

University of Western Ontario

# Distribution System Protection

ES586B: Power System Protection

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## 1 Objective of Distribution System Protection

The main objectives of distribution system protection are:

- I. To minimize the duration of a fault
- II. To minimize the number of consumers affected by the fault

The secondary objectives of distribution system protection are:

- I. To eliminate safety hazards as fast as possible
- II. To limit service outages to the smallest possible segment of the system
- III. To protect the consumers' apparatus
- IV. To protect the system from unnecessary service interruptions and disturbances
- V. To disconnect faulted lines, transformers, or other apparatus.

Overhead distribution systems are subject two types of electrical faults, namely, transient (or temporary) faults and permanent faults. Depending on the nature of the system involved, approximately 75-90% of the total number of faults are temporary in nature. Usually transient faults occur when phase conductors electrically contact other phase conductors or ground momentarily due to trees, birds or other animals, high winds, lightning, flashovers, and so on. Transient faults are cleared by a service interruption of sufficient length of time to extinguish the power arc. Here, the fault duration is minimized and unnecessary fuse blowing is prevented by using instantaneous or high-speed tripping and automatic reclosing of a relay-controlled power circuit breaker or the automatic tripping and reclosing of a circuit recloser. The breaker speed, relay settings, and recloser characteristics are selected in a manner to interrupt the fault current before a series fuse (i.e. the nearest source-side fuse) is blown, which would cause the transient fault to become permanent.

Permanent faults are those which require repairs by repair crew in terms of:

- I. Replacing burned-down conductors, blown fuses, or any other damaged apparatus
- II. Removing tree limbs from the line
- III. Manually reclosing a circuit breaker or recloser to restore service

Here, the number of customers affected by a fault is minimized by properly selecting and locating the protective apparatus on the feeder main, at the tap point of each branch, and at critical locations on branch circuits. Permanent faults are cleared by fuse cutouts installed at submain and lateral tap points. This practice limits the number of customers affected by a permanent fault and helps locate the fault point by reducing the area involved. In general, the

only part of the distribution circuit not protected by fuses is the main feeder and feeder tie line. The substation is protected from faults on feeder and tie lines by circuit breakers and/or reclosers located inside the substation.

Most of the faults are permanent on an underground distribution system, thereby requiring a different protection approach. Although the number of faults occurring on an underground system is relatively much less than that on the overhead systems, they are usually permanent and can affect a larger number of customers. Faults occurring in the underground residential distribution (URD) systems are cleared by the blowing of the nearest sectionalizing fuse or fuses. Faults occurring on the feeder are cleared by tripping and lockout of the feeder breaker.

## **2 Equipment**

A wide variety of equipment is used to protect distribution networks. The particular type of protection used depends on the system element being protected and the system voltage level, and, even though there are no specific standards for the overall protection of distribution networks, some general indication of how these systems work can be made.

The devices most used for distribution system protection are:

- I. Overcurrent Relays
- II. Reclosers
- III. Sectionalizers
- IV. Fuses

The coordination of overcurrent relays was dealt with in detail in class, and this report will cover the other three devices referred to above.

### **2.1 Reclosers**

A recloser is a device with the ability to detect phase and phase-to-ground overcurrent conditions, to interrupt the circuit if the overcurrent persists after a predetermined time, and then to automatically reclose to re-energise the line. If the fault that originated the operation still exists, then the recloser will stay open after a preset number of operations, thus isolating the faulted section from the rest of the system. In an overhead distribution system between 75 to 95 per cent of the faults are of a temporary nature and last, at the most, for a few cycles or seconds. Thus, the recloser, with its opening/closing characteristic, prevents a distribution circuit being left out of service for temporary faults. Typically, reclosers are designed to have up to three open-close operations and, after these, a final open operation to lock out the sequence. One further closing operation by manual means is usually allowed. The counting mechanisms register operations of the phase or ground-fault units which can also be initiated by externally controlled devices when appropriate communication means are available. The

operating time/current characteristic curves of reclosers normally incorporate three curves, one fast and two delayed, designated as A, B and C, respectively. Figure 1 shows a typical set of time/current curves for reclosers. However, new reclosers with microprocessor-based controls may have keyboard-selectable time/current curves which enable an engineer to produce any curve to suit the coordination requirements for both phase and ground-faults. This allows reprogramming of the characteristics to make an arrangement to a customer's specific needs without the need to change components.

