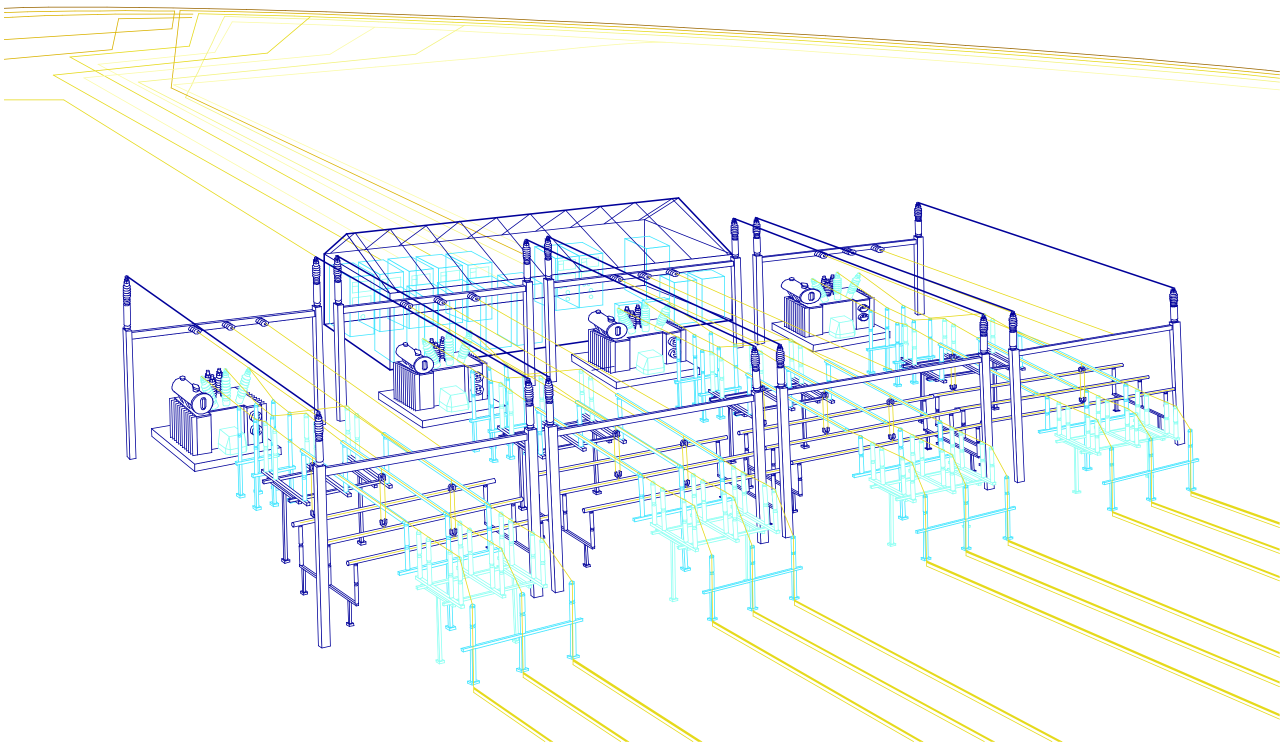
Distribution Automation Handbook

Section 8.14 Automatic Reclosing



Contents

8.14 Automatic Reclosing

8.14.1 Introduction

Most overhead line faults are transient in nature, such as an insulator or a spark gap flashover or a temporary contact with foreign objects or animals. The majority of these faults is due to weather conditions and typically results from thunderstorms, heavy wind or extreme snow and ice conditions together with high temperature changes. If these faults are not self-clearing, they result in tripping of the circuit breaker to isolate the fault spot, and they do not recur when closing the circuit breaker, that is, re-energizing the feeder after a short time delay. For the clearing of this type of faults, *automatic reclosing (AR)* is employed.

8.14.2 AR-Sequence [8.14.1], [8.14.5], [8.14.6]

After the occurrence of a fault, the circuit breaker will be tripped by the protection functionality of the protected feeder followed by an automatic reclosing or an *AR-shot*, which is a function where the circuit breaker is automatically reclosed after a set time delay. The purpose of this action is to return the status of the protected feeder automatically and in minimum time to its pre-fault, normal operating state. If after the closing of the circuit breaker the fault has disappeared, the AR-shot was successful and the objective has been reached, see Figure 8.14.1.

But if the fault still persists, the circuit breaker will be tripped again, and a new AR-shot will be made, as also, Figure 8.14.1. The operation continues like this until a predefined number of AR-shots have been performed.

If the fault is eventually a permanent one and all the allowed AR-shots have been performed, the circuit breaker will be tripped one last time, ending the automatic reclosing or the *AR-sequence*, Figure 8.14.1.

Performing of the AR-sequence is typically controlled by a separate trip counter or a *shot pointer* function. Prior to the initiation of the 1st shot, the shot pointer has the value of one. After completing of each shot, the shot pointer is set on such a value that the initiation of the shot just done and the shots whose sequence number is lower than that of the current one is not possible.

Figure 8.14.1 shows a typical sequence of events schematically.

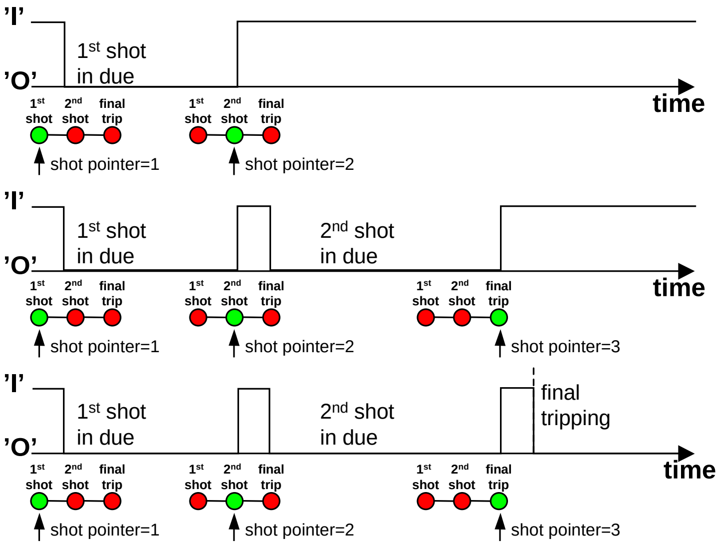


Figure 8.14.1: Typical events of a two-shot AR-sequence, top: the 1st AR-shot is successful, middle: the 2nd AR-shot is successful, bottom: both AR-shots fail, "I" = CB closed, "O" = CB open

The 1st AR-shot can be high speed or delayed. In the high-speed schemes (*high-speed autoreclosing, HSAR*), the circuit breaker is typically closed within 0.2 to 2 s after the tripping operation. If the 1st AR-shot fails and the protection functionality restarts, one or more AR-shots can be made. Typically these AR-shots are time delayed. In the delayed schemes (*delayed autoreclosing, DAR*), the reclosing of the circuit breaker is typically delayed for 10 to 180 s after the tripping operation. The closing time delay is a settable parameter and referred to as the *dead time* of the corresponding AR-shot. This parameter is also often referred to as the *shot time*, *open time* or the *reclosing time*. From the AR-unit point of view, the dead time is the time between the AR-shot being initialized and the issuing of the closing command for the circuit breaker. From the primary circuit point of view, the dead time is the time between the fault arc being extinguished and the CB main contacts making, see Figure 8.14.2.

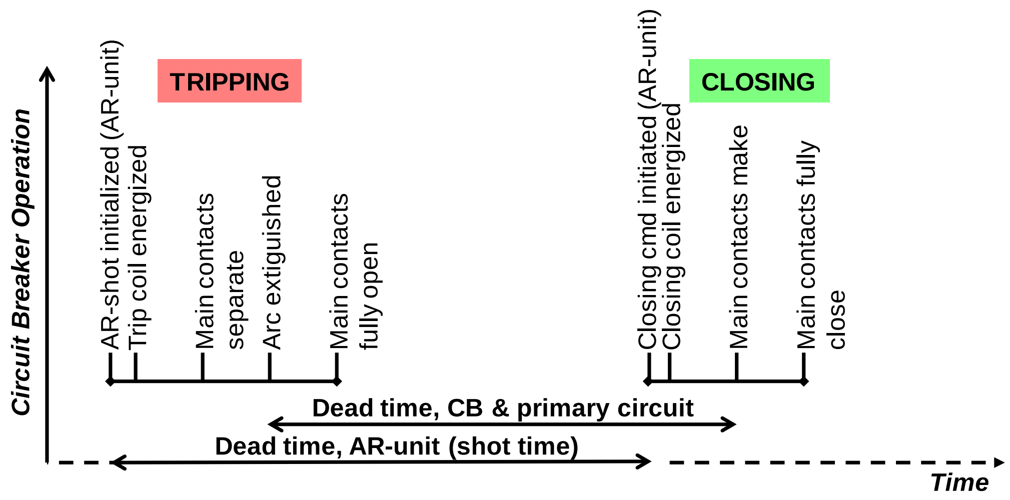


Figure 8.14.2: Definitions of the dead time

When all the predefined AR-shots have been performed, the circuit breaker remains typically open and the AR-unit *locks out*, thus preventing further attempts. This indicates that the fault is a permanent one and that corrective action from the control room operators is required for locating and isolating the fault. The resetting of the lockout condition can be made either manually or automatically by time. This resetting time is known as the *reclaim time* or the *reset time*, during which a new initiation in event of the same power system fault must come in order to the sequence to continue. Should the reclaim time elapse before new initiation, the AR-function is reset and becomes ready to start a new sequence.

