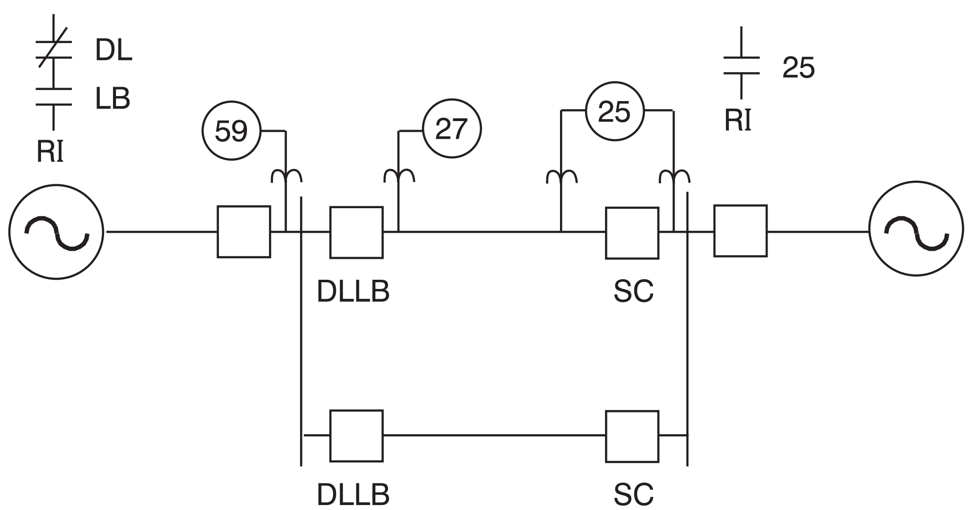

Figure 16: Transmission Line Delayed Reclosing

VII. THREE PHASE VERSUS SINGLE PHASE AUTORECLOSING

If single-phase autoreclosing is used on a transmission line for, for example, a single-line-to-ground fault, tripping only the faulted phase will allow an interchange of synchronizing power that would otherwise be unavailable through the use of three phase autoreclosing. In some installations, all three poles operate on any fault other than a single-line-to-ground fault. In other cases, selective-pole tripping is used not only for single-line faults, but also for line-to-line and two-line-to ground faults. When two conductors are open, some power is carried on the remaining conductor with a ground return.

The stability limit of the line can be raised above the limit obtainable with three-pole tripping and reclosing at the same speed. Alternatively, the same stability limit can be achieved with slower autoreclosing.

Single pole switching also has the advantage of reducing mechanical shock to generators compared to three phase reclosing.

A disadvantage of single pole switching is that each pole in the breaker must have its own tripping and closing mechanism, and the relay scheme must be able to properly select and trip the faulted phase or phases.

Figure 17 shows a comparison of the transient stability limits on a single tie line using single pole and three-pole autoreclosing. The system is that of Figure 4 during a single-line-to-ground fault. A detailed analysis is availble in reference [6].

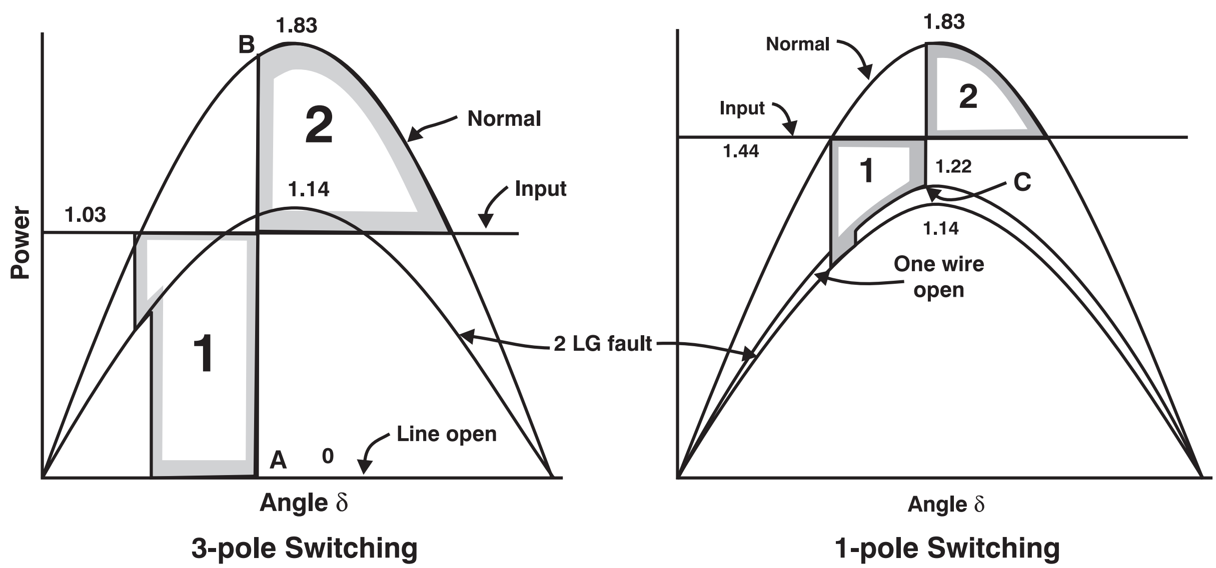

Figure 17: Comparison of Transient Stability Limits for Three-Pole and Single-Pole Switching [6]

The increase in stability limit is substantial, going from 1.03 pu for 3-pole switching to 1.44 pu for single-pole switching.