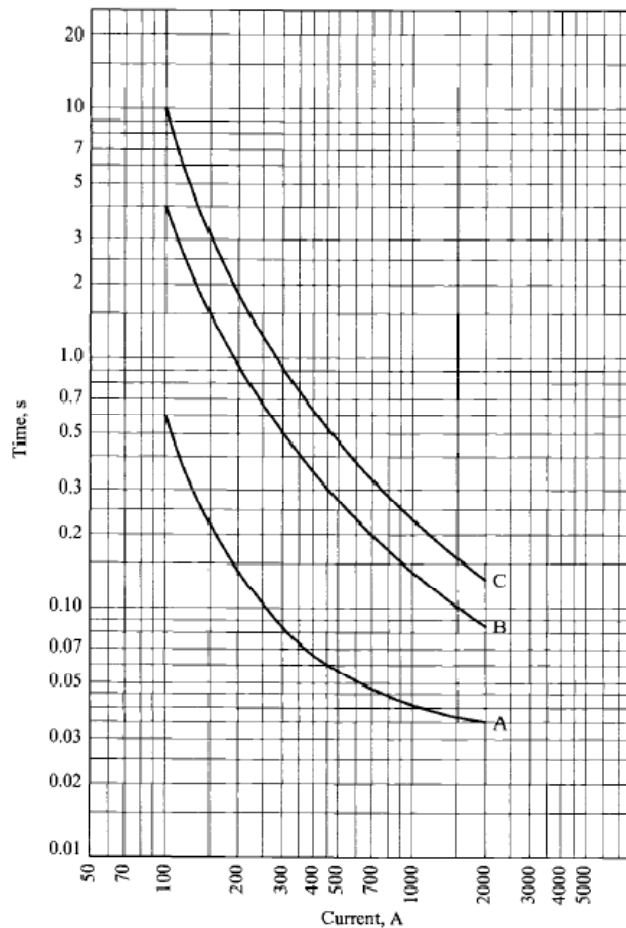


Figure 1: Time/Current Curves for Reclosers

Coordination with other protection devices is important in order to ensure that, when a fault occurs, the smallest section of the circuit is disconnected to minimise disruption of supplies to customers. Generally, the time characteristic and the sequence of operation of the recloser are selected to coordinate with mechanisms upstream towards the source. After selecting the size and sequence of operation of the recloser, the devices downstream are adjusted in order to achieve correct coordination. A typical sequence of a recloser operation for a permanent fault is shown in Figure 2. The first shot is carried out in instantaneous mode to clear temporary

faults before they cause damage to the lines. The three later ones operate in a timed manner with predetermined time settings. If the fault is permanent, the time-delay operation allows other protection devices nearer to the fault to open, limiting the amount of the network being disconnected.

Ground faults are less severe than phase faults and, therefore, it is important that the recloser has an appropriate sensitivity to detect them. One method is to use CTs connected residually so that the resultant residual current under normal conditions is approximately zero. The recloser should operate when the residual current exceeds the setting value, as would occur during ground faults.

Reclosers can be classified as follows:

- I. Single-phase and three-phase;
- II. Mechanisms with hydraulic or electronic operation;
- III. Oil, vacuum or SF6.

Single-phase reclosers are used when the load is predominantly single-phase. In such a case, when a single-phase fault occurs the recloser should permanently disconnect the faulted phase so that supplies are maintained on the other phases. Three-phase reclosers are used when it is necessary to disconnect all three phases in order to prevent unbalanced loading on the system. Reclosers with hydraulic operating mechanisms have a disconnecting coil in series with the line. When the current exceeds the setting value, the coil attracts a piston that opens the recloser main contacts and interrupts the circuit. The time characteristic and operating sequence of the recloser are dependent on the flow of oil in different chambers. The electronic type of control mechanism is normally located outside the recloser and receives current signals from a CT-type bushing. When the current exceeds the predetermined setting, a delayed shot is initiated that finally results in a tripping signal being transmitted to the recloser control mechanism. The control circuit determines the subsequent opening and closing of the mechanism, depending on its setting. Reclosers with electronic operating mechanisms use a coil or motor mechanism to close the contacts. Oil reclosers use the oil to extinguish the arc and also to act as the basic insulation. The same oil can be used in the control mechanism.

