# Basic Reliability Analysis of Electrical Power Systems

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## Introduction

This course present basic definitions and concepts that are used in determining power system reliability. It provides details about variables affecting reliability and gives information that may be useful for improving electrical system reliability. The presented information can be found and experienced in daily operation of the power system utilities.

This course was designed for both engineers in disciplines other than electrical, and electrical engineers who desire to deepen their understanding of reliability assessment. This course is adapted to the practical world of industrial and commercial electrical systems.

Numerical reliability evaluation methods define reliability indexes for any electric power system. They are computed from knowledge of the reliability performance of the constituent components of the system. Thus, different system designs can be studied to evaluate the impact on service reliability and cost of changes in component reliability, system configuration, protection and operational mode, and system switching policy including maintenance practice.

Power system design involves consideration of service reliability requirements of loads to be supplied as well as reliability of service provided by any electrical system. System reliability evaluation methods based on probability theory allow the reliability of a proposed system to be numerically assessed. These computational methods permit consistent, defensible, and unbiased evaluation of system reliability that are not otherwise defensible, and that are not otherwise possible.

This course teaches the following specific knowledge and skills:

- System reliability index
- Key definitions
- Data needed for system reliability evaluations
- Method for improving system realiability

## System reliability indexes

System reliability indexes that have proven most useful in power distribution system design are as follows:

- Load interruption frequency
- Expected duration of load interruption events

Two basic indexes of interruption frequency and expected interruption duration can be used to compute other indexes:

- Total expected interruption time per year (or other time period)
- System availability or unavailability as measured at the load supply point
- Expected but unsupplied, energy per year

Utilities most commonly use two indices, SAIFI and SAIDI, to benchmark reliability. These characterize the frequency and duration of interruptions during the reporting period (usually years). SAIFI, System average interruption frequency index, is:

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

SAIFI is also the average failure rate, which is often labelled $\lambda$. Another useful measure is the mean time between failure (MTBF), which is the reciprocal of the failure rate: MTBF in years = $1/\lambda$

SAIDI, System average interruption duration frequency index, is:

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}}$$

SAIDI quantifies the average total duration of interruptions. SAIDI is cited in units of hours or minutes per year. Other common names for SAIDI are CMI and CMO, standing for customer minutes of interruption or outage.

SAIFI and SAIDI are the most-used pair out of many reliability indices. Another related index is CAIDI.

CAIDI, Customer average interruption duration frequency index, is:

$$\text{CAIDI} = \frac{\text{SAIDI}}{\text{SAIFI}} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customer interruptions}}$$

CAIDI is the “apparent” repair time. It is generally shorter than the actual repair time because power system operators normally split circuits to reenergize as many customers as possible before actual damage is fixed. Also used in many other industries, the availability is quantified as ASAI, Average service availability index:

$$\text{ASAI} = \frac{\text{SAIDI}}{\text{SAIFI}} = \frac{\text{Customer hours service availability}}{\text{Customer hours service demanded}}$$

ASIFI can be specified from SAIDI in hours as:

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

**Load-Based Indices**

In the real world, residential customers dominate SAIFI and SAIDI since these indices treat each customer in the same way. The equivalent of SAIFI and SAIDI, but scaled by load, are ASIFI and ASIDI:

ASIFI, Average system interruption frequency index, is:

$$\text{ASIFI} = \frac{\text{Connected kVA interrupted}}{\text{Total connected kVA served}} \text{ (Average number of interruptions)}$$

ASIDI, Average system interruption frequency index, is:

$$\text{ASIDI} = \frac{\text{Connected kVA interruption duration}}{\text{Total connected kVA served}}$$

Few utilities track ASIFI and ASIDI, mainly since they are hard to track (knowing load interrupted is more difficult than knowing number of customers interrupted).