The reclaim time is started after each automatic reclosing. For example, an AR-sequence consists of two shots. After the 1st shot, the behavior of the AR-function depends on the time instant the next initiation occurs. If the reclaim time has not elapsed, the sequence is continued with the next shot, see Figure 8.14.3. After the reclaim time elapses, the function judges the previous sequence as a successful one and resets its operation to the initial state (that is, ready for the 1st shot), Figure 8.14.3. The reclaim time must be long enough, because in case of a permanent fault, the autoreclosing function must not reset during the AR-sequence. As a rule of thumb, the reclaim time must be selected to be longer than the longest operation time delay of any of the protection functions concerned.

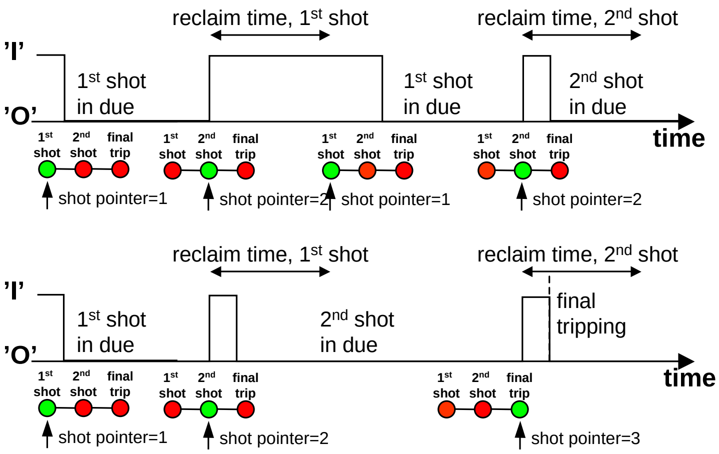


Figure 8.14.3: Effect of the reclaim time on the AR-sequence: top: new initiation after the reclaim time starts a new sequence with the 1st shot, bottom: new initiation comes within the reclaim time and the sequence is continued by the 2nd shot, "I" = CB closed, "O" = CB open.

If the manual reclosing of the circuit breaker is allowed after an unsuccessful AR-sequence, then after a possible manual closing, the circuit breaker will be tripped by the protection system. In such a case the restarting of the AR-sequence must be prevented. Similarly, when a feeder is re-energized after, for example, a maintenance work and the protection operates, the fault is likely to be a permanent one. In these cases, further autoreclosing is an undesired operation and would do no good. Typically, a modern AR-function is automatically capable of recognizing the manual re-energization of the outgoing feeder and inhibit internally the initiation of the AR: Whenever the AR-function detects that the circuit breaker status changes from open to closed position, and this control operation was not performed by the AR-function itself, it is judged as a manual closing operation, and a manual closing inhibit signal becomes activated. When this signal has been activated, all AR-initiations are inhibited and the reclaim time is started. The inhibit signal is reset when the reclaim time elapses. Another possibility to inhibit the initiation of an AR-sequence is to use a dedicated switch-onto-fault-function (SOTF). The activation of this function after a manual closing of the circuit breaker is automatic and it inhibits the possible AR-initiations for a short time.

In some cases, however, the circuit breaker can be left in the closed position after an unsuccessful AR-sequence. After the elapsing of the reclaim time, the AR-function must stay in the blocked condition and give alarm until the fault becomes cleared by manual opening control of the circuit breaker. An example of this kind of operation is the earth-fault protection that is used basically only for alarming, but in which case AR-shots are used to try to clear the fault in the first place.

8.14.3 Principal methods for autoreclosing initiation [8.14.1]

8.14.3.1 Initiation from the tripping of a protection stage, one-stage protection

The most straightforward way to initiate AR-shots is from the tripping, i.e. from the operate signal of the protection stage. According to this solution, a typical sequence of events is the following, see Figure 8.14.4:

- The 1st AR-shot is initiated from the operate signal of the protection stage, and the AR-unit recloses the circuit breaker after the set time delay
- If the fault has not been cleared, the protection stage operates again and initiates the 2nd AR-shot. The AR-unit re-closes the circuit breaker after the set time delay
- If the fault has not been cleared, the protection stage operates once more (known as a final trip)

In this scheme, the set operate delay time (i.e. trip time) of the protection stage prior to the initiation of each AR-shot is always the same, which may not be the most optimal way considering the success of the AR-sequence. Typically the 1st trip and the AR-initiation is advantageous to be performed relatively fast, so that the fault would not become any worse, for example, an earth fault would not turn to a double earth fault. The initiation of the 2nd and possibly the 3rd AR-shot can be considered to be delayed more as it may become cleared by burning fault away, for example, a tree branch in contact with the conductor. Another application requiring different operate delay times would be the coordination with the downstream fuses or other protection devices.

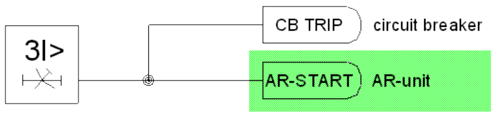


Figure 8.14.4: The use of one-stage protection for AR-initiation from the operate signal. The AR-unit controls the circuit breaker closing

8.14.3.2 Initiation from the tripping or starting of a protection stage: one- or two-stage protection

The objective is to initiate the 1st shot relatively fast from the starting or tripping of a protection stage. The most traditional way of implementing this is to use the operate signals from two protection stages for the initiation of the AR-shots. The operate delay time of one stage is short while that of the other stage is prolonged as long as, for example the coordination with the downstream fuses requires, Figure 8.14.5. The sensitivity of these stages is typically in the same order:

According to this solution, a typical sequence of events is the following:

- The 1st shot is initiated from the operate signal of the high-set (”fast”) stage, and the AR-unit recloses the circuit breaker after the set time delay.
- Prior to the 2nd shot, the high-set (”fast”) stage is blocked by the signal given by the AR-unit, the 2nd shot is initiated only from the operate signal of the low-set (”slow”) stage. The AR-unit then re-closes the circuit breaker after the set time delay.

- If the fault has not been cleared, the low-set stage trips once more (final trip).
- After the reclaim time, the above blocking signal becomes reset.

Traditionally, the high-set stage has been used for fast operation and low-set stage for slow operation because in many protection relays (IED) only the low-set stage has inverse operation characteristics and the high-set stage has only definite time delay.

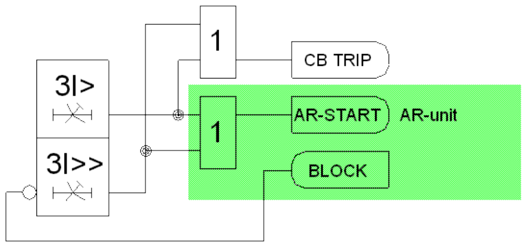


Figure 8.14.5: The use of two-stage protection for AR-initiation from operate signals. The AR-unit recloses the circuit breaker.

Principally the same operation can be achieved by using the start and operate signals of only one stage and an additional timer which can be set independently for each shot, Figure 8.14.6. This timer is typically integrated in the AR-function. The only difference now is that the operation mode of the stage initiating the 1st shot (”fast”) is definite time as the start signal is utilized. According to this solution, a typical sequence of events is the following, Figure 8.14.6, left:

- Prior to the 1st shot, a short time delay is given for the timer.
- The 1st shot is initiated from the start signal delayed by the timer, and the AR-unit trips the circuit breaker. After set 1st *dead time* the AR-unit recloses the circuit breaker.
- Prior to the 2nd shot, the timer is prolonged so that the operate signal of the protection stage now trips the circuit breaker first and initiates the 2nd shot. After set 2nd *dead time* the AR-unit recloses the circuit breaker.
- If the fault has not been cleared, the final tripping is initiated either directly from the protection stage, or the delayed start signal can be used instead by giving the timer a suitable value prior to the final tripping. In the latter case, the circuit breaker tripping is done by the AR-unit.

The advantage of the above timer is that it defines the maximum time delay after which the 2nd shot becomes initiated in any case if the tripping of the protection becomes highly prolonged due to inverse time operation.

Other possibility is that both shots can be initiated only from the start signal by giving the timer different settings prior to each shot, Figure 8.14.6, right.