VIII. AUTOMATIC RECLOSING APPLICATION CONSIDERATIONS

A. Effects of Autoreclosing on Breaker Interrupting Ratings

The design of the power circuit breaker has evolved over the years and has undergone many improvements in design, mechanism speed, and operating reliability. These improvements, as well as protective relay development and scheme sophistication, have led to higher speed, higher interrupting ratings, and longer duty ratings for the applications employed today.

When developing a reclosing philosophy, the limitations of the breaker to interrupt the fault must be considered. Circuit breaker interrupting capabilities are defined based on the Rated Standard Operating Duty (Standard Duty Cycle). The standard duty cycle, as defined by IEEE C37.04-1979, is 2 operations with a time interval of 15 seconds between operations (CO + 15 sec. + CO). This means that the breaker can operate twice to interrupt its symmetrical interrupting capability current with 15 seconds of dead time between operations.

The speed of the breaker when interrupting the fault is also important, especially where stability is critical. Therefore, breakers also have rated interrupting times. The rated interrupting time of a circuit breaker is the time between the trip circuit energization and power arc interruption on an opening operation, and is used to classify breakers at different speeds.

If the reclosing cycle is other than the standard (i.e., other than two operations and/or other than 15 seconds dead time), the breaker operating duty must be modified. ANSI C37.06-1979 gives factors to be applied to the interrupting capabilities of circuit breakers for reclosing duty cycles other than the standard operating duty.

Examples of non-standard duty cycles using the equations from IEEE C37.04-1979 are summarized in the following table. A breaker with a 39kA interrupting capability rating is modified as follows for various reclosing duty cycles with one or both of the following characteristics applied:

(1) Number of operations
(2) Reclose dead time

Reclosing Duty Cycle	Duty Cycle Characteristic Applied	Modified Interrupting Rating (kA)
CO + 10 sec. +CO	2	29.5
CO + 20 sec. + CO	None	30.0
CO + 10 sec. + CO + 45 sec. + CO	1 & 2	28.0
CO + 15 sec. + CO + 45 sec. + CO	1	28.5
CO + 0 sec. + CO + 10 sec. + CO	1 & 2	26.5

Examples of other reclosing capabilities for some reclosing duty cycles are shown graphically in Figure 18.

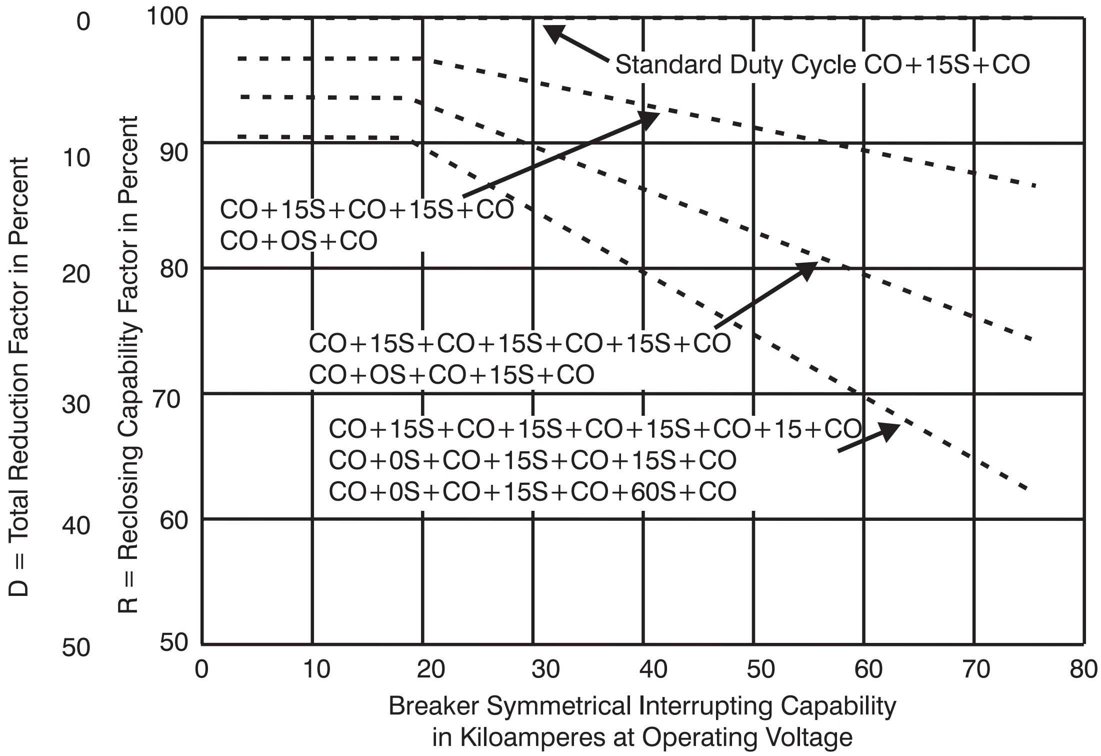

Figure 18: Examples of Reclosing Capability for Some Typical Reclosing Duty Cycles [4]