## Variables Affecting Reliability Indices

### Circuit Exposure and Load Density

Longer circuits lead to more interruptions. This is difficult to avoid on normal radial circuits, even though this can be compensated by adding reclosers, fuses, extra switching points, or automation. Most of the change is in SAIFI. The interruption duration (CAIDI) is less dependent on load circuit lengths. It is easier to provide higher reliability in urban areas; circuit lengths are shorter and more reliable distribution systems (such as a grid network) are more economical.

### Voltage

Higher primary voltages tend to be more unreliable, mainly because of longer lines. On higher-voltage primary circuits, utilities need to make more of an effort to achieve the same reliability as for lower voltage circuits: more reclosers, more sectionalizing switches, more tree trimming, etc. With the ability to build longer lines and serve more customers, it is difficult to overcome the increased exposure. Keeping reliability in mind when planning higher-voltage systems helps. On higher-voltage circuits, wider is better than longer. Burke's analysis (1994) of the service length and width for a generalized feeder shows that for the best reliability, higher-voltage circuits should be longer and wider, not just longer (see Table 9.3). Usually, higher-voltage circuits are just made longer which leads to poor reliability. Having a long skinny main feeder with short taps off of the mainline results in poor reliability performance.

### Supply Configuration

The distribution supply greatly impacts reliability. Long radial circuits provide the poorest service while grid networks provide exceptionally reliable service. Massive redundancy for grid and spot networks leads to fantastic reliability (50 plus years between interruptions). Note that the interruption duration (CAIDI) increases for the more urban configurations. Being underground and dealing with traffic increase the time for repairs.

### Computation of quantitative reliability indexes

Numerical calculation of reliability indexes can start once the minimal cut-sets of the system have been identified. The first step includes frequency computation, expected duration, and expected down-time per year of each minimal cut-set. Expected down-time per year is the product of the frequency expressed in terms of events per year and the expected duration. If the expected duration is given in years, the expected down-time will have the units of years per year and can be considered as relative proportion of time or probability the system is down due to the minimal cut-set. More frequently, anticipated duration is given in hours and the expected down-time has the units of hours per year.

### Definitions

The presented definitions provide the required nomenclature for discussions of power system reliability.

*Interruption:* The loss of electric power supply to loads.

*Forced unavailability:* The long-term average fraction of time that a system or component is out of service due to a forced outage (failure).

*Interruption frequency:* The expected number of interruptions to a load per unit time usually expressed as the number of interruptions per year.

*Exposure time:* The time during which a component performs its function and is subject to failure. Exposure time is usually expressed in years.

*Failure:* Any problem with power system equipment that causes any of the following to occur:

- Partial or complete shutdown, or below defined operation standard
- Unacceptable performance of equipment
- Operation of the electrical protective relaying or emergency operation of the electrical system

- De-energization of the electric circuit or equipment

A failure on a utility supply system can cause the user to have one of the following:

- A power interruption or loss of service
- A deviation from normal voltage or frequency

*Failure rate (forced outage rate):* The mean number of failures of a component per unit of exposure time. The failure rate is usually expressed in failures per year.

*Expected interruption duration:* Expected or average duration of an interruption event.

*Availability:* A term that applies either to the performance of individual components or to a system. Availability is the long-term average fraction of time that a component or system is in service satisfactorily performing its function. The equivalent definition for availability is the steady-state probability that a component or system is in service.

*Component:* A piece of equipment (transformer, line, circuit) or a group of items that is viewed as an entity for the purpose of reliability evaluation.

*Forced outage:* A failure of an electrical system component that causes a forced outage of the component, so that the component is unable to perform its intended function until it is repaired or replaced.

*Outage:* The state of an electrical component or a power system during which it is not available to properly perform its function due to an event directly associated with that component or system.

*Repair time:* The repair time of failed electrical equipment or the duration of a failure is the clock time from the occurrence of the failure to the time when the component is restored, either by repair or by substitution of the failed component. This includes time for diagnosing the trouble, finding the failed component, repairing or replacing, testing and commissioning. Repair time does not include the time necessary to restore service to a load by switching on alternate circuits.

*Scheduled outage:* Outage encountered when a component is taken out of service at a selected time, usually for the purpose of construction or maintenance.