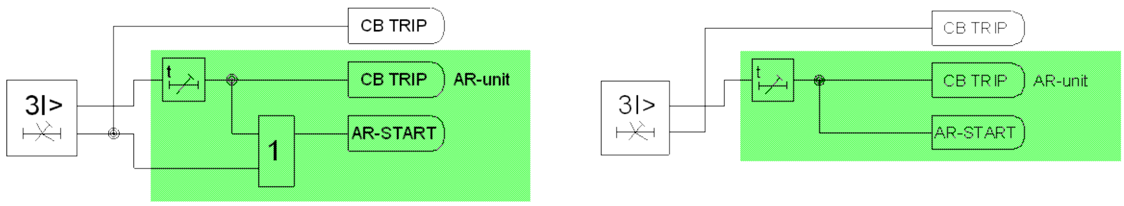


Figure 8.14.6: The use of one-stage protection for AR-initiation from start and operate signals, left, and from start signals only, right. The AR-unit recloses the circuit breaker.

When only operate signals are used for the AR-initiation, the final tripping ending the sequence comes from one of the protection stages according to its operate time setting. In many cases, this time delay can be considered to be unnecessarily long if the fault is still persisting after the 2nd shot. Therefore, the sequence would be unsuccessful in any case. To speed up the final tripping, there is typically a *fast final trip* feature in the modern AR-units. This function then gives the final tripping signal after the set time delay which is typically considerably shorter than the operate time of the corresponding protection stage. In the above schemes, this function can be accomplished by giving the timer a short value prior to the final tripping. This way the stress caused by the unsuccessful 2nd shot can be minimized.

The resulting operating characteristics of the above schemes are shown in current-time plane in Figure 8.14.8, left and middle.

If, however, inverse characteristic or different start current setting is required for the initiation of the shots, another stage must be added to the scheme. According to this solution, a typical sequence of events is the following, Figure 8.14.7:

- Prior to the 1st shot, a short or zero delay is given for the timer
- Depending on the magnitude of the fault current, the 1st shot is initiated either from the operate signal of the high-set stage or from the start signal of the low-set stage, and the AR-unit recloses the circuit breaker after the set time delay.
- Prior to the 2nd shot, the timer is given a high value
- Depending on the magnitude of the fault current, the 2nd shot is initiated either from the delayed tripping signal (operate time added by the timer value) of the high-set stage or from the operate signal of the low-set stage, and the AR-unit recloses the circuit breaker after the set time delay.
- If the fault has not been cleared, the final tripping is initiated either directly from the operate signal of the low-set stage, or the start signal can be used instead by giving the timer again a short or zero value prior to the final tripping. In the latter case, the circuit breaker tripping is done by the AR-unit.

Typical operating characteristic of this kind of scheme are shown in current-time plane in Figure 8.14.8, right.

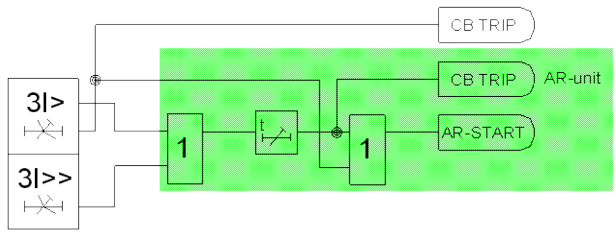


Figure 8.14.7: The use of two-stage protection for AR-initiation from start and operate signals. The AR-unit recloses the circuit breaker.

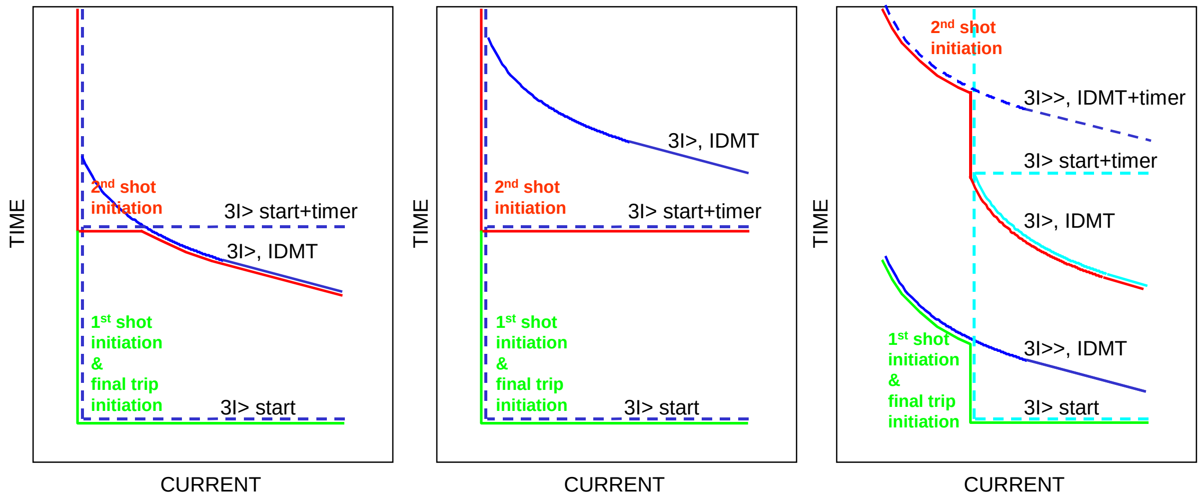


Figure 8.14.8: Different operating characteristics for AR-initiation and final trip initiation, left: initiation from start and operate signals, one-stage protection, middle: initiation from start signal only, one-stage protection, right: initiation from start and operate signals, two-stage protection

8.14.4 AR-shot and sequence characteristic

In the following, typical factors that affect the selection of AR-shot and sequence characteristic in distribution networks are discussed.

8.14.4.1 Fault type

8.14.4.1.1 Earth faults

In case of earth faults in high-impedance earthed networks, the primary target is that the delay prior to the AR-initiation must be long enough to give the possibility for the arcing fault to extinguish itself without a circuit breaker operation, thus preventing a supply interruption to the customers. If the fault is not self-cleared in due time, tripping followed by an AR-initiation takes place. The protection operate delay time must be selected considering also the safety regulations dictated by the authority, and the possibility that the AR-shots may not be successful prolonging the total fault-on time. Fulfilling the safety regulations may be a limiting factor especially in unearthed networks when considering the maximum allowed operate times. In compensated networks, where the fault currents are typically much lower, longer operate times can be allowed.

In principal, the operate times in compensated networks can be set considering the maximum expected arcing time t_{max} [s], which can be estimated, for example, with equations (8.14.1) and (8.14.2) [8.14.9]

$$t_{max} < 0.1 + 25L^2 \qquad \textbf{(8.14.1)}$$

where

$$L = I_{EFres} / I_C \qquad \textbf{(8.14.2)}$$

and

I_{EFres}	is the residual fault current in the fault spot due to compensation [A]
I_C	is the total capacitive earth-fault current of the network [A]

The residual fault current depends on the degree of compensation K and can be evaluated with equation (8.14.3).

$$I_{EFres} = \sqrt{((1-K)I_C)^2 + (I_R)^2} \qquad \textbf{(8.14.3)}$$

where

K	is the degree of compensation, which is equal to I_L / I_C [-]
I_C	is the total capacitive earth-fault current of the network [A]
I_R	is the total resistive earth fault current of the network corresponding to the parallel resistor of the Petersen coil and the coil and line losses [A]
I_L	is the current of the Petersen coil [A]

According to references [8.14.3] and [8.14.4], it was found out that in an isolated network 95% of the self-cleared faults were extinguished in less than 0.3 s from the occurrence of the fault, whereas in a compensated network 80% of the self-cleared faults were extinguished in less than 1 s. These values were based on the analysis of disturbance recorder data obtained from real distribution networks over a certain period of time.

Equation (8.14.1) does not consider the effect of fault resistance on the expected arcing time. The connection between the fault resistance and maximum arcing time has also been studied in reference [8.14.4], where the fault resistance and maximum arcing time were evaluated for faults that were self-clearing, that is, they did not cause any circuit breaker operation. According to this reference, the variation in maximum arcing times in different fault resistance ranges was found to be large, but considering the mean arcing times the summary shown in Table 8.14.1 was able to be represented, which can be treated as trendsetting. It can be seen clearly in Table 8.14.1 that especially faults with high fault resistance tend to last longer in compensated networks than in isolated networks.

8.14.1: Arcing time mean values [s] in different fault resistance ranges [8.88]

	Fault Resistance (kΩ)	<5	5-10	10-100	>100
Earthing	Isolated	0.10	0.09	0.14	0.27
	Compensated	0.67	0.29	1.95	3.68

On the other hand, prolonged operate times evidently increase the possibility that an earth fault turns into a double earth fault or a short circuit fault as the burning, energy dissipation and moving capability of the arc increase. So, in practice a compromise between the above viewpoints must be reached.

The extinguishing of a power arc depends on many factors such as the fault current magnitude, rise rate and peak value of the recovery voltage, total arcing time and the length of the applied spark gaps in the network. Considering the self-clearing possibilities, the first two factors are the most important. Figure 8.14.9 shows the dependence of the fault current magnitude on the earth fault arc self-extinguishing as a function of the system voltage. If, however, spark gaps are used in the network, lower fault current values must be applied. For example, in a 20 kV network the corresponding limits are found to be 5 A for unearthed and 20 A for compensated network when 100 mm spark gaps are used. The power arc tends to extinguish in the next zero crossing of the fault current, but it can reignite if the rising rate and the peak value of the recovery voltage are high enough. The recovery voltage peak value and its rising rate are typically much lower in compensated than in unearthed networks. This means that in compensated networks the maximum fault current cleared by self-extinguishing is typically much higher [8.14.2].