B. Lines With Generators

On single-tie circuits with dispersed generation, reclosing on the circuit must be delayed long enough for the dispersed generation to be isolated from the utility. If this does not happen, the generator may be damaged due to the utility source closing into the generator out of synchronism. As an additional safety factor, where there is customer generation, voltage supervision is often applied to the autoreclosing scheme. In this case, autoreclosing is delayed until a dead line is sensed (also known as live line blocking, or LLB), thus preventing reclosing into the dispersed generation. See Figure 19. Note that, for complete dead line sensing, all three phaes must be monitored.

Alternatively, if high-speed tripping (transfer trip, pilot wire, etc.) is used to trip the generation, high-speed reclosing may be considered. See Figure 20.

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If the dispersed generator has the capacity to maintain the connected load, it may be used to do so in the event that the utility tie is lost. In this case, the dispersed generation needs to have the ability for dead line closing. In addition, before the utility tie is reestablished, this generation must be isolated from the utility to prevent the utility from damaging the generator when re-energizing. This can be done either locally or remotely. The generation can also be tied back to the utility system using synchronism check.

If the generation capacity is insufficient to supply the connected load, it should be removed from the system upon a trip of the utility supply and prior to the utility reclosing.

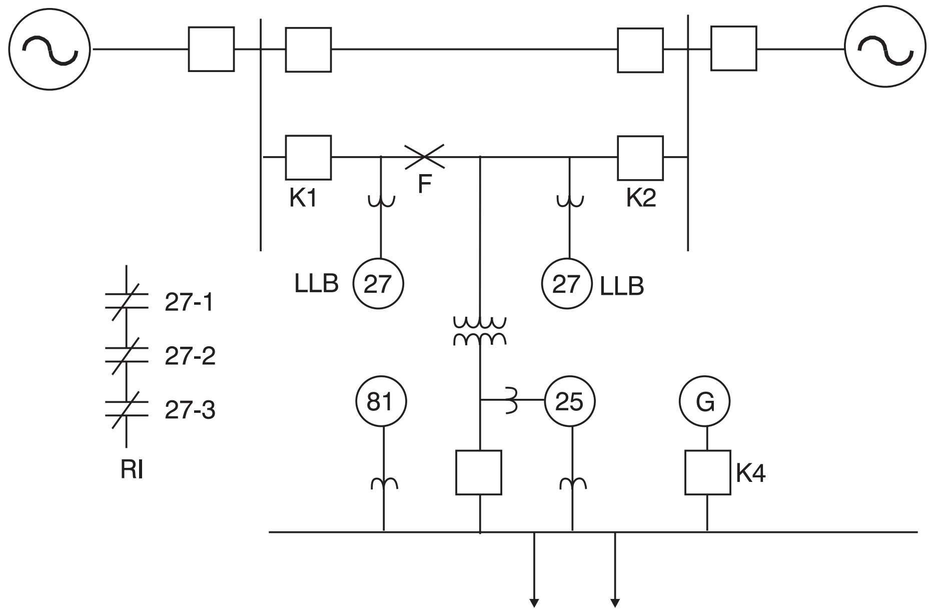

Figure 19: Delayed Autoreclosing on Lines with Generation

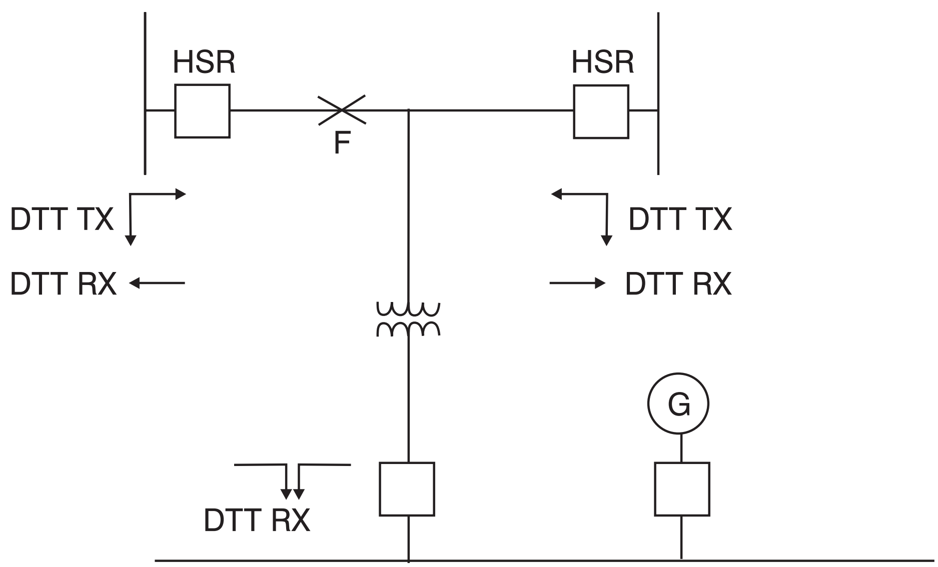

Figure 20: High-Speed Autoreclosing and DTT on Lines with Generation

1. Effects of Autoreclosing on Generator Shafts

Recent studies have raised concerns with reclosing breakers near generation and the possibility of exceeding stress limits in turbine generator shafts [1,7,8]. As early as 1944, in a paper on single pole switching, the problem of mechanical shock to generator shafts during fault clearing and reclosing was discussed. The authors concluded that the calculation of stresses "may dictate single pole switching, regardless of transient power limits."