Vacuum and SF6 reclosers have the advantage of requiring less maintenance.

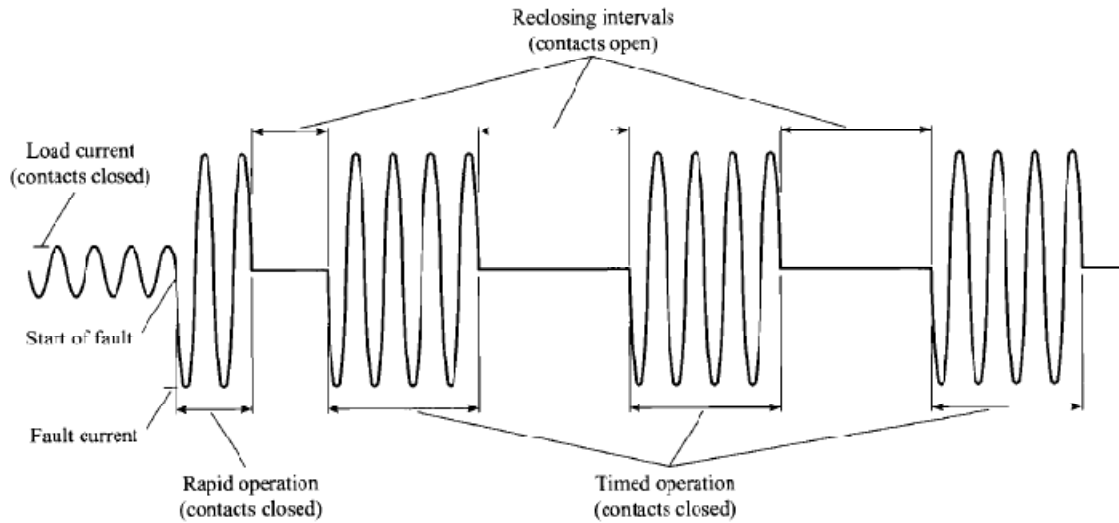


Figure 2: Typical Sequence for Recloser Operation

Reclosers are used at the following points on a distribution network:

- I. In substations, to provide primary protection for a circuit;
- II. In main feeder circuits, in order to permit the sectioning of long lines and thus prevent the loss of a complete circuit due to a fault towards the end of the circuit;
- III. In branches or spurs, to prevent the tripping of the main circuit due to faults on the spurs.

When installing reclosers it is necessary to take into account the following factors:

- I. System voltage.
- II. Short-circuit level.
- III. Maximum load current.
- IV. Minimum short-circuit current within the zone to be protected by the recloser.
- V. Coordination with other mechanisms located upstream towards the source, and downstream towards the load.
- VI. Sensitivity of operation for ground faults

The voltage rating and the short-circuit capacity of the recloser should be equal to, or greater than, the values that exist at the point of installation. The same criteria should be applied to the current capability of the recloser in respect of the maximum load current to be carried by the circuit. It is also necessary to ensure that the fault current at the end of the line being protected is high enough to cause operation of the recloser.

## 2.2 Sectionalizers

A sectionalizer is a device that automatically isolates faulted sections of a distribution circuit once an upstream breaker or recloser has interrupted the fault current and is usually installed downstream of a recloser. Since sectionalizers have no capacity to break fault current, they must be used with a back-up device that has fault current breaking capacity. Sectionalizers count the number of operations of the recloser during fault conditions. After a preselected number of recloser openings, and while the recloser is open, the sectionalizer opens and isolates the faulty section of line. This permits the recloser to close and re-establish supplies to those areas free of faults. If the fault is temporary, the operating mechanism of the sectionalizer is reset.

Sectionalizers are constructed in single- or three-phase arrangements with hydraulic or electronic operating mechanisms. A sectionalizer does not have a current/time operating characteristic, and can be used between two protective devices whose operating curves are very close and where an additional step in coordination is not practicable.