*Scheduled outage duration:* Period from the start of a scheduled outage until construction, maintenance or repair work is finished and the affected electrical component or power system is restored to perform its intended function.

*Scheduled outage rate:* An average number of scheduled outages of an electrical component per unit exposure time.

*System:* A group of electrical components connected or associated in a fixed, defined configuration to perform a specified function of distributing power.

*Unavailability:* Long-term mean fraction of time that an electrical component or system is out of operation due to faults or scheduled outages. An alternative definition is the steady-state probability that an electrical component or system is out of operation.

*Switching time:* The period from the time a switching action is necessary due to a component failure until that switching operation is finished. Switching operations include operations such as throwover to an alternate or back up circuit, opening or closing a circuit breaker, reclosing a circuit breaker following a tripout from a temporary fault, etc.

**Definition of the service interruption**

The first step in any reliability study is careful assessment of the power supply quality (e.g., sags, surges, harmonics, overall power quality etc.) continuity required by the loads. This analysis should be summarized and presented in a service interruption definition that can be used in the following steps of the reliability calculation procedure. The interruption definition defines reduced voltage level (dip) together with the minimum duration of such reduced voltage period that ends in substantial degradation or complete loss of function of the load. Reliability studies are carried out on a continuity basis, in which case, disruption definitions reduce to a minimum duration specification with voltage assumed to be zero during the interruption.

### Failure modes and effects analysis (FMEA)

The FMEA for power distribution systems equals to the definition and listing of electrical component outage events that result in an interruption of service at the load point being analysed according to the disruption definition that has been adopted. This assessment must be done taking into account different types of disruptions that electrical equipment components may exhibit and the response of the relay protection scheme to these events. Electrical component outages are summarized as follows:

- Forced outages
- Scheduled or maintenance outages
- Overload outages

Forced outages are either permanent forced outages or transient forced outages. Permanent forced outages need repair or replacement of the broken equipment before service can be restored while transient forced outages means there is no permanent damage to the electrical equipment, thus allowing its restoration by a reclosing or refusing operation. In addition, electrical equipment failures can be grouped by physical mode or type of failure. This type of failure categorization is important for circuit breakers and switching devices where the following failure types are possible:

- Faults that must be cleared by backup devices
- Fails to trip when needed
- False trips
- Failures to reclose when needed

Each failure type will produce a different impact on overall system operation.

The primary objective of the FMEA is the list of minimal cut-sets it generates. Minimal cut-set is determined to be a set of pieces of electrical equipment which, if removed from the electrical system, results in loss of continuity to the load point being investigated. In the present context, the electrical components in a cut-set are just those pieces of equipment whose overlapping outage results in a disruption according to the adopted interruption definition.

An important benefit of FMEA is thorough systematic thought process and critical investigation it needs. Weak points in system design are often identified before any quantitative reliability indexes are numerically determined. Thus, the FMEA is a useful reliability design tool even in the absence of the data required for quantitative evaluation.

**Input data for calculation of the reliability**

Necessary data for numerical evaluations of electrical system reliability depend on the nature of the system being analysed and the level of the study. In principle, data on the performance of electrical components together with the times required to complete switching operations are required.

Electrical system component data can be summarized as follows:

- Scheduled (maintenance) outage rate of electrical component
- Expected (average) time to repair or replace broken component
- Failure rates associated with different modes of equipment failure
- Expected (average) duration of a scheduled outage event

If available, electrical equipment reliability data should be based on historical performance of components in the same environment as those in a considered system. The reliability surveys provide a source of component data when such specific data is not available.

Switching time data includes the following:

- Expected times to open and close a circuit breaker
- Expected times to open and close a disconnect or throwover switch
- Expected time to replace a fuse
- Expected times to perform emergency operations

Switching times are usually estimated for the system under consideration based on experience, engineering judgment, and planned operating practices.

