· 14 · *Auto-Reclosing*

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14.1 INTRODUCTION

Faults on overhead lines fall into one of three categories:

a. transient
b. semi-permanent
c. permanent

80-90% of faults on any overhead line network are transient in nature. The remaining 10%-20% of faults are either semi-permanent or permanent.

Transient faults are commonly caused by lightning and temporary contact with foreign objects. The immediate tripping of one or more circuit breakers clears the fault. Subsequent re-energisation of the line is usually successful.

A small tree branch falling on the line could cause a semi-permanent fault. The cause of the fault would not be removed by the immediate tripping of the circuit, but could be burnt away during a time-delayed trip. HV overhead lines in forest areas are prone to this type of fault. Permanent faults, such as broken conductors, and faults on underground cable sections, must be located and repaired before the supply can be restored.

Use of an auto-reclose scheme to re-energise the line after a fault trip permits successful re-energisation of the line. Sufficient time must be allowed after tripping for the fault arc to de-energise prior to reclosing otherwise the arc will re-strike. Such schemes have been the cause of a substantial improvement in continuity of supply. A further benefit, particularly to EHV systems, is the maintenance of system stability and synchronism.

A typical single-shot auto-reclose scheme is shown in Figures 14.1 and 14.2. Figure 14.1 shows a successful reclosure in the event of a transient fault, and Figure 14.2 an unsuccessful reclosure followed by lockout of the circuit breaker if the fault is permanent.

14.2 APPLICATION OF AUTO-RECLOSING

The most important parameters of an auto-reclose scheme are:

1. dead time
2. reclaim time
3. single or multi-shot

These parameters are influenced by:

a. type of protection
b. type of switchgear
c. possible stability problems
d. effects on the various types of consumer loads