Because of the uncertainties of reclosing near generating stations, application practices vary widely and many include one or more of the following:

1. Delayed reclosing for all faults (e.g., 10 seconds or more to allow decay of oscillations)
2. Sequential reclosing, remote end first.
3. Selective HSR (e.g., Single pole operation or other type of relaying designed to avoid reclosing on multiphase faults)
4. No automatic reclosing at all.

Delayed reclosing for all faults:
One recommended alternative to HSR is to allow enough dead time (delay reclosing) for the torsional shaft oscillations produced by the initial fault to decay [7]. The damping of the subsynchronous resonant oscillations (SSR) is the damping due to the twisting of the turbine-generator interconnecting shaft and the damping associated with the oscillations of the turbine blades due to interaction with the steam.

Studies indicate that damping of the SSR oscillations is a function of load and is dominated by the steam-turbine blade interaction [7]. One study shows that damping time constants range from 8 to 30 seconds, depending on the level of excitation (due to switching, HSR, etc.). Reclosing delays of 10 seconds have been recommended in some studies.

Studies have also shown that models can be used to determine the torques that result on the turbine-generator due to various disturbances in the power system. This, by itself, does not determine the amount of damage these torques cause to the turbine-generator. A suggested fatigue model used for the evaluation of this damage is very complex and uses assumptions based on both empirical and statistical methods. This fact must be recognized when interpreting any results using this model. It is suggested that fatigue cannot be directly correlated to simple measures, such as the shaft's peak torque following a disturbance, but that it is a cumulative effect related to the overall nature of the torque transient. Further study in the area of torsional fatigue is suggested to improve techniques for predicting accumulating damage. Figure 20 shows a simple turbine-generator shaft-system model with corresponding torques and spring constants.

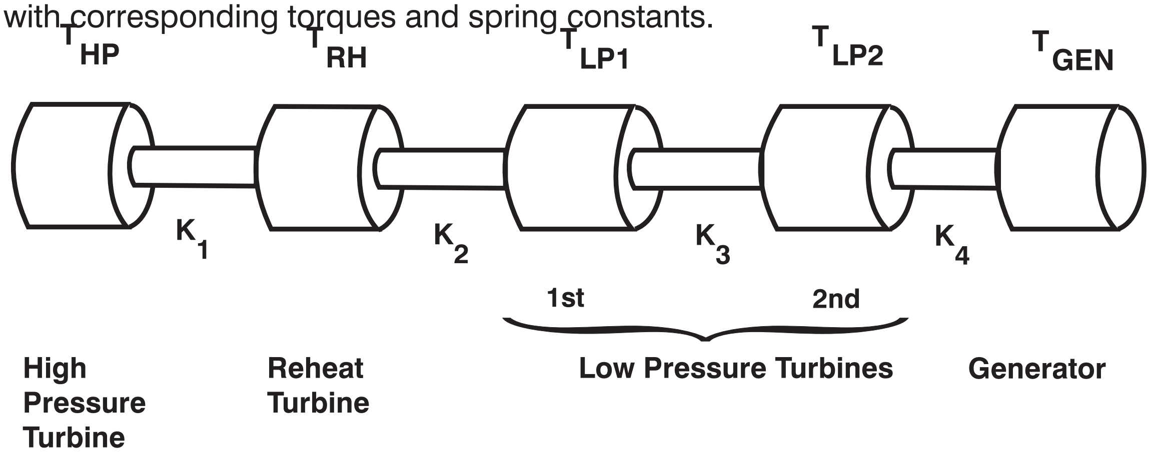

Figure 21: Shaft-System Model [7]

Sequential reclosing:
Reclosing the remote end of a line with generation will result in reduced torsional stress on the generator, provided the remote end is electrically removed enough from the generator.

See Figure 22.

