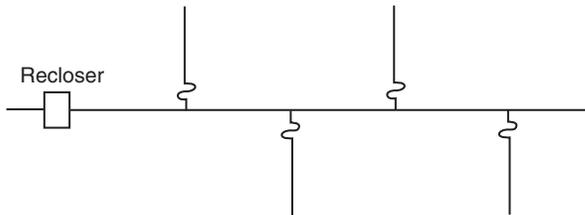


Analysis of distribution system reliability and outage rates



Reliability analysis

This document provides information on the measurement and improvement of distribution system reliability. Standard indices to measure system reliability, outage rate goals, types of faults, and types of outages will be discussed. Both transient and permanent outages are included in the measurement of reliability. Examples of various types of distribution systems will show how outage rates can be reduced and system reliability improved by the application of distribution switchgear. Improvement that can be obtained through system automation using remote identification and remote switching will be included.

Performance indices

When discussing outage rates, industry standard reliability indices will be used. Standard indices permit meaningful comparisons between utilities or between different divisions of a given utility. Most important, they allow evaluation of system changes by a direct comparison of past and future performance of a feeder or system as changes are made. An outage definition will vary from utility to utility. The standard indices used are listed below.

System average interruption frequency index (SAIFI)

Defines the average number of times that a customer's service is interrupted during a year. A customer interruption is defined as one interruption to one customer.

$$SAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers served}}$$

System average interruption duration index (SAIDI)

Defines the average interruption duration per customer served per year.

$$SAIDI = \frac{\text{sum of customer interruption durations}}{\text{total number of customers affected}}$$

Customer average interruption frequency index

Defines the average number of interruptions per customer interrupted per year.

$$CAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers affected}}$$

Customer average interruption duration index (CAIDI)

Defines the average interruption duration for those customers interrupted during a year.

$$CAIDI = \frac{\text{sum of customer interruption durations}}{\text{total number of customer interruptions}}$$

Momentary average interruption frequency index (MAIFI)

Defines the average number of times that a customer's service is momentarily interrupted during a year. A customer interruption is defined as one interruption to one customer.

$$MAIFI = \frac{\text{total number of customer momentary interruptions}}{\text{total number of customers served}}$$

Momentary average interruption frequency events index (MAIFI_E)

Defines the average number of times that a customer's service experiences a momentary interruption event during a year. An event is one, two, or more momentary interruptions during the short time period required by a device to restore service.

$$MAIFI^E = \frac{\text{total number of customer momentary interruption events}}{\text{total number of customers served}}$$

Average service availability index (ASAI)

Defines the ratio of the total number of customer hours that service was available during the year to the total customer hours demanded. (Customer hours demanded = 24 hours/day x 365 days = 8760 hours)

$$ASAI = \frac{8760 - SAIDI}{8760}$$

For example, a SAIDI of 1.0 hours per year would be figured as follows:

$$ASAI = \frac{8760 - 1.0}{8760} = 99.989\%$$

Outage rate goals

An outage definition will vary from utility to utility. Some utilities define an outage as an interruption of electric service for a period of two minutes while others may consider five minutes of interrupted service an outage. There are two types of outages covered in the analysis. A sustained outage is defined as a loss of service for more than a normal reclosing interval. A momentary outage is a brief service interruption of less than a reclosing interval. Historically, power distribution systems have been designed to reduce sustained outages. Today, because of the increasing use of electronics and computer equipment, customers are more sensitive to momentary interruptions experienced during the clearing of temporary faults. Reducing both sustained and momentary outages is now a goal in designing system reliability.

Urban and rural systems

Outage rate goals will vary depending upon the nature of the distribution system. Urban systems typically have less line exposure than do rural systems. As a result, urban systems generally experience fewer outages per year than rural systems. Typical outage rate goals for urban and rural distribution systems are to limit outages to an average of 1.0 (urban) and 1.5 (rural) outages per year (SAIFI). With each outage lasting an average duration of 1 hour, (CAIDI), the average annual interruption is 1.0 hours for urban systems and 1.5 hours for rural distribution systems.