Sectionalizers with hydraulic operating mechanisms have an operating coil in series with the line. Each time an overcurrent occurs the coil drives a piston that activates a counting mechanism when the circuit is opened and the current is zero by the displacement of oil across the chambers of the sectionalizer. After a prearranged number of circuit openings, the sectionalizer contacts are opened by means of pretensioned springs. This type of sectionalizer can be closed manually. Sectionalizers with electronic operating mechanisms are more flexible in operation and easier to set. The load current is measured by means of CTs and the secondary current is fed to a control circuit which counts the number of operations of the recloser or the associated interrupter and then sends a tripping signal to the opening mechanism. This type of sectionalizer is constructed with manual or motor closing.

The following factors should be considered when selecting a sectionalizer:

- I. System voltage.
- II. Maximum load current.
- III. Maximum short-circuit level.
- IV. Coordination with protection devices installed upstream and downstream.

The nominal voltage and current of a sectionalizer should be equal to or greater than the maximum values of voltage or load at the point of installation. The short circuit capacity (momentary rating) of a sectionalizer should be equal to or greater than the fault level at the point of installation. The maximum clearance time of the associated interrupter should not be permitted to exceed the short-circuit rating of the sectionalizer. Coordination factors that need



to be taken into account include the starting current setting and the number of operations of the associated interrupter before opening.

### 2.3 Fuses

A fuse is an overcurrent protection device; it possesses an element that is directly heated by the passage of current and is destroyed when the current exceeds a predetermined value. A suitably selected fuse should open the circuit by the destruction of the fuse element, eliminate the arc established during the destruction of the element and then maintain circuit conditions open with nominal voltage applied to its terminals, (i.e. no arcing across the fuse element).

The majority of fuses used in distribution systems operate on the expulsion principle, i.e. they have a tube to confine the arc, with the interior covered with de-ionising fibre, and a fusible element. In the presence of a fault, the interior fibre is heated up when the fusible element melts and produces de-ionising gases which accumulate in the tube. The arc is compressed and expelled out of the tube; in addition, the escape of gas from the ends of the tube causes the particles that sustain the arc to be expelled. In this way, the arc is extinguished when current zero is reached. The presence of de-ionising gases, and the turbulence within the tube, ensure that the fault current is not re-established after the current passes through zero point. The zone of operation is limited by two factors; the lower limit based on the minimum time required for the fusing of the element (minimum melting time) with the upper limit determined by the maximum total time that the fuse takes to clear the fault.

There are a number of standards to classify fuses according to the rated voltages, rated currents, time/current characteristics, manufacturing features and other considerations. For example, there are several sections of ANSI/UL 198-1982 standards that cover low voltage fuses of 600 V or less. For medium and high voltage fuses within the range 2.3-138 kV, standards such as ANSI/IEEE C37.40, 41, 42, 46, 47 and 48 apply. Other organisations and countries have their own standards; in addition, fuse manufacturers have their own classifications and designations.

In distribution systems, the use of fuse links designated K and T for fast and slow types, respectively, depending on the speed ratio, is very popular. The speed ratio is the ratio of minimum melt current that causes fuse operation at 0.1 s to the minimum melt current for 300 s operation. For the K link, a speed ratio (SR) of 6-8 is defined and, for a T link, 10-13. Figure 3 shows the comparative operating characteristics of type 200 K and 200 T fuse links. For the 200 K fuse a 4400 A current is required for 0.1 s clearance time and 560A for 300s, giving an SR of 7.86. For the 200T fuse, 6500A is required for 0.1 s clearance and 520A for 300s; for this case, the SR is 12.5.

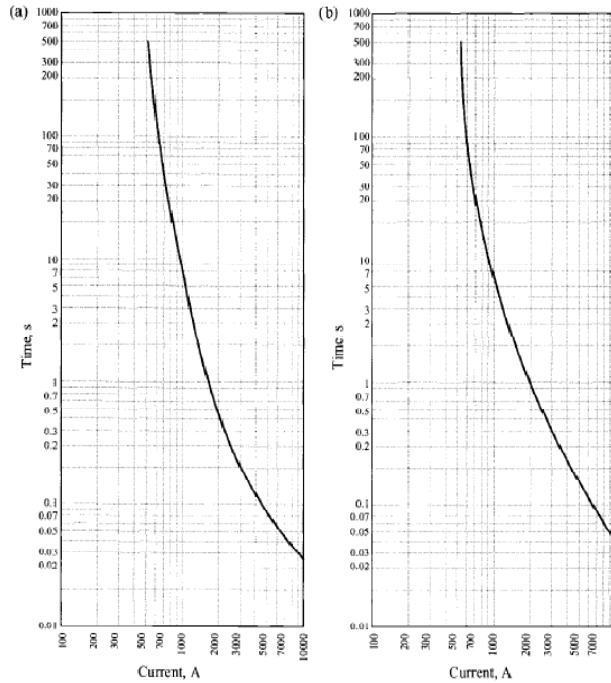


Figure 3: Time/Current Characteristics of Typical Fuse Links: (a) 200K Fuse Link; (b) 200T Fuse Link