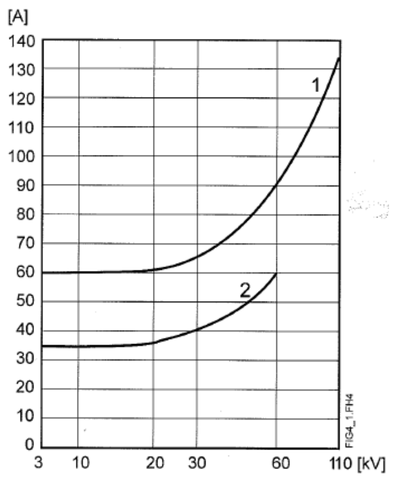


Figure 8.14.9: Current limits for the self-extinguishing of an earth fault arc: 1=compensated network, 2=isolated network [8.14.2]

In low-impedance earthed networks, the fault currents are much higher and the success of reclosing depends on the tripping speed. Generally, faults must be tripped as fast as possible to minimize thermal damage and arc ionization.

8.14.4.1.2 Short circuits

The higher the fault current is the more likely the fault is a permanent one. Another point to be considered is the fact that a short circuit fault causes a voltage dip that disturbs the whole distribution area of the substation. This is why the risk of unsuccessful AR-shots at least in the close proximity of the substation must be minimized. Typically only one high speed or one delayed AR-shot is performed from a short circuit fault.

In any case the thermal and mechanical withstand of the system in performing the desired AR-sequence must be carefully checked. The thermal withstand can be ensured by calculating the *equivalent duration of the fault,* t_{ekv} , which takes into account the accumulative heating and cooling of the concerned network components during the AR-sequence. This method can also be used for evaluating the accumulative effect of the AR-sequence on the melting time of downstream fuses. The latter issue is useful when considering e.g. the coordination between the fuses and the AR-unit in the substation.

Figure 8.14.10 gives an example of the accumulative heating of an overhead line during an unsuccessful AR-sequence.

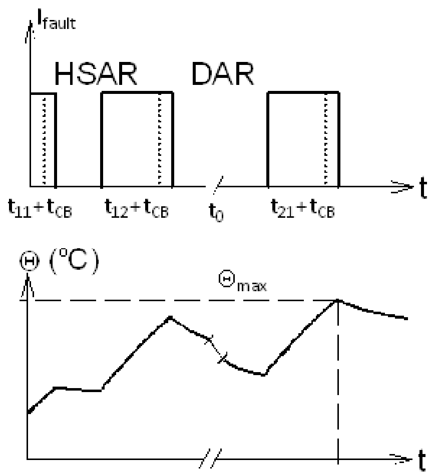


Figure 8.14.10: Schematics of heat accumulation of an overhead line during an unsuccessful AR-sequence, top: measured fault current during the sequence, bottom: corresponding conductor temperature rise

Referring to Figure 8.14.10 the temperature rise of the protected feeder due to an unsuccessful AR-sequence equals to the temperature rise with continuous fault current during the equivalent fault duration t_{eqv} which can be calculated from equation (8.14.4).

$$t_{eqv} = t_1 \cdot e^{-t_0/\tau} + t_2 \qquad \textbf{(8.14.4)}$$

with

$$t_1 = t_{11} + t_{12} + 2 \cdot t_{CB} \qquad \textbf{(8.14.5)}$$

and

$t_{11} + t_{CB}$	is the fault duration prior to HSAR initiation [s]
$t_{12} + t_{CB}$	is the fault duration prior to DAR initiation [s]

$$t_2 = t_{21} + t_{CB} \qquad \textbf{(8.14.6)}$$

and

$t_{21} + t_{CB}$	is the fault duration prior to final tripping [s]
t_{CB}	is the CB delay [s]
t_0	is the DAR dead time [s]
τ	is the time constant for heating and cooling of the overhead line type [s]

Equation (8.14.4**)** is valid for a two-shot scheme consisting of HSAR and DAR.

Example: Application of equation (8.14.4**)** for checking the thermal withstand of an overhead line consisting of 3 km ACSR type 1 (Aluminum Cable Steel Reinforced or steel reinforced aluminum conductor) and the rest being ACSR type 2. The 1-s withstand currents are 5.1 kA and 3.2 kA correspondingly. The maximum short circuit currents in the beginning of the ACSR type 1-section, i.e. in the substation, is 6 kA and in the beginning of the ACSR type 2-section 3.2 kA.

The desired AR-sequence times have been selected as follows:

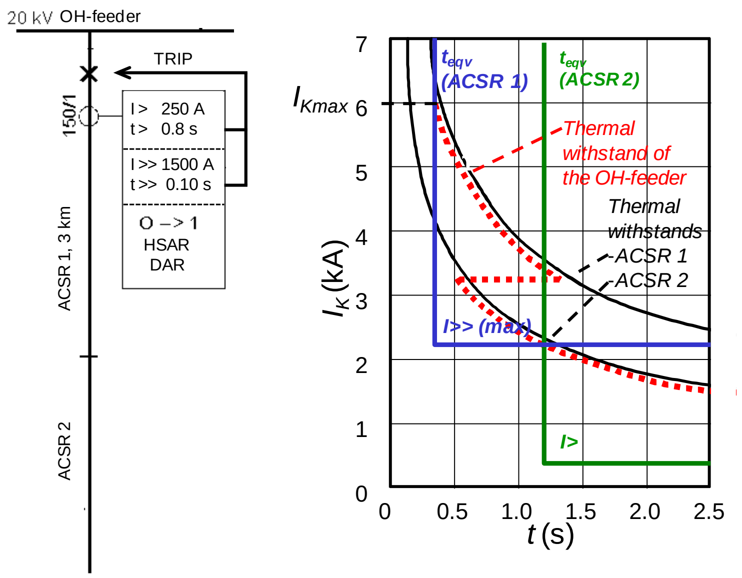
- Initiation delay before the 1st shot (HSAR) $t_{11} = 0.2$ s
- Dead time of the 1st shot (HSAR) 0.2 s
- Initiation delay before the 2nd shot (DAR) $t_{12} = 0.2$ s
- Dead time of the 2nd shot (DAR) $t_0 = 120$ s
- Final trip delay $t_{21} = 0.8$ s
- Delay of the circuit breaker $t_{CB} = 0.1$ s

Calculating the equivalent fault durations for the overhead line types, the following is obtained:

ACSR type 1: $t_{eqv} = t_1 \cdot e^{-t_0/\tau} + t_2$ where $t_1 = t_{11} + t_{12} + 2 \cdot t_{CB} = 0.6$ s, $t_0 = 120$ s, $t_2 = t_{21} + t_{CB} = 0.9$ s and $\tau = 6$ min gives $t_{eqv} = 1.3$ s

ACSR type 2: $t_{eqv} = t_1 \cdot e^{-t_0/\tau} + t_2$ where $t_1 = t_{11} + t_{12} + 2 \cdot t_{CB} = 0.6$ s, $t_0 = 120$ s, $t_2 = t_{21} + t_{CB} = 0.9$ s, and $\tau = 4$ min gives $t_{eqv} = 1.2$ s.

According to the above the conductor types should withstand the maximum expected fault current magnitudes for the time t_{ekv} which is clearly not the case. Therefore, the high-set stage must not initiate DAR at least, and its start signal can also be used for blocking the DAR-initiation. The selection of its start current value and operate delay time must be done in accordance with the thermal withstand, and the easiest way to do this is to use a coordination diagram, which is illustrated in 8.14.11.



8.14.11: Coordination curve for verifying the thermal withstand of the AR-sequence for a 20 kV overhead line

Considering the high-set stage it can be seen that the maximum allowed current start setting would be 2.2 kA and the equivalent fault duration 0.4 s. Taking into account safety margin, duration and magnitude of a possible inrush current on circuit breaker closing, and circuit breaker operating time, settings of 1500 A and 0.1 s can be suggested, if the high-set stage initiates only HSAR.

8.14.4.1.3 Double earth faults

In a double earth fault two phase conductors become in contact with earth. If these fault locations lie in different locations in the network the fault is called as a cross country fault. Typical reason for this is the increase of the healthy phase-to-earth voltages followed by a single phase-to-earth fault. If the insulation level of the other healthy phase has deteriorated for some reason, an insulation break down may occur resulting to a cross country fault. This is characterized by a fault current approaching the level of two-phase short circuit current circulating via earth between the different fault spots. Such a high earth fault current flowing in the earth electrodes and earthed metallic structures causes dangerous hazard voltages and may damage e.g. telecommunication cables, whose earthed screens become a part of the earth fault current path. This fault type can be detected by a dedicated protection function, and therefore a fast tripping and blocking of all AR-shots is typically required.

