Chapter 44

Reliability Analysis

44.1 Introduction

Reliability assessment involves determining, generally using statistical methods, the total electric interruptions for loads within a power system during an operating period. The interruptions are described by several indices that consider aspects such as:

- The number of customers [N].
- The connected load, normally expressed in [kW].
- The duration of the interruptions, normally expressed in [H] = 'hours'.
- The amount of power interrupted, expressed in [kW].
- The frequency of interruptions, normally expressed in [1/a] = 'per annum'.
- Repair times are normally expressed in [H] = 'hours'.
- Probabilities or expectancies are expressed as a fraction or as time per year ([h/a], [min/a]).

Network reliability assessment is used to calculate expected interruption frequencies and annual interruptions costs, and to compare alternative network designs. Reliability analysis is an automation and probabilistic extension of contingency evaluation. For such analysis, it is not required to pre-define outage events, instead the tool can automatically choose the outages to consider. The relevance of each outage is considered using statistical data about the expected frequency and duration of outages according to component type. The effect of each outage is analysed automatically such that the software simulates the protection system and the network operator's actions to re-supply interrupted customers. Because statistical data regarding the frequency of such events is available, the results can be formulated in probabilistic terms.

Note: Reliability assessment tools are commonly used to quantify the impact of power system equipment outages in economic terms. The results of a reliability assessment study may be used to justify investment in network upgrades such as new remote control switches, new lines / transformers, or to assess the performance of under voltage load shedding schemes.

This chapter deals with probabilistic Network Reliability Assessment. For information on *PowerFactory*'s deterministic Contingency Analysis, refer to Chapter 27 (Contingency Analysis).

The reliability assessment functions can be accessed by selecting *Reliability* toolbar from the *Change Toolbox* icon (▾) as illustrated in Figure 44.1.1.

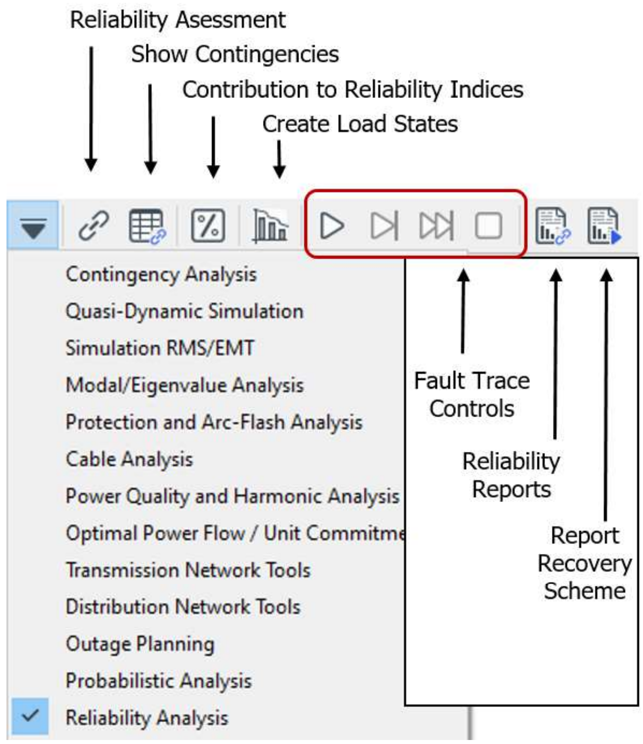

Figure 44.1.1: Reliability Toolbar Selection

The basic user procedure for completing a reliability assessment consists of the following steps as shown in Figure 44.1.2. Steps on the left are compulsory, while steps on the right are optional and can be used to increase the detail of the calculation.