**System reliability evaluation methods**

A general method for electrical system reliability assessment that is recommended and presented here is referred to as the “minimal cut-set method”. It is well suited for the assessment of electric power distribution systems that are found in industrial plants and commercial buildings. The method is straightforward and can be completed either manually or using computer software. The method feature is that the system weak points can be identified, numerically and non-numerically, thereby focusing attention on those system sections that contribute most to service unreliability.

The procedure for system reliability evaluation is outlined as follows:

- Evaluate the service reliability requirements of the loads that are supplied and calculate the appropriate service interruption definition.
- Complete failure modes and effects analysis (FMEA) that is comprised of identifying and recording electrical component failures and combinations of equipment failures that end up in service disruptions and that constitute minimal cut-sets of the system.
- Numerically determine interruption frequency contribution, expected disruption duration, and the expectancy of each of the minimal cut-sets of the system.
- Combine the results of the third step to produce system reliability indexes.

These steps are discussed below.

**Service Restoration**

Electrical service restoration affects SAIDI and CAIDI indexes. The main technique to reduce restoration time is to install as many sectionalizers as possible in order to put back in service as many consumers as possible. Other methods that can help improve service restoration time include the following:

- Prepare by using weather information including lightning detection to track storms. Maintenance teams should be on the stand-by before service disruption occurs.

- Coordinate maintenance teams and distribute them as effectively as possible.
- Train maintenance teams in order to improve their responsiveness.
- Locate the faults by using faulted circuit indicators and cable fault locating equipment. Provide GPS devices to maintenance teams for easily finding fault locations. Use more fuses since they are cheap protection devices and great fault locators. Reduce circuit lengths that are protected by a fuse since it will need less patrolling.
- Implement better communication between maintenance teams so that the right team is sent to the right location.
- Set priorities and put efforts to get the most customers back in service as soon as possible after disruption appears. These actions involve sectionalizing of the network or repair equipment that affects most consumers.
- Faults affecting small number of consumers can wait and can be replaced after major faults are cleared. It is important to remember that safety comes first and that repairs should not be rushed. All equipment that is subject to repair has to be de-energized before repair starts.
- Prevent faults by applying maintenance that would address fault types which normally require longer time to be cleared. For example, faults caused by trees have long repair times, so putting some time in trimming trees is considered a good investment.
- Implement outage management systems that should be capable to improve restoration and provide information useful for improving overall system performance. However, implementing information management systems can make reliability indices worse but consumers will see improvement since the systems will be used to improve responsiveness. Unfortunately, keeping better records and having useful and accurate information will increase reliability indices. It was reported by some utilities that SAIFI and SAIDI

indices have increased by 20% to 50% after implementing outage management systems.

- More importantly, responsiveness will improve as outage information is relayed more directly to maintenance teams. Outage management systems also evaluate reliability indices and utilities can make reports that can be used to target certain areas of concerns or to plan maintenance schedules. In addition to improved reliability, consumer satisfaction will improve as dispatchers will be able to provide more precise information on restoration times.
- Also knowing when storms tend to occur that can cause most service disruptions can help to organize maintenance teams. Typically, summer months with frequent storms are the busiest. Certainly each geographical region has its own patterns.

**Methods for Improving Reliability**

There are many different methods for the reduction of long-duration interruptions. These methods include:

- Reduction of faults — trimming of trees, animal guards, arresters, circuit patrols
- Finding and replacing faults quicker — faulted circuit indicators, management system for the outages, crew staffing, cable fault finding
- Limiting the number of interrupted customers — increase the number of fuses, reclosers and sectionalizers
- Interrupting customers only in the case of permanent faults — use reclosers instead of fuses and implement fuse saving schemes

Whether there is a need to enhance the reliability on one specific transmission line or a requirement to increase system wide reliability, the main steps that would need to be implemented can be presented as follows:

- Identification of possible projects
- Estimation of the costs of each configuration or option

- Estimation of the improvement in reliability with each selected option
- Ranking the projects based on a cost-benefit ratio

It is usually straightforward to predict the costs while predicting improvement can be more challenging. It can be difficult to attach numbers to certain projects. An important measure for improving reliability is defining what reliability measure needs to be optimized. It can be SAIFI, SAIDI, a combination of both, or something else completely different. Depending on the final objective ranking, the priority of the projects can change.