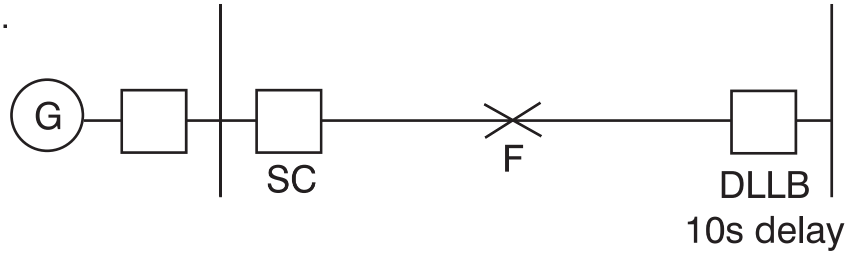

Figure 22: Sequential Reclosing on Lines with Generation Reduced Torsional Stress

Selective HSR:
Various studies have concluded that significant shaft damage is possible when high-speed reclosing into a close-in, three-phase fault. However, at least one study shows no significant damage for any fault where HSR is successful or for any line-ground fault even where HSR is not successful [7].

Past practices of eliminating HSR near generator sites are being challenged by recent studies. It has been suggested that HSR not be eliminated at these sites unless it can be shown, for a specific situation, that the risk of shaft damage is significant. High-speed reclosing near generator sites has the potential to enhance system reliability and maintain generation that would otherwise be lost during system disturbances, and these recent studies indicates possible review of existing reclosing policies.

C. Lines With Motors

Switching operations on motor loads, both induction and synchronous, can produce high transient torques on the motor and, thereby, cause damage to or destruction of the motor. One example may be in an industrial plant with critical induction motor loads that have a primary bus to supply the motors and an auxiliary bus with a separate supply.(See Figure 23.) If the voltage on the main bus is lost, a fast bus transfer is made to the auxiliary in order to maintain the critical motor load. Large torques can result. If this rapid transfer is mandatory, there are safe limits that need to be considered for reconnection of motors. These limits are complex and beyond the scope of this paper. If rapid transfer is not critical, the best policy is to delay the re-energization of the induction motors until the motor voltage has dropped to a safe level. Levels of 33% or less are in common use.

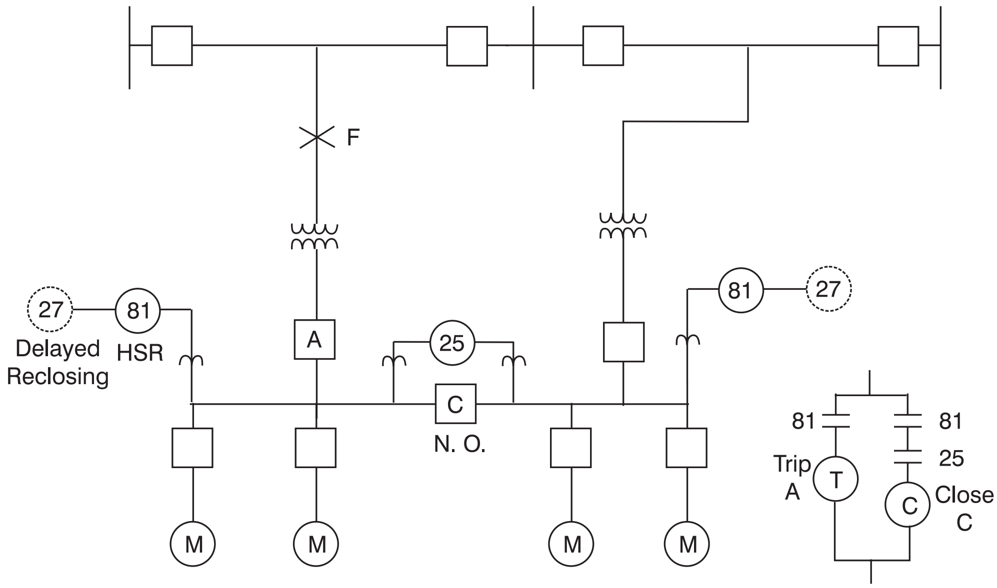

Figure 23: Bus Transfer on Lines with Motors

Another example is an industrial plant with induction motor loads that is supplied by a single utility tie. (See Figure 24.) For a fault on the utility line, the motor loads are subject to transient torques upon reclosing of the utility line breaker. In this case, either the motor loads need to be tripped prior to the utility reclosing, or the reclosing should be delayed long enough for the voltage on the motor to decay to a safe level. The rate of decay of the motor voltage is dependent upon the motor design and motor load.