Table 1. Typical utility outage rate goals

Index	System type	Operating goal
SAIFI	Urban	1.0 Outages Per Year
SAIFI	Rural	1.5 Outage Per Year
CAIDI	Rural/Urban	1.0 Hours Per Outage
SAIDI	Urban	1.0 Outage Hours Per Year
SAIDI	Rural	1.5 Outage Hours Per Year
ASAI	Urban	99.989% Annual Service Availability
ASAI	Rural	99.983% Annual Service Availability
MAIFI _E	Rural	4.0 Interruptions per year

Feeder length and voltage

Many utilities have found that their service reliability deteriorated significantly when they converted to a higher distribution voltage (for example; from 4 kV to 13 kV). The higher distribution voltage allowed them to service longer feeder lengths and more customers with a given feeder; however, each outage that occurred affected more customers. The longer feeders also require more patrol time to locate and repair a fault.

To restore service reliability, the first step is to sectionalize each feeder into smaller sections. This limits the number of customers affected by a given outage and reduces the patrol time needed to locate and repair the fault. Operating experience of a number of utilities that have adopted this sectionalizing practice suggests

that an optimum feeder segment is 3 to 5 MVA. As the load of a line segment approaches 8 to 10 MVA, outage rates increase to unsatisfactory levels.

When further reliability improvement is desired, some utilities have utilized loop operation of adjacent feeders, as shown in Figure 9. This operation not only sectionalizes the feeder into smaller segments, it allows the utility to restore service to customers at the end of a feeder, minimizing any outage to the smallest possible segment of the feeder. As an example, two large eastern utilities that have adopted this scheme have achieved the following service continuity records:

Utility A

0.715 outages per customer per year (SAIFI), 1.056 hours per outage (CAIDI), resulting in 0.767 outage hours per customer per year (SAIDI).

Utility B

0.475 outages per customer per year (SAIFI), 1.4 hours per outage (CAIDI), resulting in 0.665 hours per outage per customer per year.

Types of faults

Maximum service reliability is achieved when the distribution system is designed and operated to minimize the effect of any fault that may occur. Two types of faults are encountered on an overhead distribution system: transient and permanent.

Transient faults

A transient fault is one that does not require corrective action to remove the fault from the system. If the arc can be cleared quickly, before burning into a permanent fault, the cause of the fault is gone. Since no equipment damage has occurred, the circuit can be re-energized immediately and service returned to the entire system. A transient fault would result from occurrences such as lightning, an arc caused by an animal or tree branch that then falls clear, or the wind momentarily blowing two conductors together.

On most distribution systems, the majority of faults (60% to 90%) are transient in nature. With proper protection devices (fast tripping with fast reclosing), these faults can be cleared without a sustained outage.

Permanent faults

A permanent fault is one in which permanent damage has resulted from the cause of the fault. A permanent fault usually requires some form of repair before power can be restored. Examples include a broken insulator, a broken conductor, or an automobile knocking a pole down. It also includes faults that are initially transient in nature but result in permanent damage to the system. With permanent faults, the line must be de-energized, a line crew brought to the site, and repairs made. Outage times range from 30 minutes to many hours and produce sustained outages.

Outage rate reduction methods

For faults on the main feeder line, a line-sectionalizing device (recloser or sectionalizer) can be used to divide the feeder into smaller line segments. All taps should have a protective device (fuses for small taps, a recloser or sectionalizer for larger taps) where they connect to the main feeder. Even on very small taps, a fuse should be used. The justification is that this type of tap fuse does not protect the tap, it protects the remainder of the distribution feeder from a fault on the tap.

The extent of the outage can be minimized by limiting the size and length of the affected line. The shorter line segment minimizes the number of customers affected and minimizes the time required to

patrol the line and locate the fault.

A combination of a recloser and fuses, as shown in Figure 1, is typically used to provide protection against both transient and permanent faults.

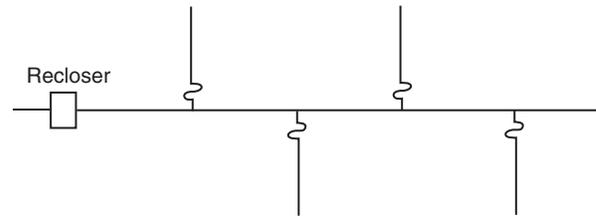


Figure 1. Reclosers and fuses provide protection against transient and permanent faults

The fast trip curve of the recloser is used to clear all transient faults on the main feeder and taps. For permanent faults on the taps, the recloser time-delay curve allows the tap fuse to clear, resulting in an outage on the tap only as shown in Figure 2.