It was shown that the interruption frequency is most important to customers certainly until interruption prolongs. System regulators keep on favouring duration indicators since they are a measure of utility responsiveness, and unrestrained cutting of costs may first appear as a prolonged response time to system disruptions. Analysis and priority ranking of the projects is usually done on a large scale. Large scale projects frequently require simplification and sometimes involve unavoidable assumptions. All of the network configuration changes, such as implementing reclosers and adding more fusing points and automating switches, can be predicted.

These improvements can also be quantified by many computer programs. However, projects with the main objective to reduce rates of faults and involve trimming trees adjacent to overhead lines, adding more arresters, installing animal guards, are challenging to quantify and measure. Improving techniques and upgrading systems that are used for locating faults and repairs are also more difficult to define numerically. Usually, sensitivity analyses are performed in order to help determine project priority. Instead of using one performance number, using a low, a best guess, and a high estimate number can be considered as a good approach but in its simplest form. Nailing causes of the faults can also help evaluate what kind and how much benefit these aimed solutions can have. For example, if there are just several faults caused by lightning, additional surge arresters will not provide major benefit.

**Targeting Identified Circuits**

Not all transmission circuits are the same. Usually, the most significant sections are not those that have the most faults per mile. The type of consumers and the number of those consumers on a particular circuit are also a very important consideration.

For example, a suburban circuit with many commercial or industrial customers should be treated in a different way from the rural and remote circuit with few residential and agricultural customers. The way these circuits are treated depends on utility philosophy and their own priority ranking. Three-phase mainline is critical on radial distribution circuits.

Sustained disruptions on the main feeders keep out all consumers until the fault is repaired. Also very long mainlines have more disruptions than shorter transmission circuits. There are many common methods that are being used to reduce risk of the mainline exposure and one of them is trimming trees more often along a transmission circuit corridor. Also sectionalizer switches used on the main distribution lines help by quickly restoring consumers upstream of the fault. Automated switches have proven even better for this purpose.

Other improvements include using normally open tie switches to other feeders and that enable maintenance crews to shift consumer load to other feeders during sectionalizing operations. Lateral faults are also important type of faults that needs to be considered. These faults can be ranked by historical performance considering lengths and number of connected customers. Experience shows that longer laterals could be better suited for single phase reclosers instead of fuses.

### Identify and Target Fault Causes

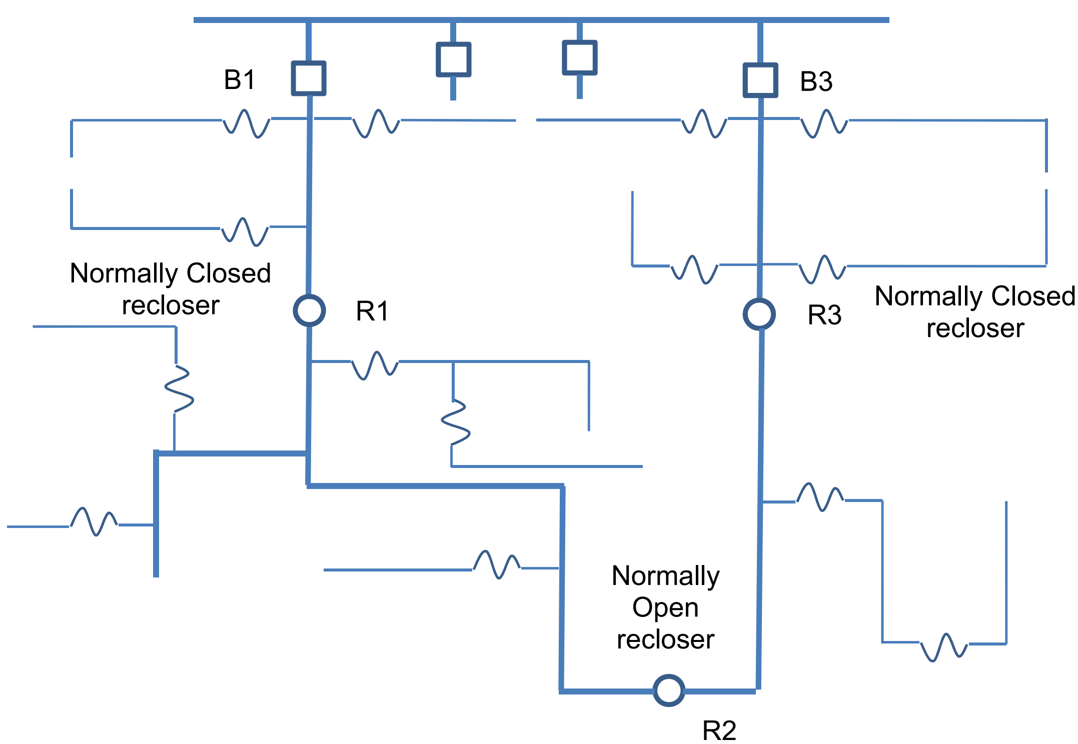
Keeping track and resolving identified types of faults help focusing on improvements. For example if animals are not causing any faults, there is no need to implement animal guards. It is a usual practice used by many utilities to tag interruptions with identifying codes. This information is usually organized in a system wide database that can provide identifications that can be used to help improve future system reliability.