8.14.4.1.4 High resistive earth faults & broken conductor

In networks consisting of overhead lines a high resistive earth fault may occur due to trees or branches touching the conductors, or in cases where a conductor breaks down and falls to ground with high resistivity either from the source or the load side. As a result an energized conductor can be reached by the public creating a very hazardous situation. Faults along covered overhead lines and in other network components, such as insulators and surge arresters (MOAs) often belong to this category. In low-impedance earthed networks the fault current range in case of high resistive fault varies typically between 10-50 A characterized by random arcing between the broken conductor and earth [8.14.9]. In high-impedance earthed networks faults with fault resistance higher than 10 kΩ are generally classified belonging to this category. Despite the neutral earthing system in question it is common for this fault type, that the sensitivity of the standard earth fault protection is not adequate. This is why dedicated functions are needed for the detection. As a common practice a start or a trip from these functions does not initiate AR-shots, because due to the fault characteristic further auto-reclosing will typically not clear the fault at all, or will clear the fault only temporarily.

8.14.4.2 Dead time

Practically the dead time can be considered being the time the feeder is being de-energized. The dead time is an essential setting parameter in the AR-function, and there are several factors that affect its selection, such as the following:

- The time required for dispersion of the ionized air must be adequate, so that the arc will not re-strike as the feeder is re-energized. This time is called as the de-ionizing time, and it depends mostly on the applied voltage level, the magnitude of the fault current and on the distance between the arc end points. Figure 8.14.12 gives some typical values at distribution and sub-transmission voltage levels [8.14.1], [8.14.5], [8.14.6].

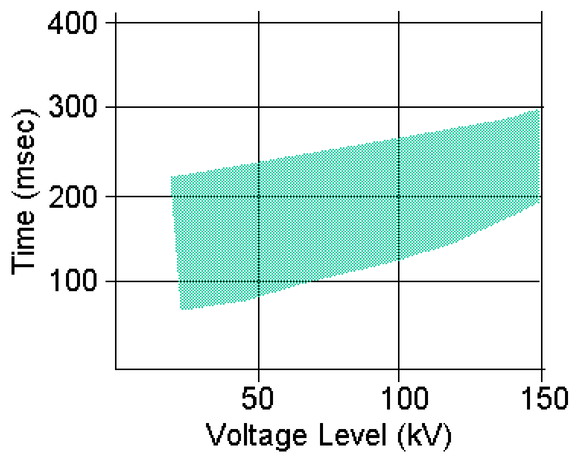


Figure 8.14.12: Typical ranges of de-ionization times as a function of system voltage

- The time required for critical load such as induction motors to be disconnected if the time allowed for re-energising is shorter than the expected dead time. An example of a LV-motor behaviour and the allowed time interval for re-energising after a loss-of-supply is shown in Figure 8.14.13. If the expected dead time of the example case is longer than 0.1 s, the disconnection of the motor during the dead time must be ensured by a suitable protection function. If the disconnection is not done the dead time must be so long that the voltage in the motor terminals has decayed adequately, e.g. below 0.3 p.u. In the example case this takes approximately 0.5 s. Also the motor loading and the ratio of rotating and non-rotating load of the feeder in question affects its behaviour during the dead time. From the dead time selection point of view these facts would indicate that it would be better of to use a somewhat longer dead time as the above mentioned 0.5 s to make sure that re-energisation occurs safely considering the motor loads.

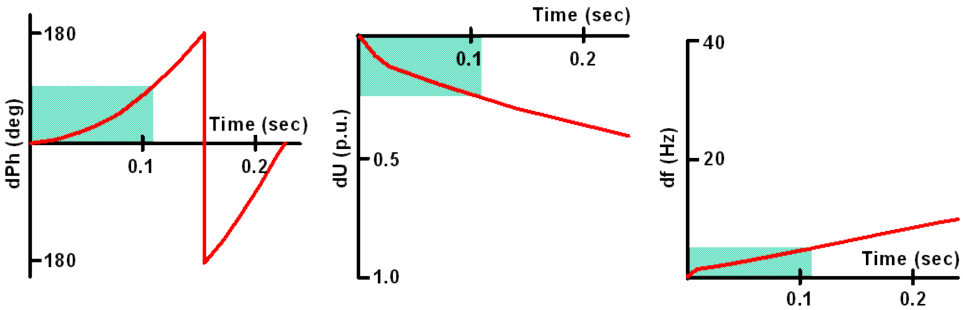


Figure 8.14.13: An example of a 75 kW LV-motor behaviour during a loss-of-supply condition due to main breaker trip [8.14.8]. *dPh, dU* and *df* are the phase angle, voltage magnitude and frequency difference between the motor terminals and the supply measured across the open circuit breaker

- Time required for distributed generators to be disconnected during the dead time. The ability of the connected generators to maintain the voltage and frequency during the dead time depends on the type and ratings of the machines and also on the remaining power balance of the island formed due to CB tripping. To avoid possible overvoltages, excessive thermal and mechanical stress and unsuccessful reclosings on feeders, where back feed exists, the disconnection of all distributed generators should occur during the AR dead time. It should be noted that it is almost always possible to adjust the AR dead time according to the operate times of the islanding detection functionality of the distributed generators.

- Time required for the automatically controlled disconnector devices such as sectionalizers to disconnect the faulted feeder section.

- Features of the circuit breaker, such as the time required for the operation mechanism to set itself for the next control sequence (typically spring charging time) and for the protection functionality to reset.

8.14.4.3 Number of shots

Performing two or more shots has formed as a general practice in many cases, because the success probability of the 2nd and even of the 3rd shot is fairly good. Figure 8.14**.**14 gives an example of the percentages of total faults that has been cleared by HSAR or DAR with different degrees of cabling [8.14.7]. This statistics is based on reported fault data collected from 59 utilities during one year period in Finland. The data shows that using more than one shot does improve the supply continuity especially when the degree of cabling is low, but clearly the additional benefit of applying the 2nd or even the 3rd shot, if used, is much less than for the preceding one. Also it is evident from Figure 8.14.14 that increasing the degree of cabling the effectiveness of AR-shots is clearly decreasing.

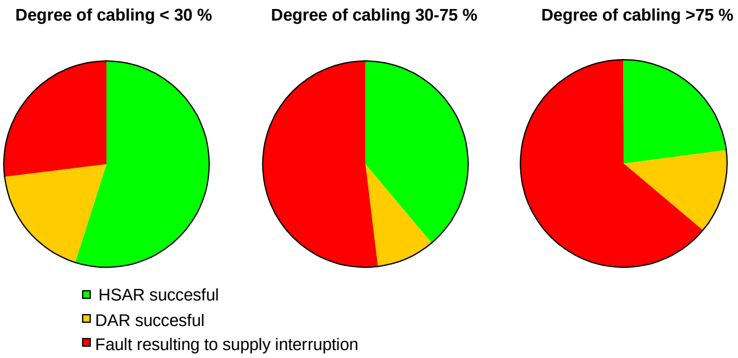


Figure 8.14.14: Percentages of successful AR-shots [8.14.7]

In addition to the fault type there are several other factors to be considered when considering the number of shots to be performed such as:

- Technical constraints related to the circuit breaker type in question
- Type of the feeder (overhead line/cable) and type of terrain, where the feeder runs (forest/field), e.g. the probability of transient faults and the success of shots is high in forested areas, whereas the probability of transient faults in 'weatherproof'-feeder sections (cable, overhead line/covered overhead line running along a wide right-of-way is low.
- The limitation of thermal and mechanical stress for the network components including the circuit breaker. For example, for feeder the equivalent fault duration calculated for the whole sequence must not exceed the thermal withstand of the conductor type. Similarly, for the main transformers the total fault duration time must not exceed the through-fault withstand time specified for faults occurring frequently [8.14.10].
- Number of count–settings of the automatic sectionalizers located along the feeder. Typically 2-3 counts are generally used, which coordinates with a four-shot AR-sequence [8.14.14].
- In compensated networks the degree of compensation affects the self-extinguishing possibilities of the earth fault arc. Therefore, depending on the degree of compensation the number of shots can be different. For example, in case of resonant condition the residual fault current is in its minimum, and the self-extinguishing possibilities are good. If the fault does not disappear in due time, only one shot is evidently enough to make sure whether the fault really is a transient one. Further shots would then do no good. If the degree of compensation deviates from the resonant condition, or when the Petersen coil becomes switched off, more shots with different durations are justified.

- Transient earth faults are typically characterized by a low fault resistance. If the measured residual current is lower, or the directly estimated fault resistance higher, than the limit specified, it may be justified to prevent the AR-initiation, or adapt the sequence characteristic.
- AR-initiation may be reasonable to be prevented in three-phase faults due to high thermal and dynamic stress to the system. Additionally three-phase faults are many times non-transient in nature.
- AR-initiation may be reasonable to be prevented due to minor overcurrents, when the measured phase current exceeds the low-set stage of the protection but is lower than the calculated actual minimum short circuit current for the feeder in question.
- AR-initiation may be reasonable to be prevented due short circuit faults, where the measured phase currents exceed the limit that has been calculated based on the severity of the resulting voltage dip.