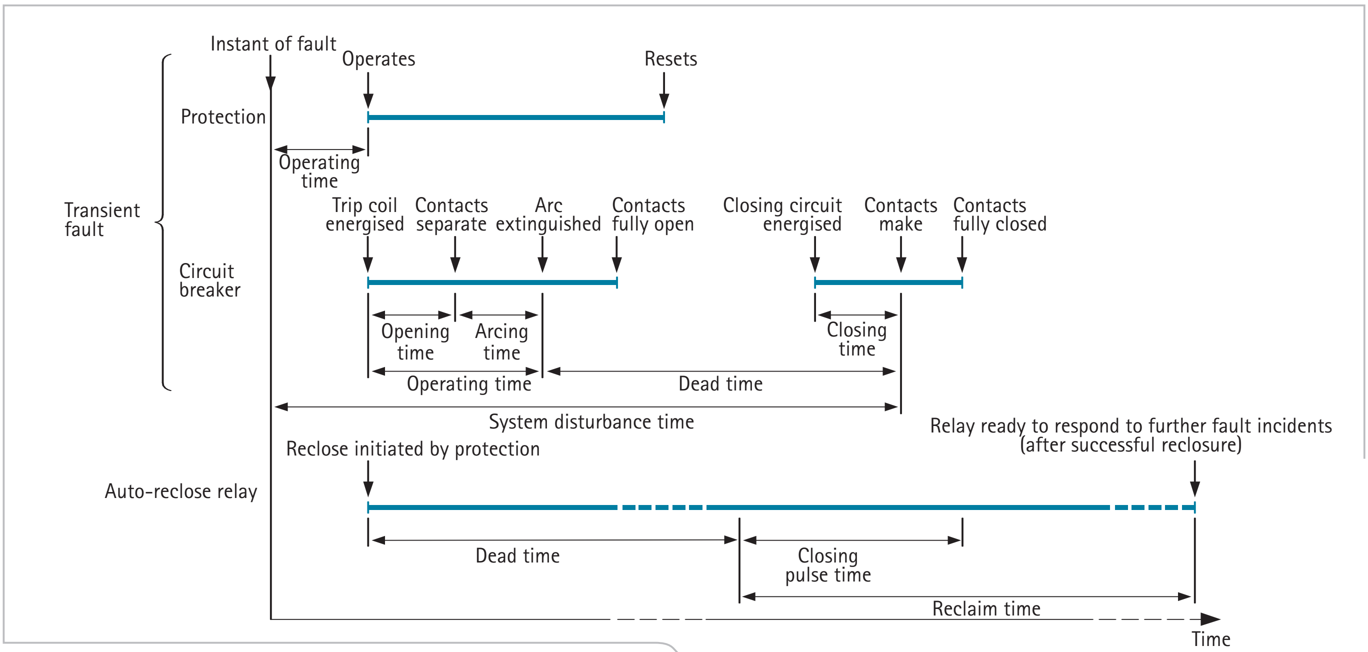


Figure 14.1: Single-shot auto-reclose scheme operation for a transient fault

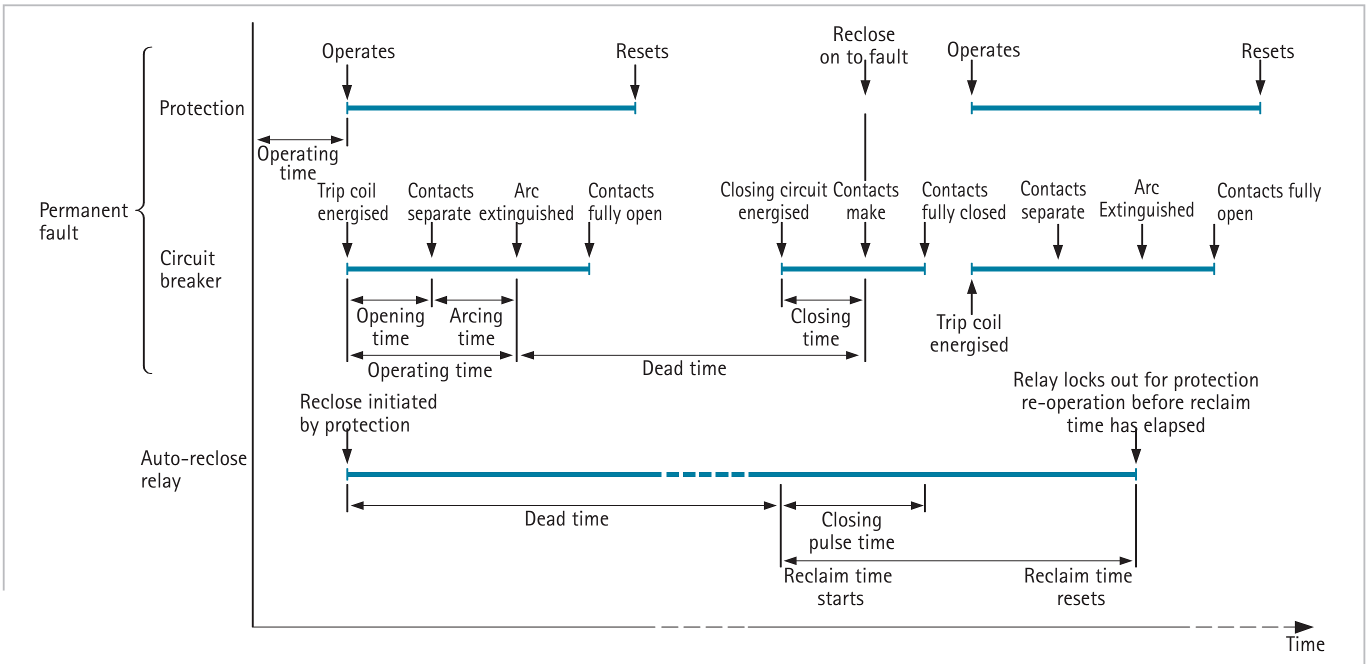


Figure 14.2: Operation of single-shot auto-reclose scheme on a permanent fault

The weighting given to the above factors is different for HV distribution networks and EHV transmission systems and therefore it is convenient to discuss them under separate headings. Sections 14.3 and 14.4 cover the application of auto-reclosing to HV distribution networks while Sections 14.5-14.9 cover EHV schemes.

The rapid expansion in the use of auto-reclosing has led to the existence of a variety of different control schemes. The various features in common use are discussed in Section 14.10. The related subject of auto-closing, that is, the automatic closing of normally open circuit breakers, is dealt with in Section 14.11.

14.3 AUTO-RECLOSING ON HV DISTRIBUTION NETWORKS

On HV distribution networks, auto-reclosing is applied mainly to radial feeders where problems of system stability do not arise, and the main advantages to be derived from its use can be summarised as follows:

a. reduction to a minimum of the interruptions of supply to the consumer

b. instantaneous fault clearance can be introduced, with the accompanying benefits of shorter fault duration, less fault damage, and fewer permanent faults

As 80% of overhead line faults are transient, elimination of loss of supply from this cause by the introduction of auto-reclosing gives obvious benefits through:

a. improved supply continuity

b. reduction of substation visits

Instantaneous tripping reduces the duration of the power arc resulting from an overhead line fault to a minimum. The chance of permanent damage occurring to the line is reduced. The application of instantaneous protection may result in non-selective tripping of a number of circuit breakers and an ensuing loss of supply to a number of healthy sections. Auto-reclosing allows these circuit breakers to be reclosed within a few seconds. With transient faults, the overall effect would be loss of supply for a very short time but affecting a larger number of consumers. If only time-graded protection without auto-reclose was used, a smaller number of consumers might be affected, but for a longer time period.

When instantaneous protection is used with auto-reclosing, the scheme is normally arranged to inhibit the instantaneous protection after the first trip. For a permanent fault, the time-graded protection will give discriminative tripping after reclosure, resulting in the isolation of the faulted section. Some schemes allow a number of reclosures and time-graded trips after the first instantaneous trip, which may result in the burning out and clearance of semi-permanent faults. A further benefit of instantaneous tripping is a reduction in circuit breaker maintenance by reducing pre-arc heating when clearing transient faults.

When considering feeders that are partly overhead line and partly underground cable, any decision to install auto-reclosing would be influenced by any data known on the frequency of transient faults. Where a significant proportion of faults are permanent, the advantages of auto-reclosing are small, particularly since reclosing on to a faulty cable is likely to aggravate the damage.

14.4 FACTORS INFLUENCING HV AUTO-RECLOSE SCHEMES

The factors that influence the choice of dead time, reclaim time, and the number of shots are now discussed.

14.4.1 Dead Time

Several factors affect the selection of system dead time as follows:

a. system stability and synchronism
b. type of load
c. CB characteristics
d. fault path de-ionisation time
e. protection reset time

These factors are discussed in the following sections.

14.4.1.1 System stability and synchronism

In order to reclose without loss of synchronism after a fault on the interconnecting feeder, the dead time must be kept to the minimum permissible consistent with de-ionisation of the fault arc. Other time delays that contribute to the total system disturbance time must also be kept as short as possible. The problem arises only on distribution networks with more than one power source, where power can be fed into both ends of an inter-connecting line. A typical example is embedded generation (see Chapter 17), or where a small centre of population with a local diesel generating plant may be connected to the rest of the supply system by a single tie-line.

The use of high-speed protection, such as unit protection or distance schemes, with operating times of less than 0.05s is essential. The circuit breakers must have very short operation times and then be able to reclose the circuit after a dead time of the order of 0.3s-0.6s to allow for fault-arc de-ionisation.

It may be desirable in some cases to use synchronism check logic, so that auto-reclosing is prevented if the phase angle has moved outside specified limits. The matter is dealt with more fully in Section 14.9 on EHV systems.

14.4.1.2 Type of load

On HV systems, the main problem to be considered in relation to dead time is the effect on various types of consumer load.

a. industrial consumers

Most industrial consumers operate mixed loads comprising induction motors, lighting, process control and static loads. Synchronous motors may also be used. Dead time has to be long enough to allow motor circuits to trip out on loos of supply. Once the supply is restored, restarting of drives can then occur under direction of the process control system in a safe and programmed manner, and can often be fast enough to ensure no significant loss of production or product quality

b. domestic consumers

It is improbable that expensive processes or dangerous conditions will be involved with domestic consumers and the main consideration is that of inconvenience and compensation for supply interruption. A dead time of seconds or a few minutes is of little importance compared with the loss of cooking facilities, central heating, light and audio/visual entertainment resulting from a longer supply failure that could occur without auto-reclosing

14.4.1.3 Circuit breaker characteristics

The time delays imposed by the circuit breaker during a tripping and reclosing operation must be taken into consideration, especially when assessing the possibility of applying high speed auto-reclosing.

a. mechanism resetting time

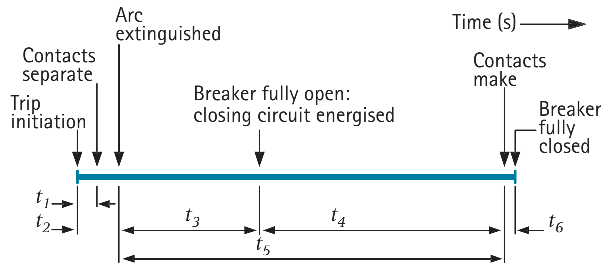
Most circuit breakers are 'trip free', which means that the breaker can be tripped during the closing stroke.

After tripping, a time of the order of 0.2s must be allowed for the trip-free mechanism to reset before applying a closing impulse. Where high speed reclosing is required, a latch check interlock is desirable in the reclosing circuit

b. closing time

This is the time interval between the energisation of the closing mechanism and the making of the contacts. Owing to the time constant of the solenoid and the inertia of the plunger, a solenoid closing mechanism may take 0.3s to close. A spring-operated breaker, on the other hand, can close in less than 0.2s. Modern vacuum circuit breakers may have a closing time of less than 0.1s

The circuit breaker mechanism imposes a minimum dead time made up from the sum of (a) and (b) above. Figure 14.3 illustrates the performance of modern HV circuit breakers in this respect. Older circuit breakers may require longer times than those shown.