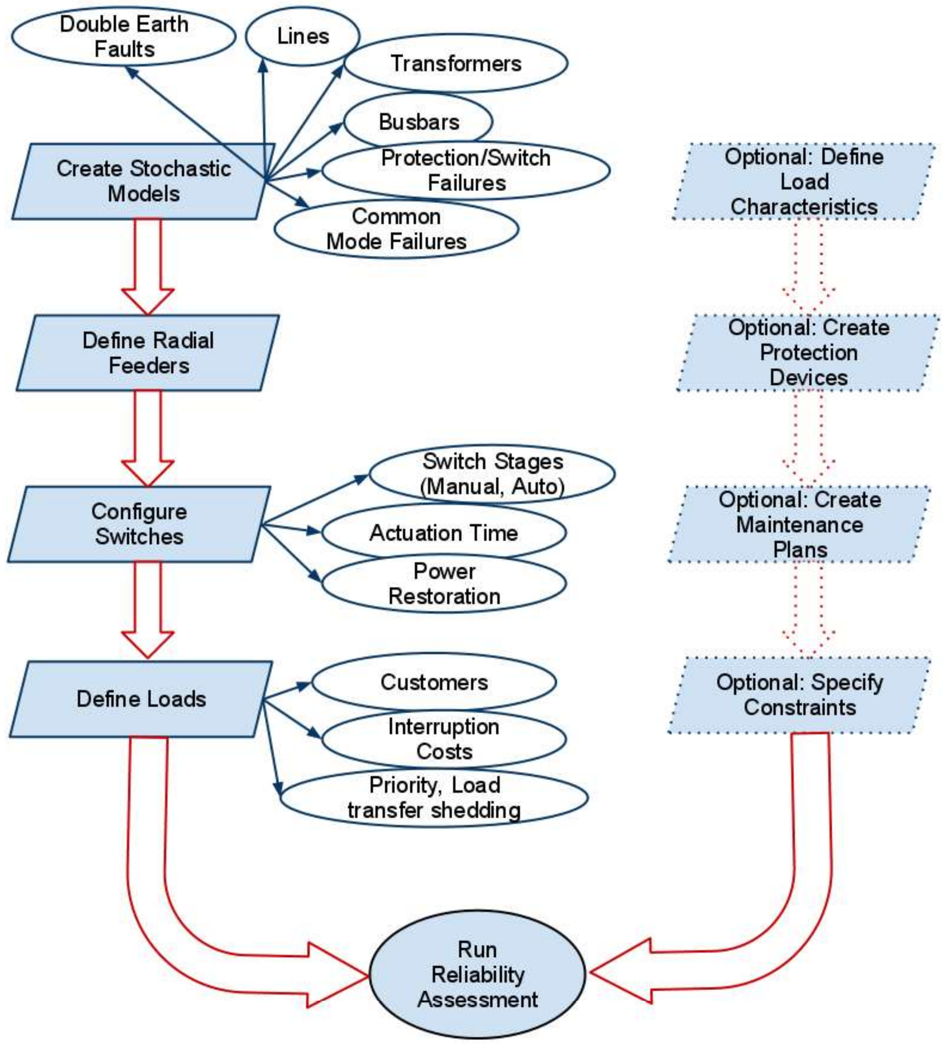

Figure 44.1.2: Reliability Assessment User Procedure

These procedures are explained in detail in the following sections.

44.2 Probabilistic Reliability Assessment Technical Background

The Reliability Assessment procedure considers the network topology, protection systems, constraints and stochastic failure and repair models to generate reliability indices. The technical background of the procedure and Stochastic Models is described in this section.

Note: A quantity is said to be stochastic when it has a random probability distribution. A simple example of a stochastic quantity is the expected repair duration for an item of equipment, which is based on the total number of repairs and repair duration. This measured data can be used to build Stochastic Models, and perform analysis using statistical calculation methods.

44.2.1 Reliability Assessment Procedure

The generation of reliability indices, using the Reliability Assessment tool also known as 'reliability analysis', consists of the following:

- Failure modelling.
- Load modelling.
- System state creation.
- Failure Effect Analysis (FEA).
- Statistical analysis.
- Reporting.

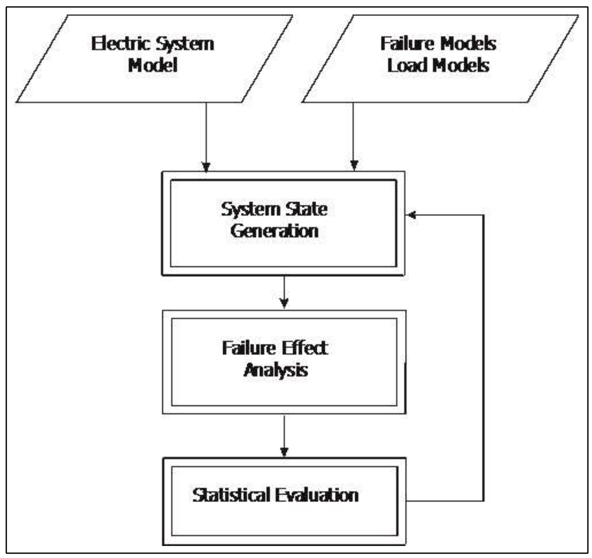

Figure 44.2.1: Reliability Analysis: Basic Flow Diagram

The reliability analysis calculation flow diagram is depicted in Figure 44.2.1. The failure models describe how system components can fail, how often they might fail and how long it takes to repair them when they fail. The load models can consist of a few possible load demands, or can be based on a user-defined load forecast and growth scenarios.