8.14.5 AR-coordination

8.14.5.1 AR – fuse coordination [8.14.11], [8.14.12], [8.14.13]

It is a common practice to use fuses on lateral or branch feeders. It is thus important that the operation of the AR-function properly coordinates with the fuses in the required manner. These operation modes are typically either *fuse saving* or *fuse clearing*.

In the fuse saving mode the AR-function is set to initiate one or two shots before the downstream fuse will clear. Thus the purpose is trying to clear a transient fault without fuse operations. If the fault is still present after these shots, the tripping will be delayed more in the further shots so that the operation becomes slower than the fuse, enabling the fuse to clear. In the fuse clearing mode the AR-function is set so that for a fault behind any downstream fuse, it will be cleared by the fuse without causing any AR-initiations. To implement these modes it is necessary to know the characteristics of the fuses, which typically have two published characteristics: *minimum melting time* and the *total clearing time*. The minimum melting time curve is the time relationship for the fuse at which the fuse element has just melted. The total clearing time curve is the time relationship for which the fuse will clear the fault, effectively isolating the part of the feeder behind it.

8.14.5.1.1 Fuse saving mode

A fuse is a thermal device and its elements respond to an accumulative heat build-up. Therefore, the accumulative heating and cooling can be described by the method of the equivalent duration of the fault in the same manner as in case of feeders (see section 8.14.4.1.2). If fuse clearing is not desired the equivalent fault duration is calculated based on one or two ‘fast’ shots and they must not damage the fuse thermally meaning that the coordination must be based on the minimum melting curve of the fuse. Figure 8.14.15 shows an example of this. In the example it is desired that that two ‘fast’ shots without a fuse operation can be done for fault current values less than indicated by the value ‘B’. In the example the both ‘fast’ and ‘slow’ shots are initiated according to inverse time operating characteristic of the protection to provide optimal coordination with fuse curves. To obtain the equivalent fault duration curve the actual operating characteristic of the protection (3I>,’fast’) must be shifted by 2 x 3I>, ‘fast’ in time providing the characteristic 3I>, ‘fast’ (eqv.). This assumes that no cooling of the fuse elements occur during the dead times. The result is that with the settings corresponding to the operating characteristics 3I>,’fast’, the fuse will not clear the fault even after two unsuccessful ‘fast’ shots provided that the fault current magnitude does not exceed the level indicated by ‘B’.

If the ‘fast’ shots do not clear the fault then it is then desired that finally the fuse clears and isolates the faulted branch during one or two ‘slow’ or delayed shots that follow the unsuccessful ‘fast’ shots. This must occur with the minimum fault current level calculated in the furthest point in the branch feeder protected by the fuse. This fault current level is indicated by ‘A’ in Figure 8.14.15. The equivalent duration of the fault must now be calculated based on the whole sequence and coordinated with the total clearing time curve of the fuse. For this the operating characteristic 3I>,’slow’ is shifted by (2*3I>,’fast’+2*3I>,’slow’) in time. For the sake of simplicity this assumes again that no cooling of the fuse elements occurs during the dead times. It can be seen in Figure 8.14.15 that the fault current being in the level ‘A’ two ‘slow’ shots will make the fuse to clear in the corresponding time. With higher fault current magnitudes even one ‘slow’ shot is sufficient for the fuse to clear.

Additionally it can be seen in Figure 8.14.15 that the coordination range in respect to the fault current magnitude is between the levels ‘A’ and ‘B’.

8.14.5.1.2 Fuse clearing mode

In this mode the total clearing time of the fuse must be faster than the operating characteristic of the protection that initiates the AR-shots. This means that the fuse clears first provided the fault current is between the levels ‘A’ and ‘B’, which is now the range of coordination, Figure 8.14.15.

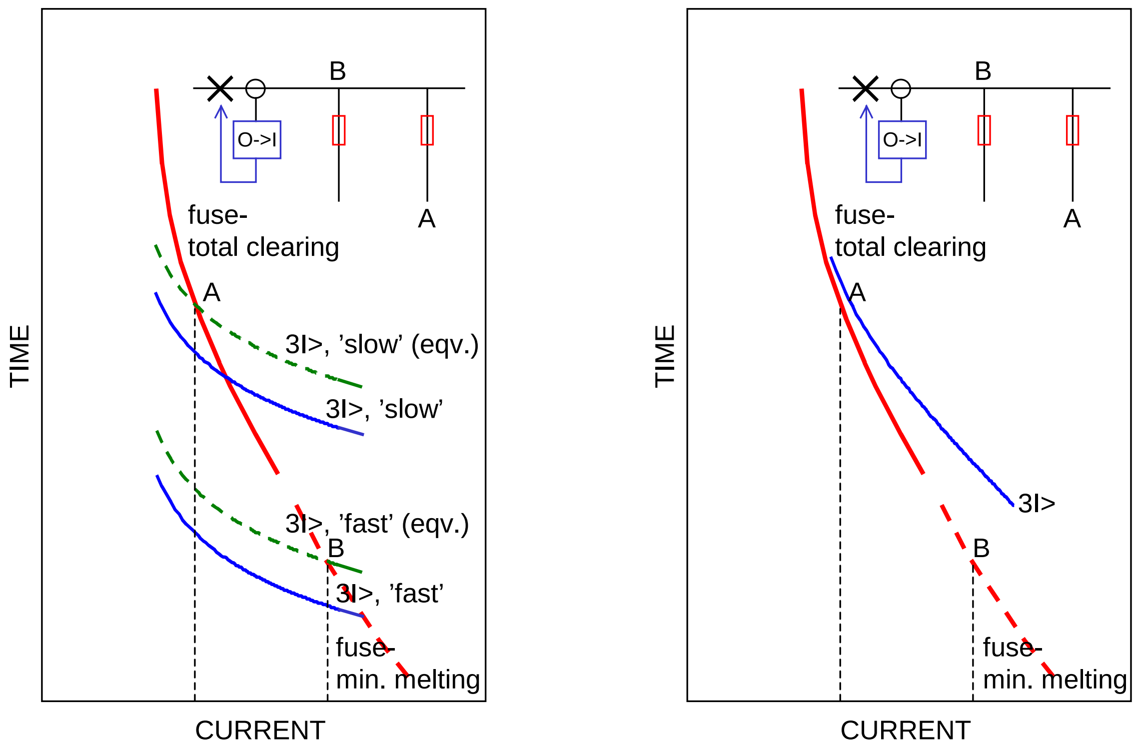


Figure 8.14.15: Left: Principle of coordination for the fuse saving mode. Right: Principle coordination for the fuse clearing mode

8.14.5.2 AR-AR-coordination [8.14.11], [8.14.12], [8.14.13]

When an AR-function is used in successive IEDs in the protection chain, the coordination between these AR-functions need to be considered. This is especially the case, when a mixture of ‘fast’ and ‘slow’ shots is applied. Figure 8.14**.**16 shows an example of successive AR-functions. Considering a fault at location F, then it is desirable for the AR-function ② to handle the isolation of the fault without causing the AR function ① to operate. Both AR-functions are set to initiate two ‘fast’ shots and one ‘slow’ shot. For coordination the operating characteristic for the protection initiating the shots has been selected in accordance with Figure 8.14**.**16. These characteristics can operate either in inverse time mode or in definite time mode, and also start signals can be applied for initiating AR. For a permanent fault at F, the operating sequence would then be the following:

- Trip ② ‘fast’ and reclose
- Trip ② ‘fast’ and reclose
- Trip ① ‘fast’ and reclose
- Trip ① ‘fast’ and reclose
- Trip ② ‘slow’ and reclose
- Trip ② ‘slow’ and lock-out

The above operating sequence has the disadvantage that the AR-function ① also operates increasing the number of customers momentarily interrupted by the fault. The problem is that after the second ‘fast’ shot of the AR-function ② its 3I>, ‘fast’-stage becomes blocked, and the same should occur in the AR-function ①. In other words, before the AR-function ② initiates the next AR-shot the trip counter or the shot pointer of the AR-function ① should have moved to the same position but without tripping its CB unless it has started the sequence by itself (i.e. in faults between ① and ②). This can be achieved by implementing a *zone sequence coordination* (ZSC) feature in the AR-function ①. The zone sequence coordination feature increments the trip counter or moves the shot pointer forward whenever a start of the protection stage becomes reset before it issues a operate command. The shot pointer takes care that the right number of shots is performed and that they are performed in the right order. An additional protection stage for coordination purposes is needed to enable this, Figure 8.14**.**16 (3I>, ‘ZSC’). The setting must be selected in such a manner that it detects all those faults that would be detected by the protection characteristic of the AR-function ①. It must also be faster than the operating characteristic initiating the ‘fast’ shots of the AR-function ②. With the zone sequence coordination feature implemented in the AR-function ①, the operation sequence for a permanent fault at F would be the following:

- Trip ② ‘fast’ and reclose
- Trip ② ‘fast’ and reclose
- Trip ② ‘slow’ and reclose
- Trip ② ‘slow’ and lock-out