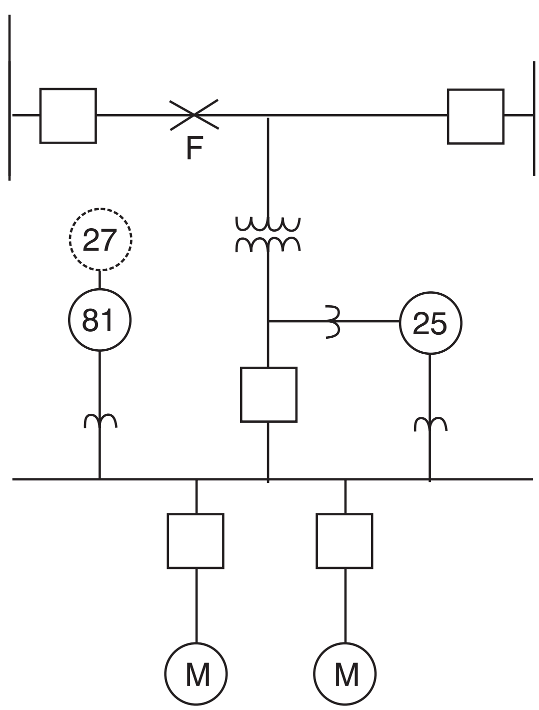

Figure 24: Autoreclosing on Lines with Motors

For synchronous motors, steps should be taken to take these motors off line prior to reclosing or re-energizing the supply. Re-energizing of the synchronous motor should be done in synchronism with the source.

An effective means to open the motor breaker during high-speed reclosing is the application of an underfrequency relay. Typical underfrequency relay (81) settings would be 98-97% of rated, with time to override the momentary voltage dip effects, but before re-energization can take place. An undervoltage relay (27) and/or synchronism check relay (25) may be used to supervise closing of the motor bus to ensure proper voltage decay, frequency, or phase angle. If the plant has local generation, or there are other ties with generation of the supply feeder, care should be taken to ensure that the frequency declines on loss of the utility. Generation sufficient to maintain load, particularly at light-load periods, results in negligible frequency change.

It is important that the system engineer be aware of the potential for damage from transient torques that may result from any of the above factors. To this extent, the above aspects should be studied in detail and their potential effect on motors connected to the system should be evaluated.

D. Lines With Cables

Faults on lines that are underground cable tend to be permanent in nature. Thus, reclosing on completely underground lines is not generally used, as doing so is likely to aggravate the damage.

Circuits comprised of both underground cable and overhead lines could have autoreclosing depending on the utility practice. In this case, the number of reclosing operations may be reduced to a single shot. The basis for determining whether autoreclosing should be used is usually based on the possibility of the fault occurring on the overhead portion of the line and, thus, being able to reclose successfully.

In some instances, where a small portion of the circuit from the substation is cable and a larger portion beyond this is overhead, an autoreclosing scheme that blocks reclosing for close-in faults (e.g., on the cable) may be used.

Another approach is to install separate relaying on the cable portion to block reclosing for a fault on the cable such as current differential or pilot wire relaying. This may be cost prohibitive as there would also be the need for some form of communication channel connecting each end of the cable protection, freestanding current transformers on the line at the cable/overhead line transition, etc.

E. Lines With Automatic Sectionalizing [5]

A sectionalizer is a circuit-isolating mechanism that is not rated to interrupt fault current. It will typically open while de-energized after counting a number of fault current pulses or on loss of potential. It will be closed either manually or, after a time delay, on restoration of potential.

Sectionalizing applications on transmission lines are similar to those on distribution lines. The line usually feeds tapped loads. By using sectionalizing schemes, a permanent fault can be isolated, and maintain power to these loads. Successful sectionalizing requires that both reclosing and reset times of the reclosing relays associated with the line breakers and the line sectionalizing equipment coordinate.

Figure 25 shows a transmission line using a sectionalizer with motor-operated disconnects. For proper sectionalizing, the reclose time of the breaker reclosing relay must be longer than the opening time of the sectionalizer and the motor operated disconnect switch combined. The opening time of the sectionalizer must include the operating time of the initiating devices. If the controlling device is a time delay undervoltage relay, its operating time must be accounted for so that the line is not re-energized while the sectionalizer or the motor operated disconnects are opening.