The combination of one or more simultaneous faults and a specific load condition is called a 'system state'. Internally, *PowerFactory*ś system state generation engine uses the failure models and load models to build a list of relevant system states. Subsequently, the Failure Effect Analysis (FEA) module analyse the faulted system states by simulating the system reactions to these faults. The FEA takes the power system through a number of post-fault operational states that can include:

- Fault clearance by tripping of protection breakers or fuses.
- Fault separation by opening separating switches.
- Power restoration by closing normally open switches.
- Overload alleviation by load transfer and load shedding.
- Voltage constraint alleviation by load shedding (only available when 'Distribution' is selected within the reliability command Basic Options).

The objective of the FEA function is to determine if system faults will lead to load interruptions and if so, which loads will be interrupted and for how long.

The results of the FEA are combined with the data that is provided by the system state generation module to create the reliability statistics including indices such as SAIFI, SAIDI and CAIFI. The system state data describes the expected frequency of occurrence of the system state and its expected duration. However, the duration of these system states should not be confused with the interruption duration. For example, a system state for a line outage, perhaps caused by a short-circuit on that line, will have a duration equal to the time needed to repair that line. However, if the line is one of two parallel lines then it is possible that no loads will be interrupted because the parallel line might be able to supply the full load current.

Even if the loads are interrupted by the outage, the power could be restored by network reconfiguration - by fault separation and closing a back-feed switch. The interruption duration will then equal the restoration time, and not the repair duration (equivalent to the system state duration).

44.2.2 Stochastic Models

A stochastic reliability model is a statistical representation of the failure rate and repair duration time for a power system component. For example, a line might suffer an outage due to a short-circuit. After the outage, repair will begin and the line will be put into service again after a successful repair. If two states for line A are defined as 'in service' and 'under repair', monitoring of the line could result in a time sequence of outages and repairs as depicted in Figure 44.2.2.

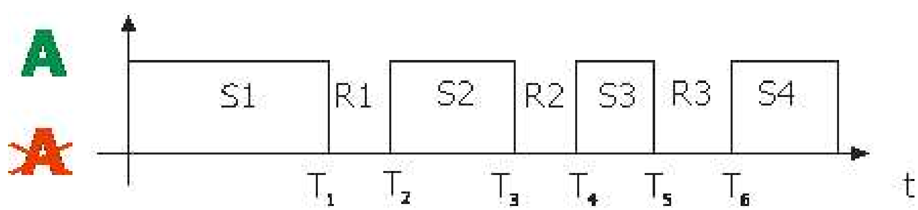

Figure 44.2.2: Line availability states are described by the status of the line (in service or under repair). Each of these states lasts for a certain time.

Line A in this example fails at time T1 after which it is repaired and put back into service at T2. It fails again at T3, is repaired again, etc. The repair durations are also called the 'Time To Repair' or 'TTR'. The service durations $S_1 = T_1, S_2 = T_3 - T_2$, etc. are called the 'life-time', 'Time To Failure' or 'TTF'.

Both the TTR and the TTF are stochastic quantities. By gathering failure data about a large group of similar components in the power system, statistical information about the TTR and TTF, such as the mean value and the standard deviation, can be calculated. The statistical information is then used to define a Stochastic Model.

There are many ways in which to define a Stochastic Model. The so-called 'homogeneous Markov-model' is a highly simplified but generally used model. A homogeneous Markov model with two states is defined by:

- A constant failure rate λ; and
- A constant repair rate μ.

These two parameters can be used to calculate the following quantities:

- mean time to failure, TTF = $1/\lambda$;
- mean time to repair, TTR = $1/\mu$;
- availability, P = TTF/(TTF+TTR);

- unavailability Q, = TTR/(TTF+TTR);

The *availability* is the fraction of time when the component is in service; the unavailability is the fraction of time when it is in repair; and P+Q = 1.0.

Reminder: TTR is the 'Time To Repair', and TTF is the 'Time To Failure'.