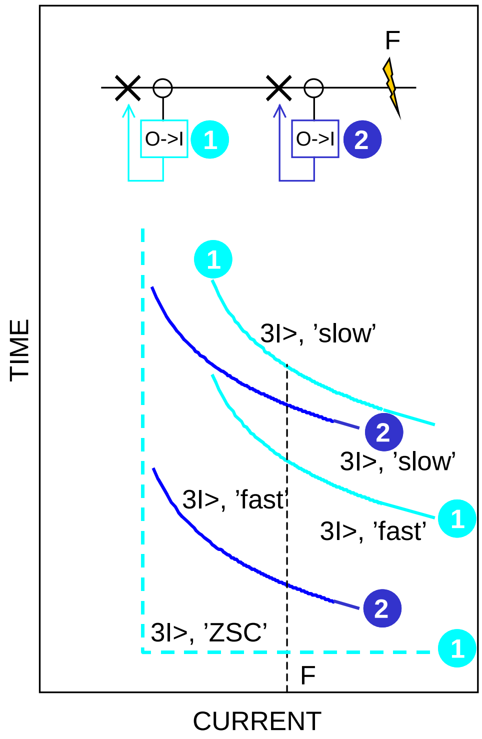


Figure 8.14.16: Principle of coordination for successive AR-functions, where the overcurrent protection functions operate in inverse time mode

8.14.6 Autoreclose with double infeed feeders [8.14.15]

Autoreclosing of feeders that can be energized from both ends can be implemented in the following ways, which are typically applied in distribution level applications in meshed type networks.

- Direct autoreclosing without synchrocheck
- High-speed or delayed autoreclosing with synchrocheck

Direct autoreclosing gives the shortest disturbance time. The tripping is performed as simultaneously as possible in the feeder ends, and the reclosing is initiated without any intentional time difference. If however a delayed operation of the protection can be expected in one feeder end, e.g. tripping by the overreaching distance zone Z_2, the dead time must be long enough to ensure that the feeder stays de-energized from both ends for an adequate time period. For example, a dead time of 0.6 s can be used in both feeder ends, which is enough for keeping the feeder de-energized for about 0.2 s, even if the tripping of the other end is delayed to 0.4 s. This mode of operation can be used in highly meshed networks, where there is no risk of losing the synchronism between the feeder ends during the time the feeder is de-energized.

In the autoreclosing with synchrocheck the tripping is performed as simultaneously as possible in the feeder ends. In the other end the autoreclosing is preceded by a live-bus dead-line check. As this condition is met and the dead time elapsed the feeder is energized from this end. Once the feeder is energized the synchronism can be checked in the other end before autoreclosing. This mode of operation requires the synchrocheck/voltage check functions in both feeder ends especially if the energisation direction can be changed due to system needs. In the high speed mode the time for synchrocheck should be as short as possible to avoid any extra delay in the reclosing. However, a possible re-trip of the other feeder end must be considered, which gives the minimum time delay for the initiation of the reclosure. In the delayed mode the long dead time takes into account this, and the effect of the synchrocheck time on the total reclose time is usually very small.

8.14.7 Application example

Figure 8.14.17 and Figure 8.14.18 show the protection functionality of a 20 kV overhead line in a substation with compensated neutral point. The functionality includes short circuit protection, earth fault protection and the autoreclosing functions, which have been implemented in a modern IED. This solution offers flexible parameterization and setting options for performing versatile AR-shots and sequences to fulfill a large variety of requirements optimally. In the following some example guidelines for applying the available features are given, and the purpose is to demonstrate the possibilities this functionality has to offer.

8.14.7.1 AR-initiation due to short circuits

This functionality has been implemented with a four-stage, three-phase overcurrent function of the IED. The following notation has been used for these overcurrent stages, Figure 8.14.17:

- 3I> i.e. the low-set stage, which can operate in definite time or inverse time mode
- 3I>> (1) i.e. the high-set stage, instance 1, which can operate in definite time or inverse time mode
- 3I>> (2)i.e. the high-set stage, instance 2, which can operate in definite time or inverse time mode
- 3I>>> i.e. the instantaneous stage, which operates in definite time mode

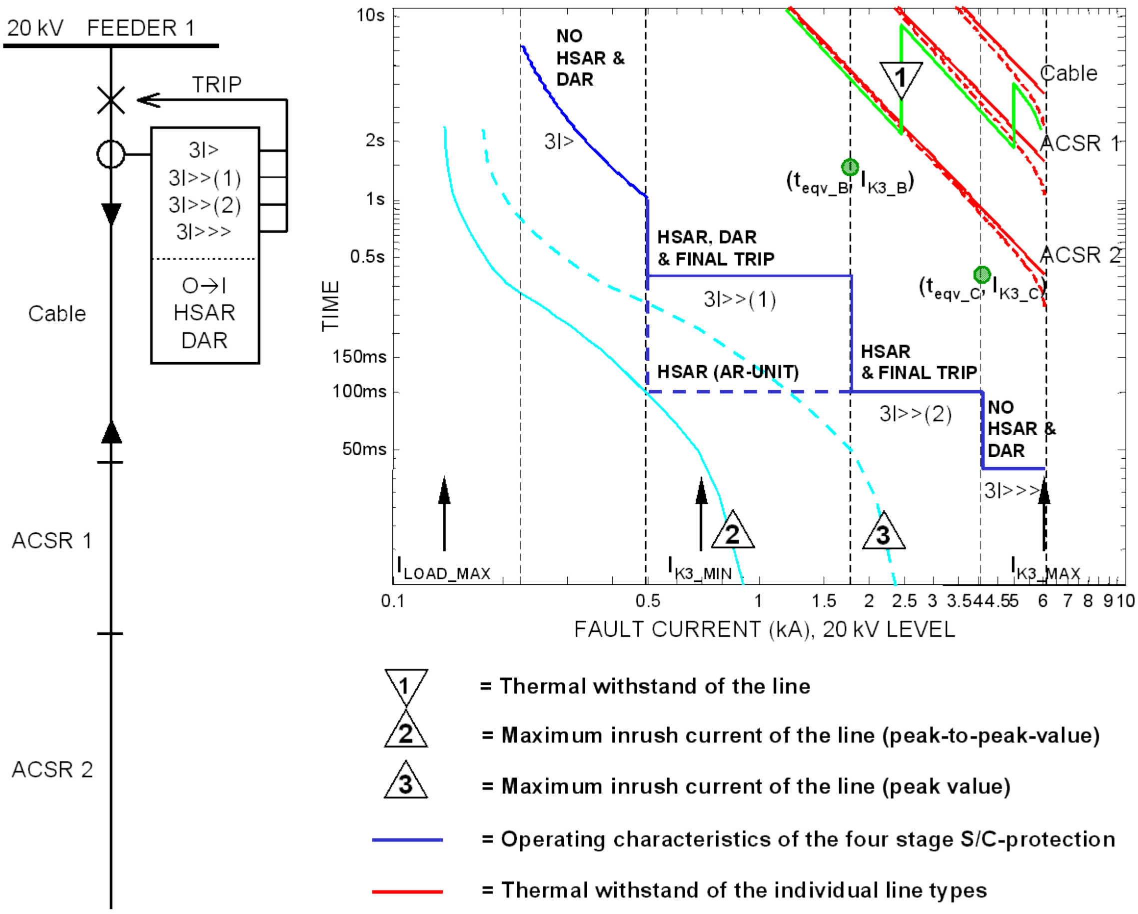


Figure 8.14.17: Coordination diagram of a 20 kV overhead line short circuit protection

The 3I>-stage operates as simplified overload protection of the OH-line. The sensitivity of this stage can sometimes be adequate for starting in case of faults located in the LV-side terminals of the distribution transformers along the feeder. Also the start current setting is typically much lower than the actual calculated minimum two-phase short circuit current in the furthest point of the feeder. Due to these reasons this stage does not initiate any AR-shots, and thus the risk of false AR-initiation due to momentary overloads and inrush currents becomes eliminated. To coordinate optimally with downstream fuses and to override momentary overcurrents due to energizing inverse time characteristic has been selected for this stage.

The start current of the 3I>>(1)-stage has been selected according to the calculated minimum two-phase short circuit current in the furthest point of the feeder. If the measured fault current exceeds this setting but is lower than the start current setting of the 3I>>(2)-stage, the measured overcurrent is surely due to a short circuit fault occurring in the MV-section of the feeder, and the resulting voltage dip experienced by the whole distribution area of the substation is still in a moderate level. Therefore, this stage can be considered to initiate both HSAR and DAR with the following features:

- HSAR is initiated from the start signal of the 3I>>(1)-stage. Additional start delay of 100 ms is set on the AR-unit.
- HSAR dead time of 200 ms is selected.