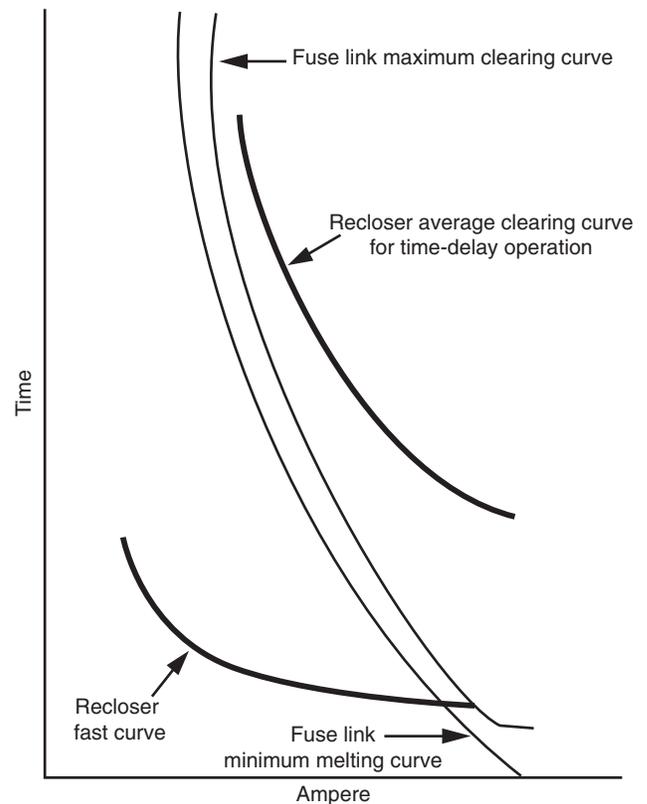


Figure 2. Recloser/fuse link coordination

Outage rate reduction examples

The following examples describe how outage rates can be reduced by various approaches to using main-line sectionalizing devices, recloser/fuse coordination, and loop schemes.

Example 1

Use of main-line-sectionalizing device

Investigate outage rates for one fault at F1 and one fault at F2 as shown in Figure 3.

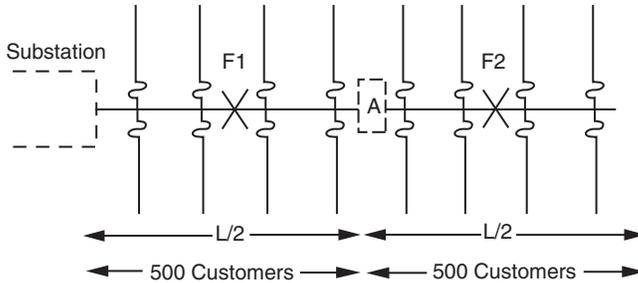


Figure 3. Calculating reliability

Each outage = 1 hour in length (time required to locate fault and restore service).

With No Line Recloser:

- Fault at F1: 1000 customers x 1 hr. = 1000 cust. hrs.
- Fault at F2: 1000 customers x 1 hr. = 1000 cust. hrs.
- Outage Total = 2000 cust. hrs.

Option to improve service reliability

Adding a recloser at point A, shown in Figure 3, as a main-line-sectionalizing device will reduce outage rates caused by faults on the main feeder.

With Recloser at A:

- Fault at F1: 1000 customers x 1 hr. = 1000 cust. hrs.
- Fault at F2: 500 customers x 1 hr. = 500 cust. hrs.
- Outage Total = 1500 customer hours

Outage rate with line recloser equals 1500/2000 or 75% of rate without line recloser; or: 500/2000 = 25% reduction in outage rate.

Note: A sectionalizer can be substituted at point A to produce the same 25% reduction in outage rate.

The actual reduction in outage rate will be greater than the 25% calculated due to the shorter time required to patrol the line and locate the fault (crew must patrol only 1/2 of total line for fault at either F1 or F2).

Example 2

Circuit breaker in substation without instantaneous tripping

All faults on taps result in an outage due to fuse operation. Refer to Figure 4.