Obviously, different causes of faults can cause different reliability indices. Also relative impacts can widely vary, for example, trees can cause higher repair time but they usually impact fewer customers. Keeping record of this type of information can help utilities to identify the frequent problems for a given service area. These numbers are not uniform and change by region depending on weather, season, used construction methods, load density and many other factors.

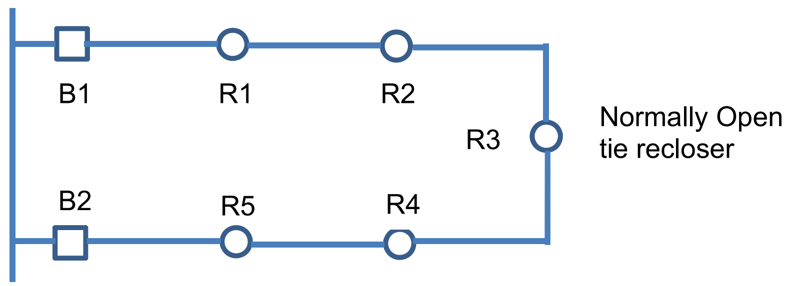
### Automation Actions

Automation of the electrical system can provide more options and alternatives for increasing the reliability of the distribution system. For example an auto loop automated distribution topology is common and a frequently used technique to increase reliability on a normally open radial circuit. These systems automatically change configuration of the distribution system; there is no need for outside intervention. In the example shown in the figure below, there are three reclosers. If the fault occurs upstream of recloser R1, normal sequence of operation would be as follows:

- Breaker B1 sees the fault and goes to reclosing cycle and lock opens.
- Recloser R1 senses the loss of voltage and opens.
- Recloser R2 or the so called tie recloser, senses the loss of voltage on the circuit and closes. Since recloser R2 can be switched into a faulted network, usually it is set for one action, if there is still fault, it will trip and remain open.




More reclosers can be added in order to divide the loop in more sections, but if that is done, coordination of all reclosers can become challenging. If we observe the loop with five reclosers, it can be noted that each feeder has two normally closed reclosers and there is one normally open recloser in the middle of the loop. If there is a fault on feeder 1, breaker B1 will lock out, recloser R1 will open and tie recloser R3 will close. If that happens, there will be a long radial circuit with station circuit breaker B2 in service and it will be in series with four reclosers.