Example

If 7500 monitored transformers were to show 140 failures over 10 years, during which a total of 7360 hours was spent on repair, then:

$$\lambda = \frac{140}{10 \cdot 7500} \cdot \frac{1}{a} = 0{,}00187 \cdot \frac{1}{a} \tag{44.1}$$

$$TTF = \frac{1}{\lambda} = 536a \tag{44.2}$$

$$TTR = \frac{7360}{140} \cdot h = 52{,}6h = 0{,}006a \tag{44.3}$$

$$\mu = \frac{1}{TTR} = 167 \cdot \frac{1}{a} \tag{44.4}$$

$$P = \frac{536}{536 + 0{,}006} = 0{,}999989 \tag{44.5}$$

$$Q = \frac{0{,}006}{536 + 0{,}006} = 6\frac{min}{a} \tag{44.6}$$

i.e. the expected outage duration is 6 minutes per annum.

44.2.3 Calculated Results for Reliability Assessment

The network reliability assessment produces two types of indices:

- Load point indices.
- System indices.

These indices are separated into frequency/expectancy indices and energy indices. Furthermore, there are indices to describe the interruption costs.

Load point indices are calculated for each load (*ElmLod*), and are used in the calculation of many system indices. This section describes the simplified equations for the reliability indices. However, note that the *PowerFactory* reliability assessment calculations use more complex calculation methods. Nevertheless, the simplified equations shown here can be used for hand calculations or to gain insight into the reliability assessment results.

44.2.3.1 Parameter Definitions

In the definitions for the reliability indices, the following parameters are used:

C_i The number of customers supplied by load point i
A_i The number of affected customers for an interruption at load point i
Fr_k The frequency of occurrence of contingency k
pr_k The probability of occurrence of contingency k
C The number of customers
A The number of affected customers
L_m The total connected kVA interrupted, for each interruption event, m
r_m Duration of each interruption event, m
L_T The total connected kVA supplied
Pc_i Contracted active power at load point i

44.2.3.2 Load Point Frequency and Expectancy Indices

ACIF: Average Customer Interruption Frequency
ACIT: Average Customer Interruption Time
LPIF: Load Point Interruption Frequency
LPIT: Load Point Interruption Time
LPIC: Load Point Interruption Costs
AID: Average Interruption Duration
TCIF: Total Customer Interruption Frequency
TCIT: Total Customer Interruption Time
TPCONTIF: Total Contracted power Interruption Frequency
TPCONTIT: Total Contracted power Interruption Time

These indices are defined as follows:

$$ACIF_i = \sum_k Fr_k \cdot frac_{i,k} \qquad Unit: 1/a \tag{44.7}$$

$$ACIT_i = \sum_k 8760 \cdot Pr_k \cdot frac_{i,k} \qquad Unit: h/a \tag{44.8}$$

$$LPIF_i = \sum_k Fr_k \qquad Unit: 1/a \tag{44.9}$$

$$LPIT_i = \sum_k 8760 \cdot Pr_k \qquad Unit: h/a \tag{44.10}$$

Note: The parameters ACIF, ACIT, LPIF and LPIT are only calculated and considered if the duration of the outage is longer than the time value "Calculation of SAIFI/SAIDI according to IEEE 1366", that is set within the Advanced Options of the Reliability Assessment command.

$$AID_i = \frac{ACIT_i}{ACIF_i} \tag{44.11}$$

$$TCIF_i = ACIF_i \cdot C_i \qquad Unit: C/a \tag{44.12}$$

$$TCIT_i = ACIT_i \cdot C_i \qquad Unit: Ch/a \tag{44.13}$$

$$TPCONTIF_i = \sum_k Fr_k \cdot frac_{i,k} \cdot Pc_i \qquad Unit: MW/a \tag{44.14}$$

$$TPCONTIT_i = \sum_k 8760 \cdot Pr_k \cdot frac_{i,k} \cdot Pc_i \qquad Unit: MWh/a \tag{44.15}$$

where

i is the load point index
k is the contingency index
$frac_{i,k}$ is the fraction of the load which is lost at load point i, for contingency k.

For unsupplied loads, or for loads that are shed completely, $frac_{i,k} = 1.0$.
For loads that are partially shed, $0.0 <= frac_{i,k} < 1.0$.

44.2.3.3 System Indices

SAIFI *System Average Interruption Frequency Index*, in units of [1/C/a], indicates how often the average customer experiences a sustained interruption during the period specified in the calculation.