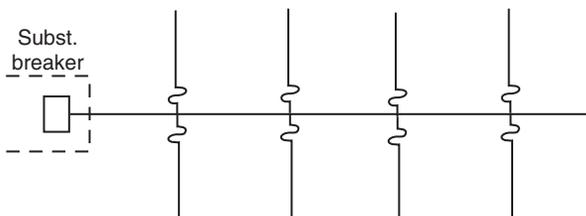


Figure 4. Substation breaker set on all delay operations to lockout

Options to improve service reliability

1. Replace breaker with recloser.
Outage rate should decrease by a rate equal to the ratio of transient faults to permanent faults on the system. Therefore, if 70% of faults are initially transient by nature, outage rates will decrease by 70%.
2. If committed to existing breaker protection, adding a recloser in line will still provide a dramatic decrease in outage rate:

Note: 25% decrease due to line sectionalizing as described in earlier systems.

Additional benefits

Reduction in tap outages due to transient fault protection provided by recloser. 50% of taps x 70% transient fault rate = 35% reduction in outage rate.

Therefore, the total reduction in outage equals 25% + 35% = 60% reduction in outage rate.

Example 3

Circuit breaker in substation with fast and delayed relay settings

A breaker utilizing a conventional relay setting of one instantaneous (INST) trip followed by time-delay trip operations, with the INST trip level set typically at 2 1/2 times the basic phase and ground trip settings, as shown in Figure 5.

Phase trip = 800 A, INST at 2000 A

Ground trip = 300 A, INST at 750 A

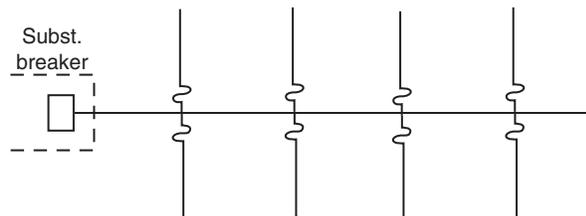


Figure 5. Substation breaker with typical relay settings

The 750 A ground trip instantaneous setting generally will not provide reach for faults distant from the substation; thus all transient faults occurring at these locations and all faults below 750 A magnitude on any tap will result in an outage.

Options to improve service reliability

1. Replace breaker with recloser using conventional recloser sequence providing fast tripping at basic trip levels selected. With electronic control the fast Time- Current Curve (TCC) can be selected with adequate time delay near minimum trip to prevent any nuisance trips. Sequence coordination feature can be used for even better coordination if any down-line reclosers are used.

The reduction in outage rate is dependent on the parameter of the circuit – how many faults below 750 A (as an example) are experienced. For a moderately long feeder with lengthy taps, a 50% reduction in the outage rate may be reasonable.

2. Add a recloser in line; even without breaker changeout, it will still provide dramatic improvement. The line recloser provides a 25% reduction in outage rate plus the reduction in outages on the taps due to the increased reach of the recloser.
3. Add a recloser in the line as shown in Figure 6. This will provide the 25% reduction in the outage rate as described earlier, plus some added improvement due to the added reach (or sensitivity) afforded by the more sensitive trip settings of the line recloser.

Note: It is generally very difficult, or impossible, for any substation device to be set to provide reach for protection to the ends of all taps.

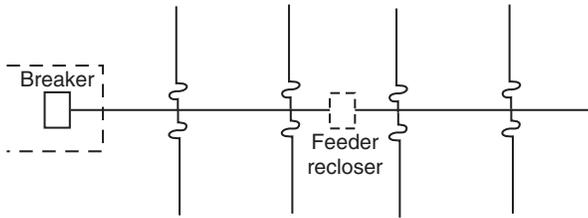


Figure 6. Feeder recloser with conventional recloser settings

Example 4

Loop schemes

For the highest level of service reliability, some utilities have chosen loop schemes. The following example shows the improvement in service reliability that can be accomplished by midpoint sectionalizing and addition of a tie recloser between feeders.

Assume one fault at each section, for one hour duration each, as shown in Figure 7.

Fault at F1: 1000 customers x 1 hr. = 1000 cust. hrs.

Fault at F2: 1000 customers x 1 hr. = 1000 cust. hrs.

Fault at F3: 1000 customers x 1 hr. = 1000 cust. hrs.