To make coordination easier, some reclosers can lower their tripping characteristics when they operate in reverse mode. So, in this particular case, recloser R2 would drop its current pickup setting. Recloser R2 sees lower fault currents than it normally does and it needs to open before reclosers R3 or R4. In the event a fault occurs between breaker B1 and recloser R1, the loop consisting of five reclosers will respond in a similar way it would respond in the case of the three-recloser loop:

- Breaker B1 will open
- Recloser R1 will open since it will detect loss of voltage
- Recloser R2 will lower its trip setting
- Recloser R3 will detect loss of voltage on feeder 1 and will close

If a fault appears between reclosers R1 and R2, operation sequence gets more complicated and can be summarized as follows:

- Recloser R1 will open
- Recloser R2 will reduce its trip setting and will go for one shot until it lockouts
- Recloser R3 will detect loss of voltage on feeder 1 (and will close with the

fault still being there)

- Recloser R2 will trip in one shot since it has lower a trip setting

Utilities use variations of this scheme and in some of them use sectionalizers instead of reclosers at positions R2 and R4 since it is easier to coordinate sectionalizers with several devices in series. Switches that are controlled remotely are an additional option for automating a distribution circuit. Switches that are controlled remotely are more flexible than auto-loop schemes because it is simpler to implement more tie points and there is no need to be concerned about coordinating protective devices. In most situations, system operators make decisions about reconfiguring the network. Even if circuit operation is automated, another step of sectionalizing within an already isolated section can further improve reliability. It was shown that sectionalizing already isolated circuit sections can reduce SAIDI index by several percent. In many other instances utility operators and maintenance teams should decide whether to sectionalize the distribution network. Auto-loops will not definitely help with momentary interruptions. Network automation can turn long duration disruptions into momentary interruptions. Following enhancements to automation, schemes can be considered in order to further improve momentary disruptions:

- Line reclosers - As part of an automated loop, line reclosers can significantly improve momentary disruptions; however, automated switches do not. Using single-phase reclosers can help to interrupt fewer consumers.

- Tap reclosers – Reclosers can be used on long lateral taps. Single phase reclosers can be considered on three-phase taps. This will interrupt fewer consumers.

**Protection and Switching Equipment**

Installing more sectionalizing switches, reclosers and fuses provides opportunity to isolate smaller parts of the distribution circuit and to interrupt fewer customers. Taps are almost always fused, primarily for reliability. Fuses are considered as one of the cheapest finders of the faults. It is a good practice to have a high percentage of a circuit’s exposure on fused taps, so when a circuit is permanently faulted on those sections, only a small number of the connected consumers gets disrupted.

**Inspection and Maintenance**

It has been proven that the best maintenance practice for many utilities is trimming trees. If these operations are complex and need to be performed in remote areas, they can be considered as one of the largest maintenance expenses for those utilities. However, maintenance of the distribution circuits beyond cutting and trimming trees can vary widely. Most of distribution equipment such as capacitors, distribution transformers, insulators, cables and wires do not need maintenance. However, reclosers, regulators and oil-filled switches need periodic maintenance. This involves identifying old and faulty equipment and targeting it for service or replacement. Most of the equipment devolves over time. Many utilities have aging infrastructure. Different equipment has different and changing failing rates over time. A curve that presents failures has a shape of a “bathtub”.

There is a high failure rate during the initial period mainly due to manufacturing defects. It is followed by a period of “normal” failure rates which eventually increase as the equipment gets older. Certain pieces of equipment have more and accelerated failure rates comparing to the others. Unfortunately, this information is difficult to find and a reliable source of information can only be the utility maintenance history records. For example, the first generations of plastic cables (high-molecular weight polyethylene and cross-linked polyethylene) had severe failure rates. Also aged distribution transformers are more prone to faults but their replacement based solely on age cannot be justified. Underground cables are the only piece of equipment that utilities replace solely based on age. Maintenance also depends on weather conditions, for example, storms can cause a lot of damage by knocking down lines and equipment.