The following information is required in order to select a suitable fuse for use on the distribution system:

- I. Voltage and insulation level.
- II. Type of system.
- III. Maximum short-circuit level.
- IV. Load current.

The above four factors determine the fuse nominal current, voltage and short circuit capability characteristics.

### 3 Criteria for Coordination of Time/Current Devices in Distribution Systems

The following basic criteria should be employed when coordinating time/current devices in distribution systems:

1. The main protection should clear a permanent or temporary fault before the backup protection operates, or continue to operate until the circuit is disconnected. However, if the main protection is a fuse and the back-up protection is a recloser, it is normally acceptable to coordinate the fast operating curve or curves of the recloser to operate first, followed by the fuse, if the fault is not cleared.

2. Loss of supply caused by permanent faults should be restricted to the smallest part of the system for the shortest time possible.

In the following sections criteria and recommendations are given for the coordination of different devices used on distribution systems.

### 3.1 Fuse-Fuse Coordination

The essential criterion when using fuses is that the maximum clearance time for a main fuse should not exceed 75 per cent of the minimum melting time of the backup fuse, for the same current level, as indicated in Figure 4. This ensures that the main fuse interrupts and clears the fault before the back-up fuse is affected in any way. The factor of 75 per cent compensates for effects such as load current and ambient temperature, or fatigue in the fuse element caused by the heating effect of fault currents that have passed through the fuse to a fault downstream but were not sufficiently large enough to melt the fuse.

The coordination between two or more consecutive fuses can be achieved by drawing their time/current characteristics, normally on log-log paper as for overcurrent relays. In the past, coordination tables with data of the available fuses were also used, which proved to be an easy and accurate method. However, the graphic method is still popular not only because it gives more information but also because computer-assisted design tools make it much easier to draw out the various characteristics.

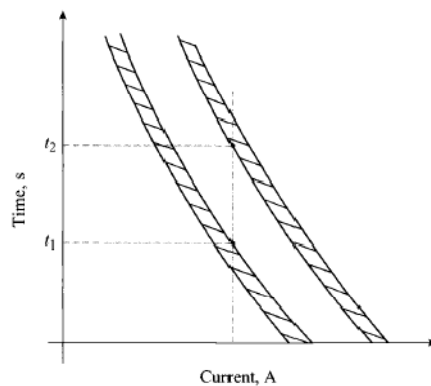


Figure 4: Criteria for Fuse-Fuse Coordination:  $t_1 < 0.75 t_2$

### 3.2 Recloser-Fuse Coordination

The criteria for determining recloser-fuse coordination depend on the relative locations of these devices, i.e. whether the fuse is at the source side and then backs up the operation of the recloser that is at the load side, or vice versa. These possibilities are treated in the following paragraphs.

#### Fuse at the Source Side

When the fuse is at the source side, all the recloser operations should be faster than the minimum melting time of the fuse. This can be achieved through the use of multiplying factors on the recloser time/current curve to compensate for the fatigue of the fuse link produced by the cumulative heating effect generated by successive recloser operations. The recloser opening curve modified by the appropriate factor then becomes slower but, even so, should be faster than the fuse curve. This is illustrated in Figure 5.