Fault at F4: 1000 customers x 1 hr. = 1000 cust. hrs.

Outage Total = 4000 cust. hrs.

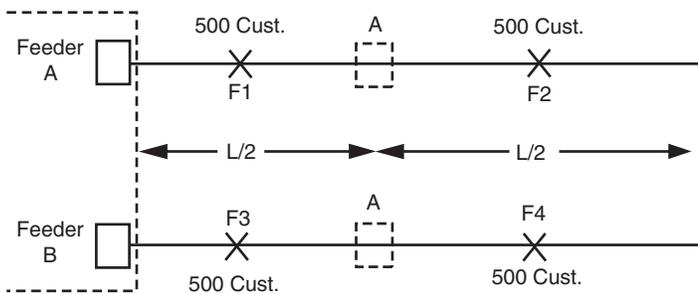


Figure 7. Typical recloser-protected feeders without midpoint sectionalizing

Options to improve service reliability

Refer to Figure 8 and assume one fault at each section, for one hour duration, to show the effects of midpoint sectionalizing.

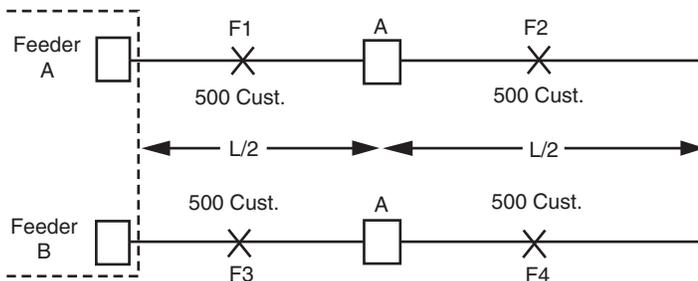


Figure 8. Reclosers at midpoint of feeders

Fault at F1: 1000 customers x 1 hr = 1000 cust. hrs.

Fault at F2: 500 customers x 1 hr = 500 cust. hrs.

Fault at F3: 1000 customers x 1 hr = 1000 cust. hrs.

Fault at F4: 500 customers at 1 hr. = 50 cust. hrs.

Outage Total = 3000 cust. hrs. (25% reduction)

Add a normally open tie recloser between feeders as shown in Figure 9, set to close upon loss of voltage from either side. The midpoint reclosers will be sectionalizing type reclosers, set to automatically open for loss of voltage from their source side.

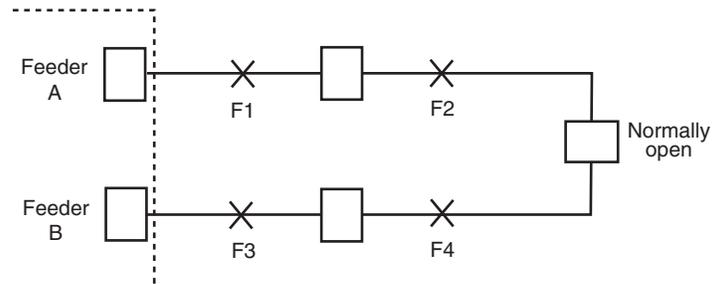


Figure 9. Normally open tie recloser between feeders

Fault at F1: 500 customers x 1 hr. = 500 cust. hrs.

Fault at F2: 500 customers x 1 hr. = 500 cust. hrs.

Fault at F3: 500 customers x 1 hr. = 500 cust. hrs.

Fault at F4: 500 customers x 1 hr. = 500 cust. hrs.

Outage Total = 2000 cust. hrs.

Adding a tie recloser as shown in Figure 9 and operating the midpoint reclosers as sectionalizing reclosers has resulted in a 33 1/3% reduction in customer outage: (3000-2000)/4000 = 33 1/3%.

Adding the three reclosers as shown in Figure 9 to the two feeders has reduced the outage rate to 50% of the original: (4000-2000)/4000 = 50%.

Example 5

Application of recloser at feeder tap

Assume the reach of recloser A extends to point D on the tap as shown in Figure 10.