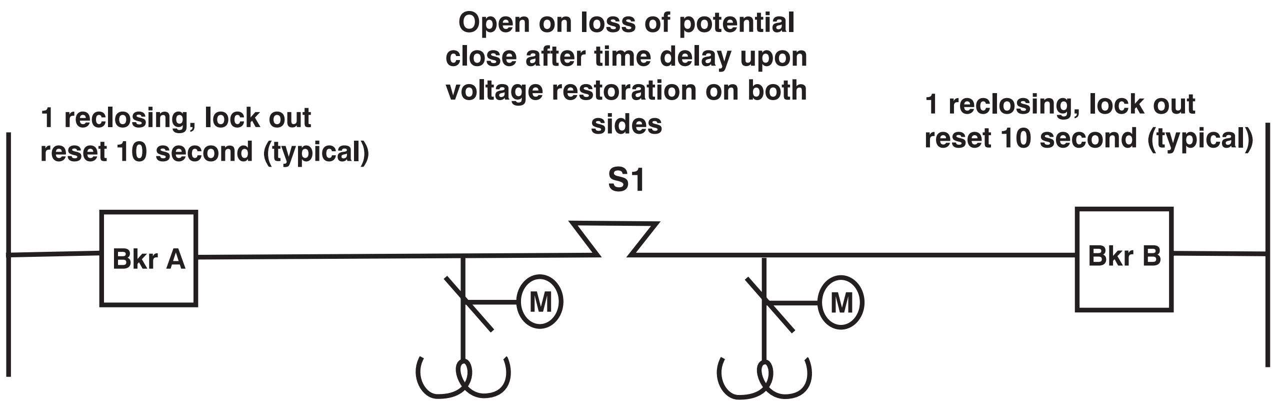

Figure 25: Transmission Lines with Automatic Sectionalizing [5]

Figure 26 shows a transmission-line sectionalizing scheme employing two sectionalizers. Note that upon voltage restoration, the reset time of the line breaker (A, B) reclosing relays must be shorter than the closing time of the sectionalizer. This ensures that the reclosing relays will not be locked out if the fault is between the breaker and the sectionalizer.

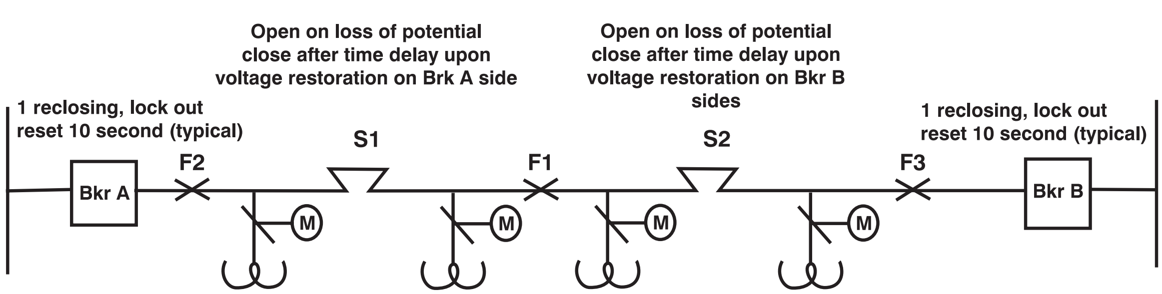

Figure 26: Transmission Lines with Automatic Sectionalizing [5]

The sequence of operation is as follows:

- Fault occurs between S1 and S2. (F1)
- Source breakers A and B open for the fault.
- S1 and S2 open on loss of potential.
- Breakers A and B reclose to reenergize the line up to S1 and S2.
- Assuming S1 delay of closing is set shorter than that of S2, S1 will close after restoration of potential on its source side. Breakers A and B reclosing relays have reset at this point. (Remember, the reset times for A and B are shorter than the time for S1 and S2 to close.)
- Breaker A senses the fault again and opens. S1 opens and locks out due to loss of potential before its reclosing relay has reset.
- Breaker A recloses and remains closed.
- Upon restoration of potential on its source side, S2 reclosing relay times out and closes S2.
- Breaker B senses the fault again and opens. S2 opens and locks out.
- Breaker B closes and remains closed.
- The faulted section has now been isolated between S1 and S2.

For faults between breaker A and S1 (F2) or between breaker B and S2 (F3), the respective source breaker will reclose and operate to lock out. The respective sectionalizer will open and remain open until potential has been restored on the source breaker side of the sectionalizer.

F. Lines With Transformers

The protection on transmission lines that have tapped transformers without breakers or that terminate in transformers without a breaker should be blocked from reclosing for faults within the transformer. It is normal practice not to re-energize the faulted transformer until the unit has been inspected and repaired. See Figure 27.

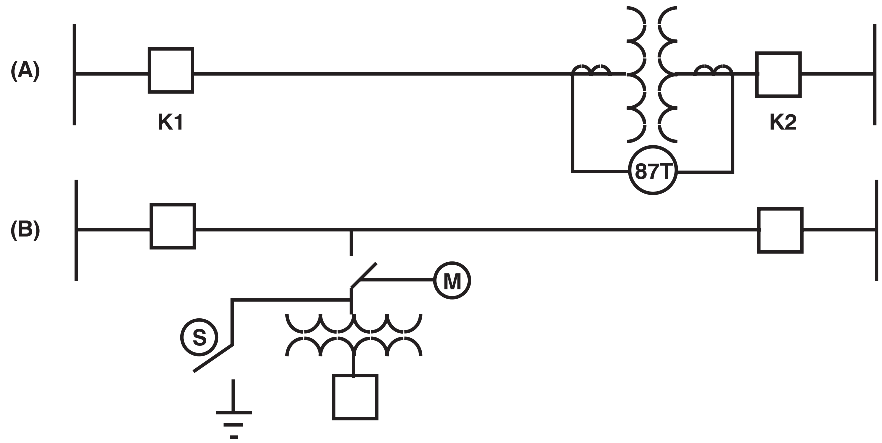

Figure 27: Autoreclosing on Lines with Transformers

In Figure 27A, differential protection at the transformer can also be used to initiate the sending of a direct transfer trip signal to trip and block automatic reclosing of the remote breaker. Automatic reclosing of the terminal breakers (K1, K2) for a line fault should be permitted. This scheme requires a signaling channel.