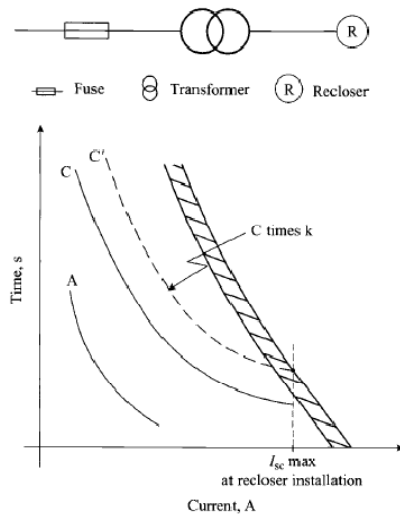


Figure 5: Criteria for Source-Side Fuse and Recloser Coordination

The multiplying factors referred to above depend on the reclosing time in cycles and on the number of the reclosing attempts. Some values proposed by Cooper Power Systems are reproduced in Figure 6. It is convenient to mention that if the fuse is at the high voltage side of a power transformer and the recloser at the low voltage side, either the fuse or the recloser curve should be shifted horizontally on the current axis to allow for the transformer turns ratio. Normally it is easier to shift the fuse curve, based on the transformer tap that produces the highest current on the high voltage side.

Reclosing time in cycles	Multipliers for:		
	two fast, two delayed sequence	one fast, three delayed sequence	four delayed sequence
25	2.70	3.20	3.70
30	2.60	3.10	3.50
50	2.10	2.50	2.70
90	1.85	2.10	2.20
120	1.70	1.80	1.90
240	1.40	1.40	1.45
600	1.35	1.35	1.35

The  $k$  factor is used to multiply the time values of the delayed curve of the recloser.

Figure 6:  $k$  Factor for Source-Side Fuse Link

## Fuses at the Load Side

The procedure to coordinate a recloser and a fuse, when the latter is at the load side, is carried out with the following rules:

1. The minimum melting time of the fuse must be greater than the fast curve of the recloser times the multiplying factor, given in Figure 7 and taken from the same reference as above;
2. The maximum clearing time of the fuse must be smaller than the delayed curve of the recloser without any multiplying factor; the recloser should have at least two or more delayed operations to prevent loss of service in case the recloser trips when the fuse operates.

Reclosing time in cycles	Multipliers for:	
	one fast operation	two fast operations
25–30	1.25	1.80
60	1.25	1.35
90	1.25	1.35
120	1.25	1.35

The *k* factor is used to multiply the time values of the recloser fast curve.

Figure 7: *k* Factor for the Load-Side Fuse Link

The application of the two rules is illustrated in Figure 8.

Better coordination between a recloser and fuses is obtained by setting the recloser to give two instantaneous operations followed by two timed operations. In general, the first opening of a recloser will clear 80 per cent of the temporary faults, while the second will clear a further 10 per cent. The load fuses are set to operate before the third opening, clearing permanent faults. A less effective coordination is obtained using one instantaneous operation followed by three timed operations.

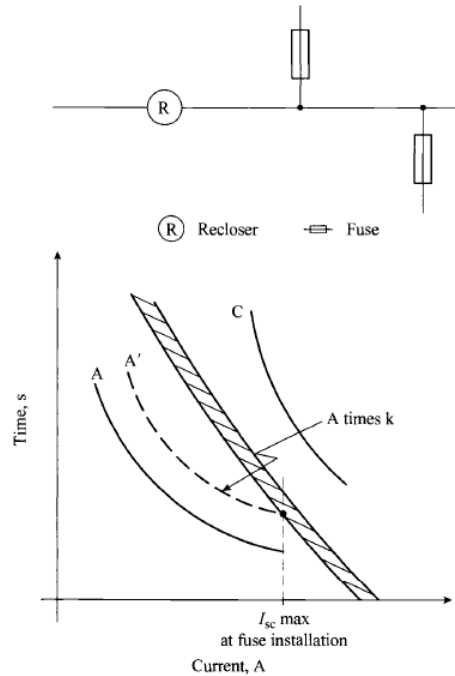


Figure 8: Criteria for Recloser and Load-Side Fuse Coordination

### 3.3 Recloser-Recloser Coordination

The coordination between reclosers is obtained by appropriately selecting the amperes setting of the trip coil in the hydraulic reclosers, or of the pick-ups in electronic reclosers.

#### Hydraulic Reclosers

The coordination margins with hydraulic reclosers depend upon the type of equipment used. In small reclosers, where the current coil and its piston produce the opening of the contacts, the following criteria must be taken into account:

- I. Separation of the curves by less than two cycles always results in simultaneous operation;
- II. Separation of the curves by between two and 12 cycles could result in simultaneous operation;
- III. Separation greater than 12 cycles ensures non-simultaneous operation.