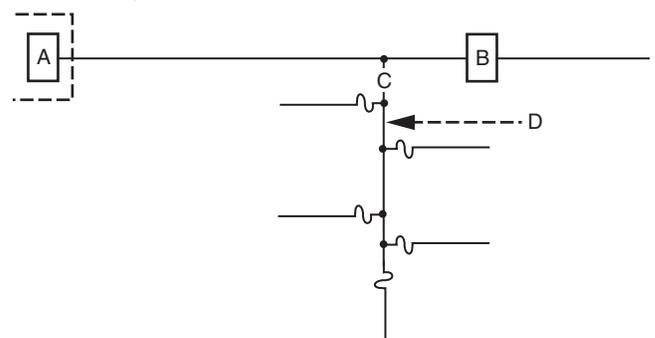


Figure 10. Feeder tap without recloser protection

If a fuse is used at location C:

1. Any transient fault on the main tap line beyond location D will cause the fuse at C to operate, resulting in an outage on the entire tap for a fault that was initially transient.
2. Service restoration can be delayed since crew may spend considerable time looking for a fault that no longer exists.
3. For a transient fault beyond any of the downline fuses, the downline fuse will operate, again resulting in an unnecessary outage for a fault that was initially transient. Use of a recloser at location C can normally be sized to provide reach for the entire tap. The fast trip of the recloser (as shown in Figure 2) will then clear transient faults, the reclosing operation then restoring service to all customers on the tap.

Underground distribution

Reliability comparisons between overhead and underground feeders and distribution systems present a unique problem. Underground installation is more costly than overhead. Since there is no exposure to wind, trees, or ice, an underground system has few transient faults. This means there is no need for fast tripping or reclosing operations. Typically, protection at the substation consists of a single time-delay trip operation and lock open.

When a fault does occur, the outage duration can be long. It takes time to patrol the line and locate the fault. Equipment or cable repair can require considerably more time than equivalent overhead equipment repair. Fewer outages in an underground system means a lower SAIFI ratio, while significantly longer repair times will drive the SAIDI ratio up. The end result may be an unacceptable average outage ratio.

Option to improve service reliability

The addition of a midpoint fault-sensing and interrupting device can be used to reduce the number of customers affected and reduce the time required for fault location.

System automation

After protective devices are properly applied on a distribution system, the next higher level of system reliability can be achieved by automating the entire system for remote identification of faulted sections and rapid isolation of these sections by means of remote switching operations.

Remote identification of the faulted section eliminates the time required for line patrol. The remote switching function allows the faulted line to be isolated and service restored to all other line sections (assuming availability of an alternate feed to the remote sections) in less than 2 minutes. Thus, the outage is limited to only the faulted portion of the line.

Figure 11 illustrates a distribution system using both switches and line reclosers that can all be operated remotely.

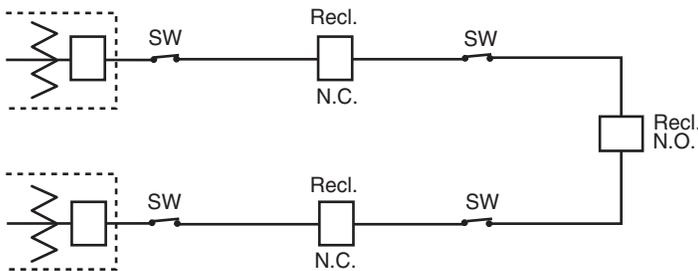


Figure 11. Automated distribution system

For this automated operation, switches have been developed that have stored energy operators (allowing remote switching without power at the switch location) and fault indicators to provide remote indication of fault location. The use of switches allows more sectionalizing points on the feeder without adding any steps of coordination. Reclosers are used to provide immediate local fault clearing capabilities that are independent of the communication system or remote computer control.

Summary

Increased usage of electricity has led to the need to increase distribution system voltages. Utilization of these higher distribution voltages has resulted in decreased system reliability and higher customer outage rates. Efficient application of reclosers and sectionalizers can provide dramatic improvements in distribution system reliability.

Using reclosers to provide transient fault protection on the entire distribution system can improve outage rates by 50–90%. Reclosers or sectionalizers used as mainline- sectionalizing devices can improve outage rates an additional 25%.

Even greater service continuity can be achieved by using nearby feeders as backup supplies. By using reclosers or sectionalizers as normally open feeder ties with local supervisory controls, outage rates can be improved by an additional 50% over unsectionalized systems.

Additional improvements in distribution system reliability can be obtained through the application of supervisory control or distribution automation.

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