SAIFI_P *Average Interruption Frequency (Contracted Power)*, in units of [1/a], indicates how often there are contracted power interruptions during the period of the calculation.

CAIFI *Customer Average Interruption Frequency Index*, in units of [1/A/a], is the mean frequency of sustained interruptions for those customers experiencing sustained interruptions. Each customer is counted once regardless of the number of times interrupted for this calculation.

ASIFI *Average System Interruption Frequency Index*, in units of [1/a], The calculation of this index is based on load rather than customers affected. ASIFI can be used to measure distribution performance in areas that supply relatively few customers having relatively large concentrations of load, predominantly industrial/commercial customers

SAIDI *System Average Interruption Duration Index*, in units of [h/C/a], indicates the total duration of interruption for the average customer during the period in the calculation. It is commonly measured in customer minutes or customer hours of interruption.

SAIDI_P *Average Interruption Duration (Contracted Power)*, in units of [h/a], indicates the total duration of contracted power interruptions during the period of the calculation.

CAIDI *Customer Average Interruption Duration Index*, in units of [H], is the mean time to restore service.

ASIDI *Average System Interruption Duration Index*, in units of [h/a], is the equivalent of SAIDI but based on load, rather than customers affected.

ASAI *Average Service Availability Index*, this represents the fraction of time that a customer is connected during the defined calculation period.

ASUI *Average Service Unavailability Index*, is the probability of having all loads supplied.

MAIFI *Momentary Average Interruption Frequency Index*, in units of [1/Ca], evaluates the average frequency of momentary interruptions. The calculation is described in the IEEE Standard 1366 'IEEE Guide for Electric Power Distribution Reliability Indices'.

$$SAIFI = \frac{\sum ACIF_i \cdot C_i}{\sum C_i} \qquad Unit: 1/C/a \tag{44.16}$$

$$SAIFI\_P = \frac{\sum TPCONTIF_i}{\sum PCONTRACT_i} \qquad Unit: 1/a \tag{44.17}$$

$$CAIFI = \frac{\sum ACIF_i \cdot C_i}{\sum A_i} \qquad Unit: 1/A/a \tag{44.18}$$

$$SAIDI = \frac{\sum ACIT_i \cdot C_i}{\sum C_i} \qquad Unit: h/C/a \tag{44.19}$$

$$SAIDI\_P = \frac{\sum TPCONTIT_i}{\sum PCONTRACT_i} \qquad Unit: h/a \tag{44.20}$$

$$CAIDI = \frac{SAIDI}{SAIFI} \qquad Unit: h \tag{44.21}$$

$$ASUI = \frac{\sum ACIT_i \cdot C_i}{8760 \cdot \sum C_i} \tag{44.22}$$

$$ASAI = 1 - ASUI \tag{44.23}$$

$$ASIDI = \frac{\sum (r_m * L_m)}{L_T} \qquad Unit: h/a \tag{44.24}$$

$$ASIFI = \frac{\sum L_m}{L_T} \qquad Unit: 1/a \tag{44.25}$$

$$MAIFI = \frac{\sum IM_i \cdot N_{mi}}{\sum N_i} \tag{44.26}$$

44.2.3.4 Load Point Energy Indices

LPENS: Load Point Energy Not Supplied

LPES: Load Point Energy Shed

These indices are defined as follows:

$$LPENS_i = ACIT_i \cdot (\widehat{Pd}_i + \widehat{Ps}_i) \qquad in \quad MWh/a \tag{44.27}$$

$$LPES_i = ACIT_i \cdot \widehat{Ps}_i \qquad in \quad MWh/a \tag{44.28}$$

Where
Pd_i is the weighted average amount of power disconnected
Ps_i is the weighted average amount of power shed at load point i.

44.2.3.5 Indices for Busbars/Terminals

AID: Average Interruption Duration [H]

AIF: Yearly Interruption Frequency [1/y]

AIT: Yearly Interruption Time [h/y]

44.2.3.6 System Energy Indices

ENS *Energy Not Supplied*, in units of [MWh/a], is the total amount of energy on average not delivered to the system loads.

SES *System Energy Shed*, in units of [MWh/a], is the total amount of energy on average expected to be shed in the system.

AENS *Average Energy Not Supplied*, in units of [MWh/Ca], is the average amount of energy not supplied, for all customers.