	Oil 11kV	Vacuum 15kV	Oil 132kV	Air 380kV	SF_6 132kV	SF_6 380kV
t_1	0.06	0.038	0.03	0.035	0.04	0.02
t_2	0.1	0.053	0.06	0.045	0.07	0.05
t_3	0.08	0.023	0.2	0.235	0.03	0.01
t_4	0.16	0.048	0.35	0.065	0.08	0.06
t_5	0.24	0.28	0.55	0.3	0.11	0.07
t_6	0.02	0.07	0.01	0.02	0.12	0.04

Note: 380kV data applicable to 400kV also. All times in seconds

Figure 14.3: Typical circuit breaker trip-close operation times

14.4.1.4 De-ionisation of fault path

As mentioned above, successful high speed reclosure requires the interruption of the fault by the circuit breaker to be followed by a time delay long enough to allow the ionised air to disperse. This time is dependent on the system voltage, cause of fault, weather conditions and so on, but at voltages up to 66kV, 0.1s-0.2s should be adequate. On HV systems, therefore, fault de-ionisation time is of less importance than circuit breaker time delays.

14.4.1.5 Protection reset time

If time delayed protection is used, it is essential that the timing device shall fully reset during the dead time, so that correct time discrimination will be maintained after reclosure on to a fault. The reset time of the electromechanical I.D.M.T. relay is 10 seconds or more when on maximum time setting, and dead times of at least this value may be required.

When short dead times are required, the protection relays must reset almost instantaneously, a requirement that is easily met by the use of static, digital and numerical I.D.M.T. relays.

14.4.2 Reclaim Time

Factors affecting the setting of the reclaim time are discussed in the following sections.

14.4.2.1 Type of protection

The reclaim time must be long enough to allow the protection relays to operate when the circuit breaker is reclosed on to a permanent fault. The most common forms of protection applied to HV lines are I.D.M.T. or definite time over-current and earth-fault relays. The maximum operating time for the former with very low fault levels could be up to 30 seconds, while for fault levels of several times rating the operating time may be 10 seconds or less.

In the case of definite time protection, settings of 3 seconds or less are common, with 10 seconds as an absolute maximum. It has been common practice to use reclaim times of 30 seconds on HV auto-reclose schemes. However, there is a danger with a setting of this length that during a thunderstorm, when the incidence of transient faults is high, the breaker may reclose successfully after one fault, and then trip and lock out for a second fault within this time. Use of a shorter reclaim time of, say, 15 seconds may enable the second fault to be treated as a separate incident, with a further successful reclosure.

Where fault levels are low, it may be difficult to select I.D.M.T. time settings to give satisfactory grading with an operating time limit of 15 seconds, and the matter becomes a question of selecting a reclaim time compatible with I.D.M.T. requirements.

It is common to fit sensitive earth-fault protection to supplement the normal protection in order to detect high resistance earth faults. This protection cannot possibly be stable on through faults, and is therefore set to have an operating time longer than that of the main protection. This longer time may have to be taken into consideration when deciding on a reclaim time. A broken overhead conductor in contact with dry ground or a wood fence may cause this type of fault. It is rarely if ever transient and may be a danger to the public. It is therefore common practice to use a contact on the sensitive earth fault relay to block auto-reclosing and lock out the circuit breaker.

Where high-speed protection is used, reclaim times of 1 second or less would be adequate. However, such short times are rarely used in practice, to relieve the duty on the circuit breaker.

14.4.2.2 Spring winding time

The reclaim time of motor-wound spring-closed breakers must be at least as long as the spring winding time, to ensure that the breaker is not subjected to a further reclosing operating with a partly wound spring.

14.4.3 Number of Shots

There are no definite rules for defining the number of shots for any particular auto-reclose application, but a number of factors must be taken into account.

14.4.3.1 Circuit breaker limitations

Important considerations are the ability of the circuit breaker to perform several trip and close operations in quick succession and the effect of these operations on the maintenance period. Maintenance periods vary according to the type of circuit breaker used and the fault current broken when clearing each fault. Use of modern numerical relays can assist, as they often have a CB condition-monitoring feature included that can be arranged to indicate to a Control Centre when maintenance is required. Auto-reclose may then be locked out until maintenance has been carried out.

14.4.3.2 System conditions

If statistical information on a particular system shows a moderate percentage of semi-permanent faults that could be burned out during 2 or 3 time-delayed trips, a multi-shot scheme may be justified. This is often the case in forest areas. Another situation is where fused 'tees' are used and the fault level is low, since the fusing time may not discriminate with the main I.D.M.T. relay. The use of several shots will heat the fuse to such an extent that it would eventually blow before the main protection operated.

14.5 AUTO-RECLOSING ON EHV TRANSMISSION LINES

The most important consideration in the application of auto-reclosing to EHV transmission lines is the maintenance of system stability and synchronism. The problems involved are dependent on whether the transmission system is weak or strong. With a weak system, loss of a transmission link may lead quickly to an excessive phase angle across the CB used for re-closure, thus preventing a successful re-closure. In a relatively strong system, the rate of change of phase angle will be slow, so that delayed auto-reclose can be successfully applied.

An illustration is the interconnector between two power systems as shown in Figure 14.4. Under healthy conditions, the amount of synchronising power transmitted, P, crosses the power/angle curve OAB at point X, showing that the phase displacement between the two systems is θ_0. Under fault conditions, the curve OCB is applicable, and the operating point changes to Y. Assuming constant power input to both ends of the line, there is now an accelerating power XY. As a result, the operating point moves to Z, with an increased phase displacement, θ_1, between the two systems. At this point the circuit breakers trip and break the connection. The phase displacement continues to increase at a rate dependent on the inertia of the two power sources. To maintain synchronism, the circuit breaker must be reclosed in a time short enough to prevent the phase angle exceeding θ_2. This angle is such that the area (2) stays greater than the area (1), which is the condition for maintenance of synchronism.

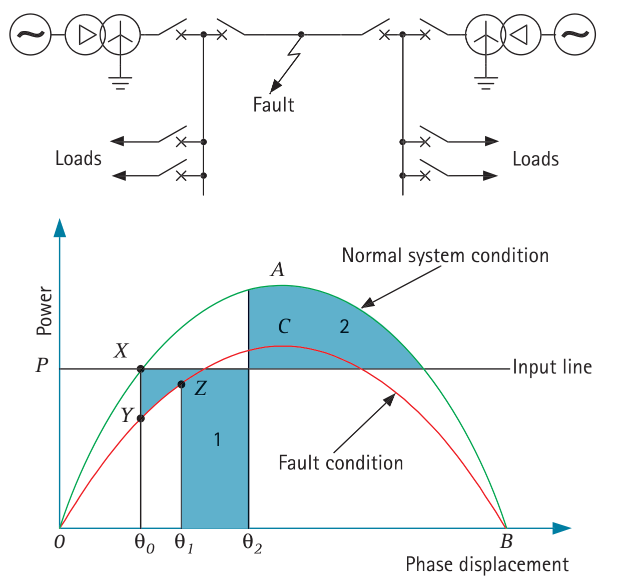


Figure 14.4: Effect of high-speed three-phase auto-reclosing on system stability for a weak system

This example, for a weak system, shows that the successful application of auto-reclosing in such a case needs high-speed protection and circuit breakers, and a short dead time. On strong systems, synchronism is unlikely to be lost by the tripping out of a single line. For such systems, an alternative policy of delayed auto-reclosing may be adopted. This enables the power swings on the system resulting from the fault to decay before reclosure is attempted.