- DAR is initiated from the operate signal of the 3I>>(1)-stage (delay: 400 ms). This delay will override effectively the possible inrush current followed by CB closing after a successful HSAR in this case.
- DAR dead time of 10 sec is selected, because no actual cooling of the conductors is required due to high thermal withstand of the feeder.
- Final tripping ending the sequence due to unsuccessful DAR is initiated from the operate signal of the 3I>>(1)-stage (delay: 400 ms).
- If no practical cooling is assumed during the DAR dead time the equivalent fault duration in case both AR-shots are unsuccessful according to the above settings can be calculated. This is indicated by the point (t_{eqv_B}, I_{K3_B}) in Figure 8.14**.**17, which verifies that the thermal withstand of the feeder is adequate with a good margin for performing the whole AR-sequence.

The start current setting of the 3I>>(2)-stage has been selected according to the severity of the resulting voltage dip that is experienced in the distribution area of the whole substation. It has been calculated that due to faults with fault currents higher than this start current setting the magnitude of the voltage dip would exceed the acceptable level. Therefore, in this fault current range unsuccessful AR-shots should be avoided, or at least the maximum fault-on time should be minimized, if AR-shots are to be initiated. Due to these facts only HSAR is initiated with the following features:

- HSAR is initiated from the operate signal of the 3I>>(2)-stage (delay:100 ms).
- HSAR dead time of 200 ms is selected.
- Final tripping ending the sequence due to unsuccessful HSAR is initiated from the operate signal of the 3I>>(2)-stage (delay: 100 ms).
- The equivalent fault duration in case of an unsuccessful HSAR according to the above settings can be calculated. This is indicated by the point (t_{eqv_C}, I_{K3_C}) in Figure 8.14**.**17, which verifies that the thermal withstand of the feeder is adequate with a good margin for performing the HSAR-sequence.

The start current setting of the 3I>>>-stage has been selected according to the fact that if this stage starts the fault must locate in the cable section of the feeder or just in the beginning of the succeeding overhead line section. Because the probability of transient faults on this section of the feeder is evidently low, all AR-shots should be prevented. Therefore, the start of this stage is used to block all shots. Another point justifying this is the objective to limit unnecessary mechanical and thermal stress to the feeder and to the main transformer to a moderate level.

8.14.7.2 AR-initiation due to earth faults

This functionality has been implemented with a four-stage directional zero-sequence overcurrent function of the IED. Additionally the scheme has been completed with one non-directional zero-sequence overcurrent stage, which has been set in such a way that it operates only in case of a cross country fault. The following notation has been used for these directional zero-sequence overcurrent stages in Figure 8.14**.**18:

- I_0> → (1) i.e. the directional low-set stage, instance 1, which can operate in definite time or inverse time mode

- $I_0> \rightarrow$ (2) i.e. the directional low-set stage, instance 2, which can operate in definite time or inverse time mode
- $I_0> \rightarrow$ (3) i.e. the directional low-set stage, instance 3, which can operate in definite time or inverse time mode
- $I_0>> \rightarrow$ i.e. the directional high-set stage, which can operate in definite time or inverse time mode
- $I_0>>$ i.e. the non-directional high-set stage, which can operate in definite time or inverse time mode

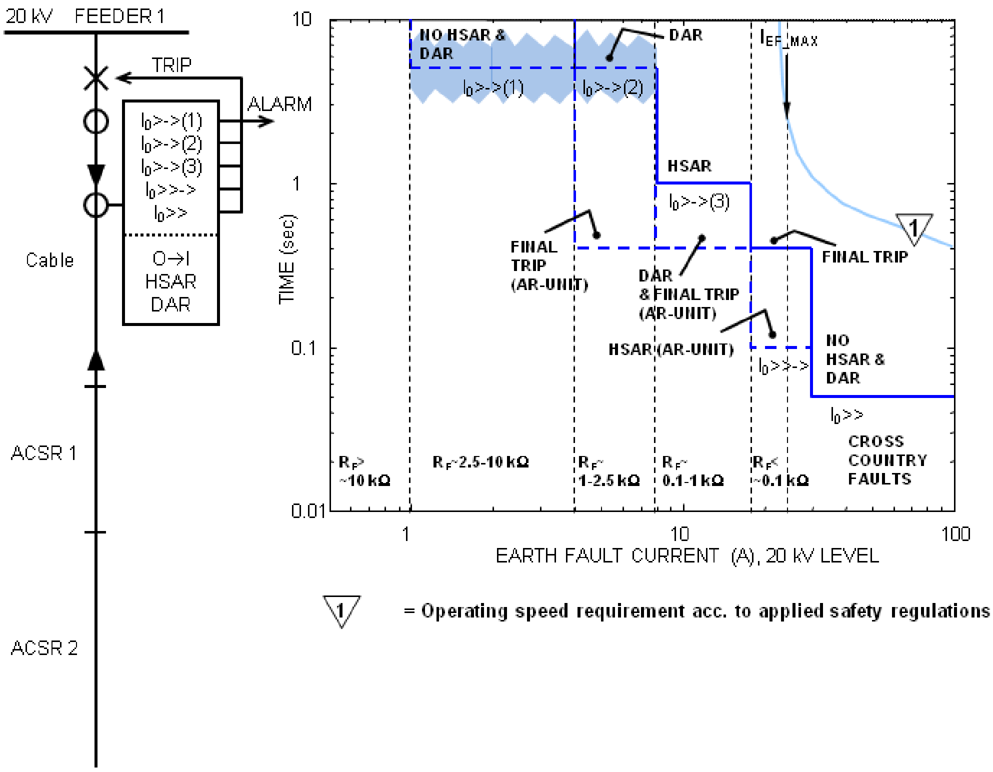


Figure 8.14.18: Coordination diagram of a 20 kV overhead line earth fault protection. The neutral point of the network is compensated.

The start current and voltage settings of the $I_0>>\rightarrow$-stage have been selected with a consideration of faults occurring in such locations where the MV-equipment earthing exists, like distribution transformer and disconnector substations along the feeder. In these fault cases the fault resistance is typically quite low, e.g. a flash over across a spark gap. On the other hand also the earth fault current magnitude is at its highest level decreasing the probability of self-extinguishing. It is therefore concluded that it is necessary to initiate

HSAR after a short time delay, and DAR would not improve the situation much after an unsuccessful HSAR. Therefore, only HSAR is initiated with the following features:

- HSAR is initiated from the start signal of the I_0>>→-stage. Additional start delay of 100 ms is set on the AR-unit.
- HSAR dead time of 200 ms is selected.
- Final tripping ending the sequence due to an unsuccessful HSAR is initiated from the operate signal of the I_0>>→-stage (delay: 400 ms).

With the above delay settings the operating speed requirement of the protection is fulfilled with a margin when the magnitude of earth fault current is between the corresponding start settings of I_0>>- and I_0>>→ -stages.

As the earth fault current becomes lower the probability of self-extinguishing is getting better. This is due to increased fault resistance, or due to faults occurring in locations where no direct MV-equipment earthing exists resulting to somewhat higher earthing resistance. The start current and voltage settings of the I_0>→(3)-stage have been selected considering these kinds of faults and it initiates both HSAR and DAR with the following features:

- HSAR is initiated from the operate signal of the I_0>→(3)-stage (delay: 1 s). This is delayed adequately giving good possibilities for self-extinguishing.
- HSAR dead time of 200 ms is selected.
- DAR is initiated from the start signal of the I_0>→(3)-stage. Additional start delay of 400 ms is set on the AR-unit.
- DAR dead time of 10 s is selected.
- Final tripping ending the sequence due to an unsuccessful DAR is initiated from the start signal of the I_0>→(3)-stage. Additional start delay of 400 ms is set on the AR-unit.

With the above delay settings the operating speed requirement of the protection is fulfilled with a good margin when the magnitude of earth fault current is between the corresponding start settings of I_0>>→- and I_0>→ (3)-stages.

In the fault resistance range matching the earth fault current values between the corresponding start settings of the I_0>→(2)- and I_0>→(3)-stages it may be useful to try to burn the fault away, e.g. in cases where a branch of a tree is touching the conductors of the overhead line. The start current and voltage settings of the I_0>→(2)-stage have been selected considering this. Because the fault is tried to be burned away i.e. by delaying the tripping relatively long, only DAR is initiated with the following features:

- DAR is initiated from the operate signal of the I_0>→(2)-stage (delay: 10 s).
- DAR dead time of 10 s is selected.
- Final tripping due to unsuccessful DAR is initiated from the start signal of the I_0>→(2)-stage. Additional start delay of 400 ms is set on the AR-unit.

The start current and voltage settings of the I_0>→(1)-stage have been selected so that it detects faults up to as high fault resistance value as possible without endangering the security of the protection. It also fulfils the sensitivity requirement set on the protection by the authority. In this fault resistance range AR-shots would probably do no good, or would clear the fault only temporarily. Therefore, this stage is not used for initiating any AR-shots, and therefore it is used only to give a selective alarm indicating the faulty feeder after the set time delay.

The start current setting of the non-directional stage I_0>> has been selected so that it operates only with fault currents higher than the maximum evaluated single-phase earth fault current. This means that operation is expected only in cross-country faults in which case the single-phase-to-earth faults locate in different phases of different feeders. Due to this and the safety reasons the start signal of this stage is set to prevent all AR-shots and to trip the faulty feeders in the shortest possible time.

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