ACCI *Average Customer Curtailment Index*, in units of [MWh/Ca], is the average amount of energy not supplied, for all affected customers.

$$ENS = \sum LPENS_i \qquad in \quad MWh/a \tag{44.29}$$

$$SES = \sum LPES_i \qquad in \quad MWh/a \tag{44.30}$$

$$AENS = \frac{ENS}{\sum C_i} \qquad in \quad MWh/Ca \tag{44.31}$$

$$ACCI = \frac{ENS}{\sum A_i} \qquad in \quad MWh/Ca \tag{44.32}$$

44.2.3.7 Load Point Interruption Cost

LPEIC is defined as

$$LPEIC_i = \sum LPEIC_{i,k} \qquad in \quad \$/a \tag{44.33}$$

where

$LPEIC_{i,k}$
is the average interruption cost for load point i and contingency case k, considering the load point interruption costs function and the assessed distribution of the durations of the interruptions at this load point for contingency case k. The interruption costs are calculated differently for different cost functions. All cost functions express the costs as a function of the interruption duration. For cost functions expressed in money per interrupted customer, the number of interrupted customers is estimated for each interruption as the highest number of customers interrupted at any time during the whole interruption duration.

44.2.3.8 System Interruption Costs

EIC *Expected Interruption Cost*, in units of [M$/y], is the total expected interruption cost.

IEAR *Interrupted Energy Assessment Rate*, in units of [$/kWh], is the total expected interruption cost per not supplied kWh.

$$EIC = \sum LPEIC_i \qquad in \quad M\$/a \tag{44.34}$$

$$IEAR = \frac{EIC}{ENS} \qquad in \quad \$/kWh \tag{44.35}$$

44.2.4 System State Enumeration in Reliability Assessment

In *PowerFactory*, Reliability Assessment uses a System State Enumeration to analyse all possible system states, one by one. A fast 'topological' method is used which ensures that each possible system state is only analysed once. State frequencies (average occurrences per year) are calculated by considering only the transitions from a healthy situation to an unhealthy one and back again. This is important because the individual system states are analysed one by one, and the (chronological) connection between them is therefore lost.

The enumerated calculation method is fast for quick investigation of large distribution networks, but does not compromise accuracy. Exact analytic averages are calculated. Distributions of reliability indices, however, cannot be calculated. For example, the average annual unavailability in hours/year can be calculated, but the probability that this unavailability is less than 15 minutes for a certain year cannot be calculated.

The state enumeration algorithm can include independent failures, simultaneous (n-2) failures, common mode failures, numerous load states and planned outages.

An overview flow diagram for the reliability assessment by state enumeration is shown in Figure 44.2.3.