The various factors to be considered when using EHV auto-reclose schemes are now dealt with. High-speed and delayed auto-reclose schemes are discussed separately.

14.6 HIGH SPEED AUTO-RECLOSING ON EHV SYSTEMS

The first requirement for the application of high-speed auto-reclosing is knowledge of the system disturbance time that can be tolerated without loss of system stability. This will normally require transient stability studies to be conducted for a defined set of power system configurations and fault conditions. With knowledge of protection and circuit breaker operating characteristics and fault arc de-ionisation times, the feasibility of high-speed auto-reclosing can then be assessed. These factors are now discussed.

14.6.1 Protection Characteristics

The use of high-speed protection equipment, such as distance or unit protection schemes, giving operating times of less than 50ms, is essential. In conjunction with fast operating circuit breakers, high-speed protection reduces the duration of the fault arc and thus the total system disturbance time.

It is important that the circuit breakers at both ends of a fault line should be tripped as rapidly as possible. The time that the line is still being fed from one end represents an effective reduction in the dead time, and may well jeopardise the chances of a successful reclosure. When distance protection is used, and the fault occurs near one end of the line, special measures have to be adopted to ensure simultaneous tripping at each end. These are described in Section 14.8.

14.6.2 De-Ionisation of Fault Arc

It is important to know the time that must be allowed for complete de-ionisation of the arc, to prevent the arc restriking when the voltage is re-applied.

The de-ionisation time of an uncontrolled arc, in free air depends on the circuit voltage, conductor spacing, fault currents, fault duration, wind speed and capacitive coupling from adjacent conductors. Of these, the circuit voltage is the most important, and as a general rule, the higher the voltage the longer the time required for de-ionisation. Typical values are given in Table 14.1.

Line voltage (kV)	Minimum de-energisation time (seconds)
66	0.2
110	0.28
132	0.3
220	0.35
275	0.38
400	0.45
525	0.55

Table 14.1: Fault-arc de-ionisation times

If single-phase tripping and auto-reclosing is used, capacitive coupling between the healthy phases and the faulty phase tends to maintain the arc and hence extend the dead time required. This is a particular problem on long distance EHV transmission lines.

14.6.3 Circuit Breaker Characteristics

The high fault levels involved in EHV systems imposes a very severe duty on the circuit breakers used in high-speed auto-reclose schemes. The accepted breaker cycle of break-make-break requires the circuit breaker to interrupt the fault current, reclose the circuit after a time delay of upwards of 0.2s and then break the fault current again if the fault persists. The types of circuit breaker commonly used on EHV systems are oil, air blast and SF6 types.

14.6.3.1 Oil circuit breakers

Oil circuit breakers are used for transmission voltages up to 300kV, and can be subdivided into the two types: 'bulk oil' and 'small oil volume'. The latter is a design aimed at reducing the fire hazard associated with the large volume of oil contained in the bulk oil breaker.

The operating mechanisms of oil circuit breakers are of two types, 'fixed trip' and 'trip free', of which the latter is the most common. With trip-free types, the reclosing cycle must allow time for the mechanism to reset after tripping before applying the closing impulse.

Special means have to be adopted to obtain the short dead times required for high-speed auto-reclosing. Various types of tripping mechanism have been developed to meet this requirement.

The three types of closing mechanism fitted to oil circuit breakers are:

- **i.** solenoid
- **ii.** spring
- **iii.** pneumatic

CB's with solenoid closing are not suitable for high-speed auto-reclose due to the long time constant involved. Spring, hydraulic or pneumatic closing mechanisms are universal at the upper end of the EHV range and give the fastest closing time. Figure 14.3 shows the operation times for various types of EHV circuit breakers, including the dead time that can be attained.

14.6.3.2 Air blast circuit breakers

Air blast breakers have been developed for voltages up to the highest at present in use on transmission lines. They fall into two categories:

- **a.** pressurised head circuit breakers
- **b.** non-pressurised head circuit breakers

In pressurised head circuit breakers, compressed air is maintained in the chamber surrounding the main contacts. When a tripping signal is received, an auxiliary air system separates the main contacts and allows compressed air to blast through the gap to the atmosphere, extinguishing the arc. With the contacts fully open, compressed air is maintained in the chamber.

Loss of air pressure could result in the contacts reclosing, or, if a mechanical latch is employed, restriking of the arc in the de-pressurised chamber. For this reason, sequential series isolators, which isolate the main contacts after tripping, are commonly used with air blast breakers. Since these are comparatively slow in opening, their operation must be inhibited when auto-reclosing is required. A contact on the auto-reclose relay is made available for this purpose.

Non-pressurised head circuit breakers are slower in operation than the pressurised head type and are not usually applied in high-speed reclosing schemes.

14.6.3.3 SF6 circuit breakers

Most EHV circuit breaker designs now manufactured use SF6 gas as an insulating and arc-quenching medium. The basic design of such circuit breakers is in many ways similar to that of pressurised head air blast circuit breakers, and normally retain all, or almost all, of their voltage withstand capability, even if the SF6 pressure level falls to atmospheric pressure. Sequential series isolators are therefore not normally used, but they are sometimes specified to prevent damage to the circuit breaker in the event of a lightning strike on an open ended conductor. Provision should therefore be made to inhibit sequential series isolation during an auto-reclose cycle.

14.6.4 Choice of Dead Time

At voltages of 220kV and above, the de-ionisation time will probably dictate the minimum dead time, rather than any circuit breaker limitations. This can be deduced from Table 14.1. The dead time setting on a high-speed auto-reclose relay should be long enough to ensure complete de-ionisation of the arc. On EHV systems, an unsuccessful reclosure is more detrimental to the system than no reclosure at all.

14.6.5 Choice of Reclaim Time

Where EHV oil circuit breakers are concerned, the reclaim time should take account of the time needed for the closing mechanism to reset ready for the next reclosing operation.

14.6.6 Number of Shots

High-speed auto-reclosing on EHV systems is invariably single shot. Repeated reclosure attempts with high fault levels would have serious effects on system stability, so the circuit breakers are locked out after one unsuccessful attempt. Also, the incidence of semi-permanent faults which can be cleared by repeated reclosures is less likely than on HV systems.