With large capacity reclosers, the piston associated with the current coil only actuates the opening mechanism. In such cases the coordination margins are as follows:

- I. Separation of the curves by less than two cycles always results in simultaneous operation;
- II. A separation of more than eight cycles guarantees non-simultaneous operation.

The principle of coordination between two large units in series is based on the time of separation between the operating characteristics, in the same way as for small units.

### **Electronically-Controlled Reclosers**

Adjacent reclosers of this type can be co-ordinated more closely since there are no inherent errors such as those that exist with electromechanical mechanisms (due to overspeed, inertia, etc.). The downstream recloser must be faster than the upstream recloser, and the clearance time of the downstream recloser plus its tolerance should be lower than the upstream recloser clearance time less its tolerance. Normally, the setting of the recloser at the substation is used to achieve at least one fast reclosure, in order to clear temporary faults on the line between the substation and the load recloser. The latter should be set with the same, or a larger, number of rapid operations as the recloser at the substation. It should be noted that the criteria of spacing between the time/current characteristics of electronically controlled reclosers are different to those used for hydraulically controlled reclosers.

### **3.4 Recloser-Relay Coordination**

Two factors should be taken into account for the coordination of these devices; the interrupter opens the circuit some cycles after the associated relay trips, and the relay has to integrate the clearance time of the recloser. The reset time of the relay is normally long and, if the fault current is re-applied before the relay has completely reset, the relay will move towards its operating point from this partially reset position.

For example, consider a recloser with two fast and two delayed sequence with reclosing intervals of two seconds, which is required to coordinate with an inverse time-delay overcurrent relay that takes 0.6 s to close its contacts at the fault level under question, and 16 s to completely reset. The impulse margin time of the relay is neglected for the sake of this illustration. The rapid operating time of the recloser is 0.030 s, and the delayed operating time is 0.30 s. The percentage of the relay operation during which each of the two rapid recloser openings takes place is  $(0.03 \text{ s}/0.6 \text{ s}) \times 100 \text{ per cent} = 5 \text{ per cent}$ . The percentage of relay reset that takes place during the recloser interval is  $(2 \text{ s}/16 \text{ s}) \times 100 \text{ per cent} = 12.5 \text{ per cent}$ . Therefore, the relay completely resets after both of the two rapid openings of the recloser.

The percentage of the relay operation during the first time-delay opening of the recloser is  $(0.3 \text{ s}/0.6 \text{ s}) \times 100 \text{ per cent} = 50 \text{ per cent}$ . The relay reset for the third opening of the recloser--12.5 per cent, as previously, so that the net percentage of relay operation after the third opening of the recloser =  $50 \text{ per cent} - 12.5 \text{ per cent} = 37.5 \text{ per cent}$ . The percentage of the relay operation during the second time delay opening of the recloser takes place =  $(0.3 \text{ sec.}/0.6 \text{ sec}) \times 100 \text{ per cent} = 50 \text{ per cent}$ , and the total percentage of the relay operation after the fourth opening of the recloser =  $37.5 \text{ per cent} + 50 \text{ per cent} = 87.5 \text{ per cent}$ .

From the above analysis it can be concluded that the relay does not reach 100 per cent operation by the time the final opening shot starts, and therefore coordination is guaranteed.

### **3.5 Recloser-Sectionalizer Coordination**

Since the sectionalizers have no time/current operating characteristic, their coordination does not require an analysis of these curves.

The coordination criteria in this case are based upon the number of operations of the back-up recloser. These operations can be any combination of rapid or timed shots as mentioned previously, for example two fast and two delayed. The sectionalizer should be set for one shot less than those of the recloser, for example three disconnections in this case. If a permanent fault occurs beyond the sectionalizer, the sectionalizer will open and isolate the fault after the third opening of the recloser. The recloser will then re-energise the section to restore the circuit. If additional sectionalizers are installed in series, the furthest recloser should be adjusted for a smaller number of counts. A fault beyond the last sectionalizer results in the operation of the recloser and the start of the counters in all the sectionalizers.

### **3.6 Recloser-Sectionalizer-Fuse Coordination**

Each one of the devices should be adjusted in order to co-ordinate with the recloser. In turn, the sequence of operation of the recloser should be adjusted in order to obtain the appropriate coordination for faults beyond the fuse by following the criteria already mentioned.

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