Some transformer installations as shown in Figure 27, use a motor operated air switch on the high side for isolation of the transformer under normal switching conditions. The switch is often used in conjunction with a direct transfer trip scheme or an automatic ground switch as shown in Figure 27B. Opening of the air switch may be initiated directly by operation of the transformer protective relays, or it may be supervised by a voltage relay so that it opens only after the line is de-energized. In either case, the reclosing time of the remote line breakers must be coordinated with the switch opening time to prevent re-energizing when the switch is partially open.

G. Lines With Capacitors

Series and shunt capacitors are used in power systems to increase power transfer characteristics (series), to reduce system losses by improving the power factor, and to aid in the regulation of the system voltages (shunt). Series capacitors are generally used on transmission lines while shunt banks are generally located on distribution stations and feeders.

Energizing and de-energizing shunt capacitor banks or switching banks back-to-back, can produce severe transients and possible overvoltages. These need to be considered when applying autoreclosing near shunt capacitor banks.

When the source feeding a line with a shunt bank is interrupted, the shunt bank also tends to hold up the voltage longer than if no bank were in service. This can effect, for example, the voltage decay time on a motor disconnected from the bus. If autoreclosing is used on the motor bus, longer delay times or voltage supervision may be required. See Figure 28.

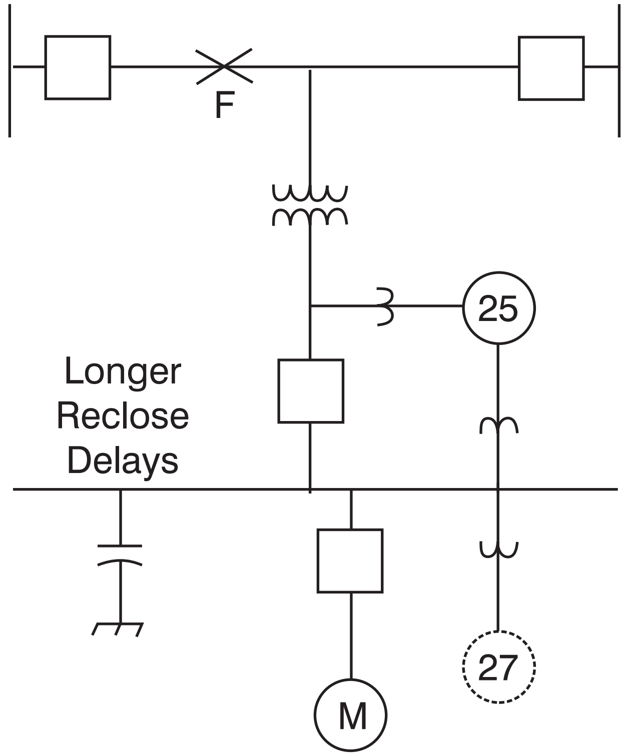

Figure 28: Autoreclosing on Lines with Capacitors and Motors

IX. RECLOSE SUPERVISION/RECLOSE BLOCKING

A number of the applications considered in this paper includes a requirement for some form of recloser supervision and/or reclose blocking for various situations. Below is a summary of some of these conditions that use reclose supervision and blocking.

Consider blocking autoreclosing for the following conditions:
Receipt of transfer trip
Manual trip
Breaker failure
Hot line maintenance
Three phase faults
Faults on buses - bus differential relay operation
Faults on transformers - transformer differential relay operation
Faults on underground cables
Out-of-step condition
Underfrequency / undervoltage load shedding trips
High impedance fault detection on distribution lines
High current, close-in faults

Line side voltage supervision
Autoreclosing will be blocked for sensed voltage on the line. Live line blocking is generally used where large motors or generators are connected to the line. This blocking prevents damage to the motor or generator from being energized out of phase with the system. To ensure complete line side voltage supervision, all three phases should be monitored.

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If you have any questions or need
additional information, please contact

Basler Electric Company

12570 State Route 143, Highland, Illinois U.S.A. 62249-1074
Tel +1 618.654.2341 Fax +1 618.654.2351
e-mail: info@basler.com

www.basler.com

No. 59 Heshun Road Loufeng District (N),
Suzhou Industrial Park, 215122, Suzhou, P.R.China
Tel +86(0)512 8227 2888 Fax +86(0)512 8227 2887
e-mail: chinainfo@basler.com

111 North Bridge Rd #15-06 Peninsula Plaza
Singapore 179098
Tel +65 68.44.6445 Fax +65 65.68.44.8902
e-mail: singaporeinfo@basler.com