14.7 SINGLE-PHASE AUTO-RECLOSING

Single phase to earth faults account for the majority of overhead line faults. When three-phase auto-reclosing is applied to single circuit interconnectors between two power systems, the tripping of all three phases may cause the two systems to drift apart in phase, as described in Section 14.5. No interchange of synchronising power can take place during the dead time. If only the faulty phase is tripped, synchronising power can still be interchanged through the healthy phases. Any difference in phase between the two systems will be correspondingly less, leading to a reduction in the disturbance on the system when the circuit breaker recloses.

For single-phase auto-reclosing each circuit breaker pole must be provided with its own closing and tripping mechanism; this is normal with EHV air blast and SF6 breakers. The associated tripping and reclosing circuitry is therefore more complicated, and, except in distance schemes, the protection may need the addition of phase selection logic.

On the occurrence of a phase-earth fault, single-phase auto-reclose schemes trip and reclose only the corresponding pole of the circuit breaker. The auto-reclose function in a relay therefore has three separate elements, one for each phase. Operation of any element energises the corresponding dead timer, which in turn initiates a closing pulse for the appropriate pole of the circuit breaker. A successful reclosure results in the auto-reclose logic resetting at the end of the reclaim time, ready to respond to a further fault incident. If the fault is persistent and reclosure is unsuccessful, it is usual to trip and lock out all three poles of the circuit breaker.

The above describes only one of many variants. Other possibilities are:

- **a.** three-phase trip and lockout for phase-phase or 3-phase faults, or if either of the remaining phases should develop a fault during the dead time
- **b.** use of a selector switch to give a choice of single or three-phase reclosing
- **c.** combined single and three-phase auto-reclosing; single phase to earth faults initiate single-phase tripping and reclosure, and phase-phase faults initiate three-phase tripping and reclosure

Modern numerical relays often incorporate the logic for all of the above schemes, for the user to select as required. Use can be made of any user-definable logic feature in a numerical relay to implement other schemes that may be required.

The advantages of single-phase auto-reclosing are:

a. the maintenance of system integrity

b. on multiple earth systems, negligible interference with the transmission of load. This is because the current in the faulted phase can flow through earth via the various earthing points until the fault is cleared and the faulty phase restored

The main disadvantage is the longer de-ionisation time resulting from capacitive coupling between the faulty and healthy lines. This leads to a longer dead time being required. Maloperation of earth fault relays on double circuit lines owing to the flow of zero sequence currents may also occur. These are induced by mutual induction between faulty and healthy lines (see Chapter 13 for details).

14.8 HIGH-SPEED AUTO-RECLOSING ON LINES EMPLOYING DISTANCE SCHEMES

The importance of rapid tripping of the circuit breakers at each end of a faulted line where high-speed auto-reclosing is employed has already been covered in Section 14.6. Simple distance protection presents some difficulties in this respect.

Owing to the errors involved in determining the ohmic setting of the distance relays, it is not possible to set Zone 1 of a distance relay to cover 100% of the protected line – see Chapter 11 for more details. Zone 1 is set to cover 80-85% of the line length, with the remainder of the line covered by time-delayed Zone 2 protection.

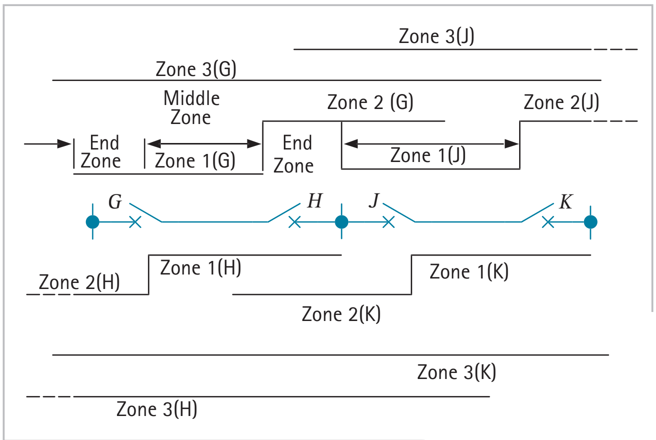


Figure 14.5: Typical three zone distance scheme

Figure 14.5 illustrates this for a typical three-zone distance scheme covering two transmission lines.

For this reason, a fault occurring in an end zone would be cleared instantaneously, by the protection at one end of the feeder. However, the CB at the other end opens in 0.3-0.4 seconds (Zone 2 time). High-speed auto-reclosing applied to the circuit breakers at each end of the feeder could result either in no dead time or in a dead time insufficient to allow de-ionisation of the fault arc. A transient fault could therefore be seen as a permanent one, resulting in the locking out of both circuit breakers.

Two methods are available for overcoming this difficulty. Firstly, one of the transfer-trip or blocking schemes that involves the use of an intertrip signal between the two ends of the line can be used. Alternatively, a Zone 1 extension scheme may be used to give instantaneous tripping over the whole line length. Further details of these schemes are given in Chapter 12, but a brief description of how they are used in conjunction with an auto-reclose scheme is given below.

14.8.1 Transfer-Trip or Blocking Schemes

This involves use of a signalling channel between the two ends of the line. Tripping occurs rapidly at both ends of the faulty line, enabling the use of high-speed auto-reclose. Some complication occurs if single-phase auto-reclose is used, as the signalling channel must identify which phase should be tripped, but this problem does not exist if a modern numerical relay is used.

Irrespective of the scheme used, it is customary to provide an auto-reclose blocking relay to prevent the circuit breakers auto-reclosing for faults seen by the distance relay in Zones 2 and 3.

14.8.2 Zone 1 Extension

In this scheme, the reach of Zone 1 is normally extended to 120% of the line length and is reset to 80% when a command from the auto-reclose logic is received. This auto-reclose logic signal should occur before a closing pulse is applied to the circuit breaker and remain operated until the end of the reclaim time. The logic signal should also be present when auto-reclose is out of service.

14.9 DELAYED AUTO-RECLOSING ON EHV SYSTEMS

On highly interconnected transmission systems, where the loss of a single line is unlikely to cause two sections of the system to drift apart significantly and lose synchronism, delayed auto-reclosing can be employed. Dead times of the order of 5s-60s are commonly used. No problems are presented by fault arc de-ionisation times and circuit breaker operating characteristics, and power swings on the system decay before reclosing. In addition, all tripping and reclose schemes can be three-phase only, simplifying control circuits in comparison with single-phase schemes. In systems on which delayed auto-reclosing is permissible, the chances of a reclosure being successful are somewhat greater with delayed reclosing than would be the case with high-speed reclosing.

14.9.1 Scheme Operation

The sequence of operations of a delayed auto-reclose scheme can be best understood by reference to Figure 14.6. This shows a transmission line connecting two substations *A* and *B*, with the circuit beakers at *A* and *B* tripping out in the event of a line fault. Synchronism is unlikely to be lost in a system that employs delayed auto-reclose. However, the transfer of power through the remaining tie-lines on the system could result in the development of an excessive phase difference between the voltages at points *A* and *B*. The result, if reclosure takes place, is an unacceptable shock to the system. It is therefore usual practice to incorporate a synchronism check relay into the reclosing system to determine whether auto-reclosing should take place.