Those conditions require restoration by maintenance teams. Tracking equipment quality and condition from the early start can help improve overall equipment reliability. On many overhead lines, major causes of the faults are external and are not introduced by malfunction of the equipment (usually about 10 to 20% can be considered as equipment failures). Nevertheless, keeping track of equipment failures and targeting those pieces that may be prone to malfunctioning can help improve reliability. Unfortunately, many utilities do not track electrical equipment failures but some utilities have enforced systems for tracking electrical equipment and their failures. It was noted that failures appear in clusters and can be grouped based on particular manufacturers, particular models or particular production dates. Whether it is a certain type of connector, fuse or a specific insulator, some equipment has much higher than expected failure rates.

Proper application of the equipment can also help increase the overall reliability; for example, not overloading equipment and applying proper protection against surges. Equipment failures cause a number of interruptions if they appear on underground circuits. Keeping track of those failures (either by year of installation or installation type) and failures of accessory and then replacing equipment with reliability indexes can help to improve reliability. Monitoring and keeping information of circuit loadings can help distinguish circuits that may fail from thermal stresses.

Poor equipment can be identified before it gets into service by conducting quality acceptance tests. These tests are particularly important for underground cables. These tests can include evaluation of slices of cables to discover voids in samples. Bad cable batches can be discovered by a high-pot test. Workmanship plays an important role in the quality of underground cable splices; therefore, keeping track of this information can also prevent future problems. For example, if a cable splice breaks down after 6 months and if it is known who made the splice, future problems can be eradicated or prevented regardless whether the break was due to workmanship or improper manufacturing quality.

Electrical utilities use different inspection programs and methods to improve overall system reliability. Few of the distribution line inspection techniques are:

- Visual inspections – maintenance teams often find gross problems such as seriously degraded poles, damaged or broken conductor strands, and broken insulators. Particular electrical utilities conduct frequent and planned visual inspections but more commonly, maintenance teams inspect circuits during other activities. In certain situations same teams conduct targeted visual inspections based on the circuit performance. The most efficient visual inspections are those focused on finding fault sources which may be subtle. Maintenance teams need to be educated to discover them.

- Infrared thermography — approximately 40% of electrical utilities use infrared inspection tests for overhead and underground electrical circuits. Basically maintenance teams search for 20°C rise and immediately initiate repair if 30°C or higher temperature rise is detected. Infrared scanning discovers poor connectors and loose connections. Experience shows that some electrical utilities do not use infrared monitoring since they found it to be ineffective. On the other hand, many utilities found significant benefits of infrared monitoring.

- Tests of wood poles – Weak poles are commonly identified by conducting visual inspections. Several utilities have more accurate techniques for quantifying mechanical strength of poles. These techniques include hammer tests and whacking the pole with a sledge. Also sonic testing machines can determine wood density and detect voids.

- Operation counters – Many utilities occasionally read recloser operation and regulator tap changer counter in order to determine if maintenance is needed.

- Tests of the oil – Some electrical utilities conduct tests of oil on distribution transformers, reclosers and regulators. These tests are very effective since they can show deterioration through the presence of water of dissolved gases in the oil which can effectively lead to oil electrical breakdown. Unfortunately, these tests can be expensive and they cannot be easily justified for most electrical distribution equipment.

Inspection of distribution substations and their maintenance is widely accepted. The majority of the utilities track operation counts of reclosers, regulators and circuit breakers and most utilities check the condition of the distribution station transformer oil.

**Reduction of Fault**

The most straightforward approach to improve reliability is to reduce the number of faults. In addition to long interruptions, this approach decreases the number of voltage sags and momentary disruptions and makes the overall system more reliable for general public and utilities. Also site investigations and fault investigations can help prevent similar situations in the future but only in the case lessons are learnt and adequate course of action is implemented. This is important since many faults follow the same or similar patterns and locations. For example, a particular type of connector or isolator can have a high failure rate and may be suitable for implementation in certain conditions. If this kind of approach is implemented, problems can be found and resulting interruptions can be avoided.

## Summary

This course presented fundamental facts about electrical system reliability. Basic definitions were listed with the necessary explanations and methods to quantify system performance. Moreover, this course provided information about distribution system operation, the most frequent problems in daily electrical utility operation, and how these problems can be mitigated.