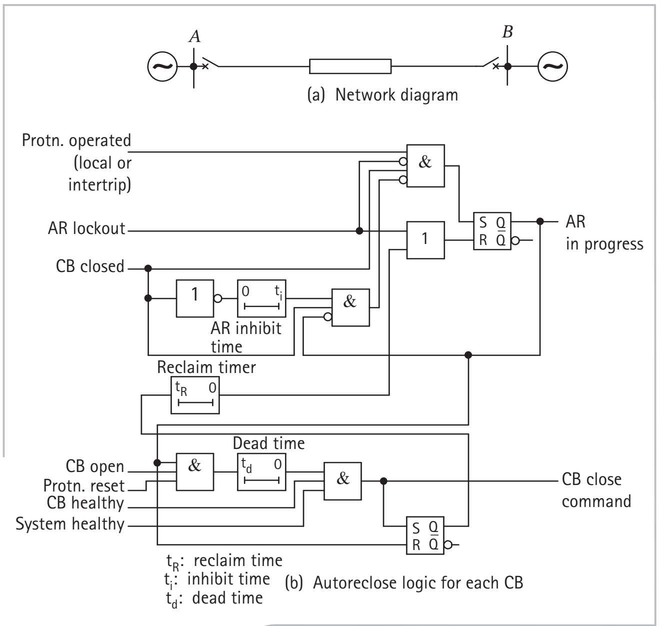


Figure 14.6: Delayed auto-reclose scheme logic

After tripping on a fault, it is normal procedure to reclose the breaker at one end first, a process known as 'live bus/dead line charging'. Reclosing at the other and is then under the control of a synchronism check relay element for what is known as 'live bus/live line reclosing'.

For example, if it were decided to charge the line initially from station *A*, the dead time in the auto-reclose relay at *A* would be set at, say, 5 seconds, while the corresponding timer in the auto-reclose relay at *B* would be set at, say, 15 seconds. The circuit beaker at *A* would then reclose after 5 seconds provided that voltage monitoring relays at *A* indicated that the busbars were alive and the line dead. With the line recharged, the circuit breaker at *B* would then reclose with a synchronism check, after a 2 second delay imposed by the synchronism check relay element.

If for any reason the line fails to 'dead line charge' from end *A*, reclosure from end *B* would take place after 15 seconds. The circuit breaker at *A* would then be given the opportunity to reclose with a synchronism check.

14.9.2 Synchronism Check Relays

The synchronism check relay element commonly provides a three-fold check:

i. phase angle difference
ii. voltage
iii. frequency difference

The phase angle setting is usually set to between 20°–45°, and reclosure is inhibited if the phase difference exceeds this value. The scheme waits for a reclosing opportunity with the phase angle within the set value, but locks out if reclosure does not occur within a defined period, typically 5s.

A voltage check is incorporated to prevent reclosure under various circumstances. A number of different modes may be available. These are typically undervoltage on either of the two measured voltages, differential voltage, or both of these conditions.

The logic also incorporates a frequency difference check, either by direct measurement or by using a timer in conjunction with the phase angle check. In the latter case, if a 2 second timer is employed, the logic gives an output only if the phase difference does not exceed the phase angle setting over a period of 2 seconds. This limits the frequency difference (in the case of a phase angle setting of 20°) to a maximum of 0.11% of 50Hz, corresponding to a phase swing from +20° to -20° over the measured 2 seconds. While a significant frequency difference is unlikely to arise during a delayed auto-reclose sequence, the time available allows this check to be carried out as an additional safeguard.

As well as 'live bus/dead line' and 'live bus/live line' reclosing, sometimes 'live line/dead bus' reclosing may need to be implemented. A numerical relay will typically allow any combination of these modes to be implemented. The voltage settings for distinguishing between 'live' and 'dead' conditions must be carefully chosen. In addition, the locations of the VT's must be known and checked so that the correct voltage signals are connected to the 'line' and 'bus' inputs.

14.10 OPERATING FEATURES OF AUTO-RECLOSE SCHEMES

The extensive use of auto-reclosing has resulted in the existence of a wide variety of different control schemes. Some of the more important variations in the features provided are described below.

14.10.1 Initiation

Modern auto-reclosing schemes are invariably initiated by the tripping command of a protection relay function. Some older schemes may employ a contact on the circuit breaker. Modern digital or numerical relays often incorporate a comprehensive auto-reclose facility within the relay, thus eliminating the need for a separate auto-reclose relay and any starter relays.

14.10.2 Type of Protection

On HV distribution systems, advantage is often taken of auto-reclosing to use instantaneous protection for the first trip, followed by I.D.M.T. for subsequent trips in a single fault incident. In such cases, the auto-reclose relay must provide a means of isolating the instantaneous relay after the first trip. In older schemes, this may be done with a normally closed contact on the auto-reclose starting element wired into the connection between the instantaneous relay contact and the circuit breaker trip coil. With digital or numerical relays with in-built auto-reclose facilities, internal logic facilities will normally be used.

With certain supply authorities, it is the rule to fit tripping relays to every circuit breaker. If auto-reclosing is required, electrically reset tripping relays must be used, and a contact must be provided either in the auto-reclose logic or by separate trip relay resetting scheme to energise the reset coil before reclosing can take place.

14.10.3 Dead Timer

This will have a range of settings to cover the specified high-speed or delayed reclosing duty. Any interlocks that are needed to hold up reclosing until conditions are suitable can be connected into the dead timer circuit. Section 14.12.1 provides an example of this applied to transformer feeders.

14.10.4 Reclosing Impulse

The duration of the reclosing impulse must be related to the requirements of the circuit breaker closing mechanism. On auto-reclose schemes using spring-closed breakers, it is sufficient to operate a contact at the end of the dead time to energise the latch release coil on the spring-closing mechanism. A circuit breaker auxiliary switch can be used to cancel the closing pulse and reset the auto-reclose relay. With solenoid operated breakers, it is usual to provide a closing pulse of the order of 1-2 seconds, so as to hold the solenoid energised for a short time after the main contacts have closed. This ensures that the mechanism settles in the fully latched-in position. The pneumatic or hydraulic closing mechanisms fitted to oil, air blast and SF6 circuit breakers use a circuit breaker auxiliary switch for terminating the closing pulse applied by the auto-reclose relay.

14.10.5 Anti-Pumping Devices

The function of an anti-pumping device is to prevent the circuit breaker closing and opening several times in quick succession. This might be caused by the application of a closing pulse while the circuit breaker is being tripped via the protection relays. Alternatively, it may occur if the circuit breaker is closed on to a fault and the closing pulse is longer than the sum of protection relay and circuit breaker operating times. Circuit breakers with trip free mechanisms do not require this feature.

14.10.6 Reclaim Timer

Electromechanical, static or software-based timers are used to provide the reclaim time, depending on the relay technology used. If electromechanical timers are used, it is convenient to employ two independently adjustable timed contacts to obtain both the dead time and the reclaim time on one timer. With static and software-based timers, separate timer elements are generally provided.

14.10.7 CB Lockout

If reclosure is unsuccessful the auto-reclose relay locks out the circuit breaker. Some schemes provide a lockout relay with a flag, with provision of a contact for remote alarm. The circuit breaker can then only be closed by hand; this action can be arranged to reset the auto-reclose relay element automatically. Alternatively, most modern relays can be configured such that a lockout condition can be reset only by operator action.

Circuit breaker manufacturers state the maximum number of operations allowed before maintenance is required. A number of schemes provide a fault trip counting function and give a warning when the total approaches the manufacturer's recommendation. These schemes will lock out when the total number of fault trips has reached the maximum value allowed.

14.10.8 Manual Closing

It is undesirable to permit auto-reclosing if circuit breaker closing is manually initiated. Auto-reclose schemes include the facility to inhibit auto-reclose initiation for a set time following manual CB closure. The time is typically in the range of 2-5 seconds.

14.10.9 Multi-Shot Schemes

Schemes providing up to three or four shots use timing circuits are often included in an auto-reclose relay to provide different, independently adjustable, dead times for each shot. Instantaneous protection can be used for the first trip, since each scheme provides a signal to inhibit instantaneous tripping after a set number of trips and selects I.D.M.T. protection for subsequent ones. The scheme resets if reclosure is successful within the chosen number of shots, ready to respond to further fault incidents.

14.11 AUTO-CLOSE SCHEMES

Auto-close schemes are employed to close automatically circuit breakers that are normally open when the supply network is healthy. This may occur for a variety of reasons, for instance the fault level may be excessive if the CB's were normally closed. The circuits involved are very similar to those used for auto-reclosing. Two typical applications are described in the following sections.

14.11.1 Standby Transformers

Figure 14.7 shows a busbar station fed by three transformers, *T1*, *T2* and *T3*. The loss of one transformer might cause serious overloading of the remaining two. However, connection of a further transformer to overcome this may increase the fault level to an unacceptable value.

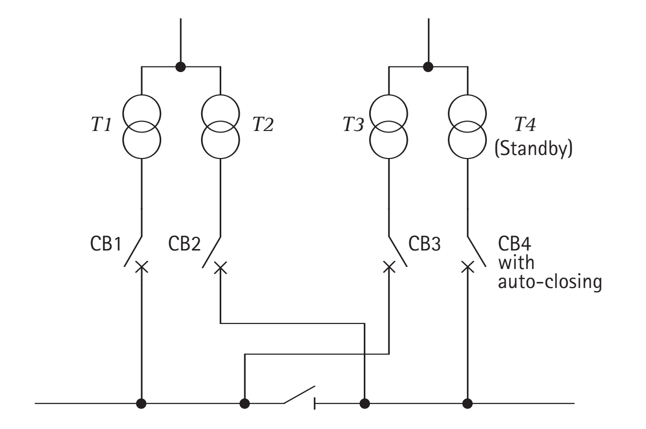


Figure 14.7: Standby transformer with auto-closing

The solution is to have a standby transformer *T4* permanently energised from the primary side and arranged to be switched into service if one of the others trips on fault.

The starting circuits for breaker *CB4* monitor the operation of transformer protection on any of the transformers *T1*, *T2* and *T3* together with the tripping of an associated circuit breaker *CB1*-*CB3*. In the event of a fault, the auto-close circuit is initiated and circuit breaker *CB4* closes, after a short time delay, to switch in the standby transformer. Some schemes employ an auto-tripping relay, so that when the faulty transformer is returned to service, the standby is automatically disconnected.

14.11.2 Bus Coupler or Bus Section Breaker

If all four power transformers are normally in service for the system of Figure 14.7, and the bus sections are interconnected by a normally-open bus section breaker instead of the isolator, the bus section breaker should be auto-closed in the event of the loss of one transformer, to spread the load over the remaining transformers. This, of course, is subject to the fault level being acceptable with the bus-section breaker closed.
Starting and auto-trip circuits are employed as in the stand-by scheme. The auto-close relay used in practice is a variant of one of the standard auto-reclose relays.

14.12 EXAMPLES OF AUTO-RECLOSE APPLICATIONS

Auto-reclose facilities in common use for a number of standard substation configurations are described in the following sections.

14.12.1 Double Busbar Substation

A typical double busbar station is illustrated in Figure 14.8. Each of the six EHV transmission lines brought into the station is under the control of a circuit breaker, *CB1* to *CB6* inclusive, and each transmission line can be connected either to the main or to the reserve busbars by manually operated isolators.

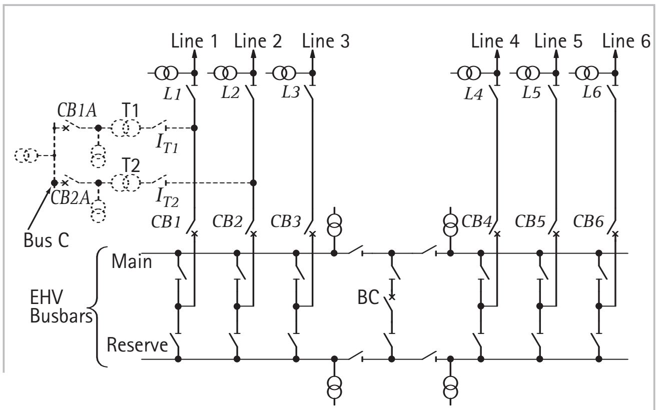


Figure 14.8: Double busbar substation

Bus section isolators enable sections of busbar to be isolated in the event of fault, and bus coupler breaker BC permits sections of main and reserve bars to be interconnected.

14.12.1.1 Basic scheme – banked transformers omitted

Each line circuit breaker is provided with an auto-reclose relay that recloses the appropriate circuit breakers in the event of a line fault. For a fault on Line 1, this would require opening of *CB1* and the corresponding CB at the remote end of the line. The operation of either the busbar protection or a VT Buchholz relay is arranged to lock out the auto-reclosing sequence. In the event of a persistent fault on Line 1, the line circuit breakers trip and lock out after one attempt at reclosure.

14.12.1.2 Scheme with banked transformers

Some utilities use a variation of the basic scheme in which Transformers *T1* and *T2* are banked off Lines 1 and 2, as shown in Figure 14.8. This provides some economy in the number of circuit breakers required. The corresponding transformer circuits 1 and 2 are tee'd off Lines 1 and 2 respectively. The transformer secondaries are connected to a separate HV busbar system via circuit breakers *CB1A* and *CB2A*.

Auto-reclose facilities can be extended to cover the circuits for banked transformers where these are used. For example, a fault on line 1 would cause the tripping of circuit breakers *CB1*, *CB1A* and the remote line circuit breaker. When Line 1 is re-energised, either by auto-reclosure of *CB1* or by the remote circuit breaker, whichever is set to reclose first, transformer *T1* is also energised. *CB1A* will not reclose until the appearance of transformer secondary voltage, as monitored by the secondary VT; it then recloses on to the HV busbars after a short time delay, with a synchronism check if required.

In the event of a fault on transformer *T1*, the local and remote line circuit breakers and breaker *CB1A* trip to isolate the fault. Automatic opening of the motorised transformer isolator I_{T1} follows this. The line circuit breakers then reclose in the normal manner and circuit breaker *CB1A* locks out.

A shortcoming of this scheme is that this results in healthy transformer *T1* being isolated from the system; also, isolator *L1* must be opened manually before circuit breakers *CB1* and *CB1A*, can be closed to re-establish supply to the HV busbars via the transformer. A variant of this scheme is designed to instruct isolator *L1* to open automatically following a persistent fault on Line *1* and provide a second auto-reclosure of *CB1* and *CB1A*. The supply to Bus C is thereby restored without manual intervention.

14.12.2 Single Switch Substation

The arrangement shown in Figure 14.9 consists basically of two transformer feeders interconnected by a single circuit breaker *120*. Each transformer therefore has an alternative source of supply in the event of loss of one or other of the feeders.

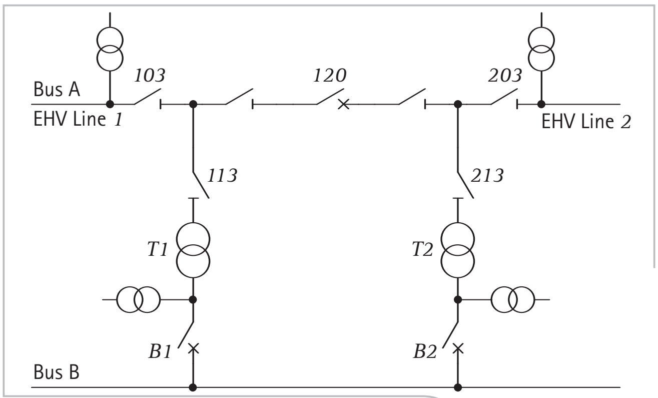


Figure 14.9: Single switch substation

For example, a transient fault on Line *1* causes tripping of circuit breakers *120* and *B1* followed by reclosure of CB *120*. If the reclosure is successful, Transformer *T1* is re-energised and circuit breaker *B1* recloses after a short time delay.

If the line fault is persistent, *120* trips again and the motorised line isolator *103* is automatically opened. Circuit breaker *120* recloses again, followed by *B1*, so that both transformers *T1* and *T2* are then supplied from Line *2*.

A transformer fault causes the automatic opening of the appropriate transformer isolator, lock-out of the transformer secondary circuit breaker and reclosure of circuit breaker *120*. Facilities for dead line charging or reclosure with synchronism check are provided for each circuit breaker.

14.12.3 Four-Switch Mesh Substation

The mesh substation illustrated in Figure 14.10 is extensively used by some utilities, either in full or part. The basic mesh has a feeder at each corner, as shown at mesh corners *MC2*, *MC3* and *MC4*. One or two transformers may also be banked at a mesh corner, as shown at *MC1*. Mesh corner protection is required if more than one circuit is fed from a mesh corner, irrespective of the CT locations – see Chapter 15 for more details.

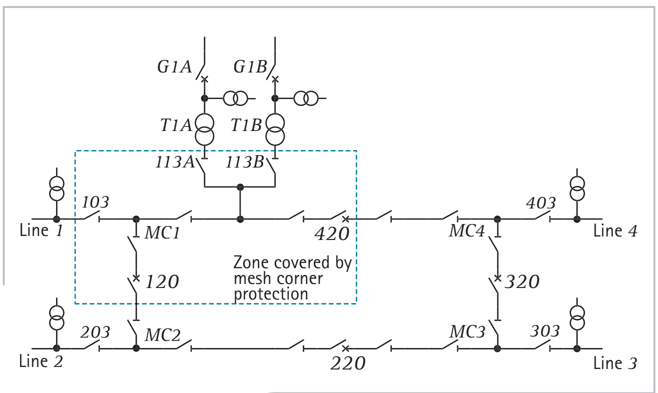


Figure 14.10: Four-switch mesh substation

Considerable problems can are encountered in the application of auto-reclosing to the mesh substation. For example, circuit breakers *120* and *420* in Figure 14.10 are tripped out for a variety of different types of fault associated with mesh corner 1 (*MC1*), and each requires different treatment as far as auto-reclosing is concerned. Further variations occur if the faults are persistent.

Following normal practice, circuit breakers must be reclosed in sequence, so sequencing circuits are necessary for the four mesh breakers. Closing priority may be in any order, but is normally *120*, *220*, *320*, and *420*.

A summary of facilities is now given, based on mesh corner *MC1* to show the inclusion of banked transformers; facilities at other corners are similar but omit the operation of equipment solely associated with the banked transformers.

14.12.3.1 Transient fault on Line 1

Tripping of circuit breakers *120*, *420*, *G1A* and *G1B* is followed by reclosure of *120* to give dead line charging of Line *1*. Breaker *420* recloses in sequence, with a synchronism check. Breakers *G1A*, *G1B* reclose with a synchronism check if necessary.

14.12.3.2 Persistent fault on Line 1

Circuit breaker *120* trips again after the first reclosure and isolator *103* is automatically opened to isolate the faulted line. Breakers *120*, *420*, *G1A* and *G1B* then reclose in sequence as above.

14.12.3.3 Transformer fault (local transformer 1A)

Automatic opening of isolator *113A* to isolate the faulted transformer follows tripping of circuit breakers *120*, *420*, *G1A* and *G1B*. Breakers *120*, *420* and *G1B* then reclose in sequence, and breaker *G1A* is locked out.

14.12.3.4 Transformer fault (remote transformer)

For a remote transformer fault, an intertrip signal is received at the local station to trip breakers *120*, *420*, *G1A* and *G1B* and inhibit auto-reclosing until the faulted transformer has been isolated at the remote station. If the intertrip persists for 60 seconds it is assumed that the fault cannot be isolated at the remote station. Isolator *103* is then automatically opened and circuit breakers *120*, *420*, *G1A* and *G1B* are reclosed in sequence.

14.12.3.5 Transient mesh corner fault

Any fault covered by the mesh corner protection zone, shown in Figure 14.10, results in tripping of circuit breakers *120*, *420*, *G1A* and *G1B*. These are then reclosed in sequence.

There may be circumstances in which reclosure onto a persistent fault is not permitted – clearly it is not known in advance of reclosure if the fault is persistent or not. In these circumstances, scheme logic inhibits reclosure and locks out the circuit breakers.

14.12.3.6 Persistent mesh corner fault

The sequence describe in Section 14.12.3.5 is followed initially. When CB *120* is reclosed, it will trip again due to the fault and lock out. At this point, the logic inhibits the reclosure of CB's *420*, *G1A* and *G1B* and locks out these CB's. Line isolator *103* is automatically opened to isolate the fault from the remote station.