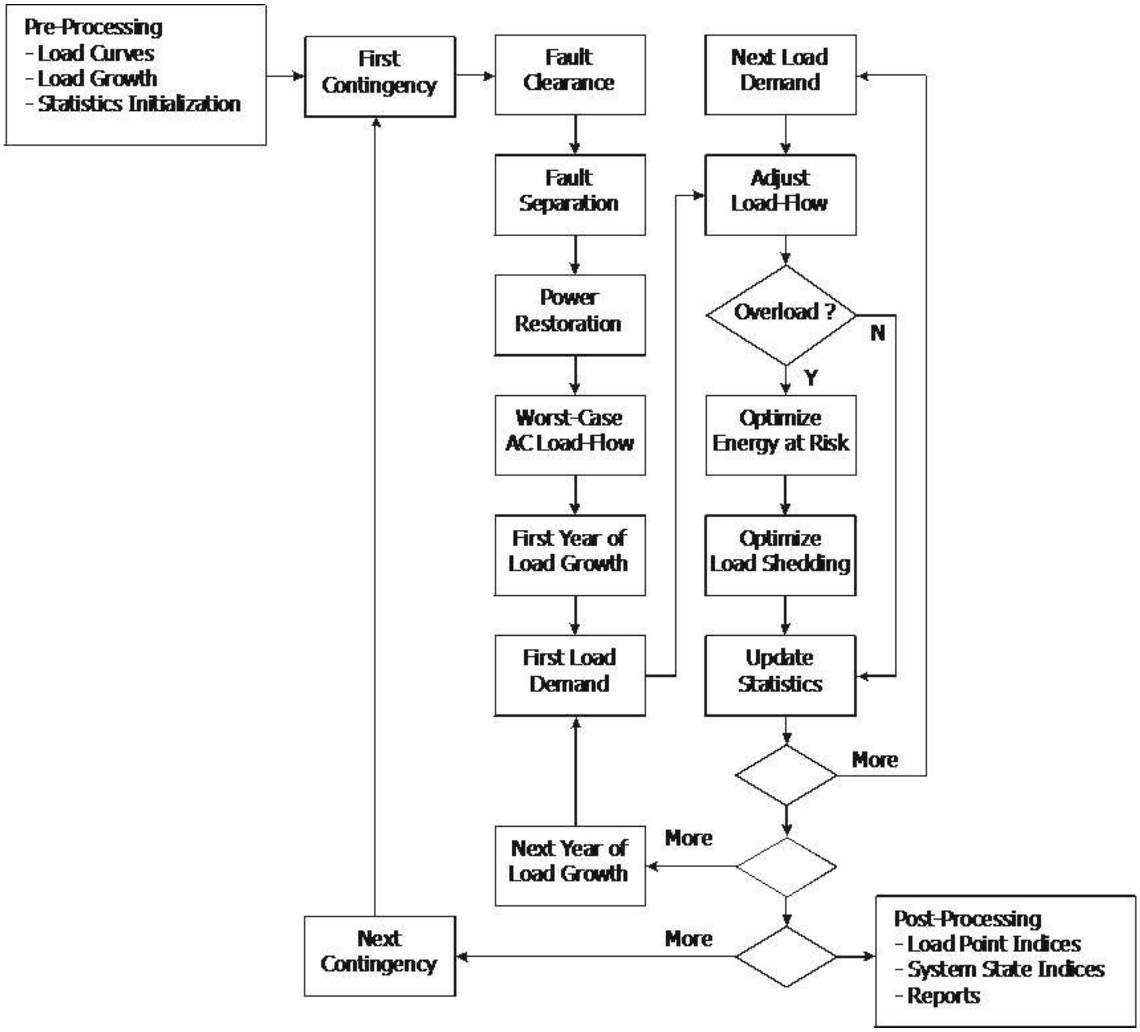

Figure 44.2.3: Overview Flow Diagram for Reliability Assessment by State Enumeration

After the State Enumeration is complete, each simulated system state can be viewed using the 'tracing tool' on the Reliability Toolbar, see Section 45.2 for more information.

44.3 Setting up the Network Model for Reliability Assessment

Prior to starting a Reliability Assessment Calculation, you must setup the Network Model with specific reliability data models. This chapter discusses the following procedures:

- How to Define Stochastic Failure and Repair Models.
- How to Create Feeders for Reliability Assessment.
- How to Configure Switches for the Reliability Assessment.
- Load Modelling for Reliability Assessment.
- Considering Multiple System Demand Levels.
- Defining Fault Clearance Based on Protection Device Location.
- How to Consider Planned Maintenance.

- Specifying Individual Component Constraints.

44.3.1 How to Define Stochastic Failure and Repair models

Stochastic Failure models define the probability that a component will fail and when it does fail, the mean time to repair the component. The following Stochastic failure models are supported by *PowerFactory*:

- Busbar/Terminal Stochastic Model.
- Line/Cable Stochastic Model.
- Transformer Stochastic Model.
- Distribution Transformer Stochastic Model for MV Loads
- Generator Stochastic Model
- Common Mode Stochastic Model.
- Protection/Switch Failure Model.
- Double Earth Fault Failure Model.

This section describes each of these Stochastic Models and the procedure for defining them.

44.3.1.1 Busbar/Terminal Stochastic Model (StoTypbar)

It is possible to define a Stochastic Model for every busbar and terminal within the network. The Stochastic Model can be defined either through the object type or through the object element. If you want to use the same Stochastic Model for a number of different busbars/terminals then you should define it through the object type. Alternatively, if you want to use a Stochastic Model for only one element, then you should define it through the element *Reliability* page.

Busbar/Terminal type definition

You can use Stochastic Models defined through types and elements together as required - the element definition always overrides the type definition.

To define a Stochastic Model for a busbar type follow these steps:

1. Open the dialog for the busbar type and select the Reliability tab.
2. Using the 'Stochastic Model' selection control click the black triangle and select the option 'New project type'. The dialog for the 'Bar Type Failures' will appear.
3. Enter the failure data *for the busbar* and the failure data *per connection*. Note that the probability of the busbar failure is the sum of these two failure frequencies. For example a busbar with 3 connections, a failure frequency *for the busbar* of 0.002 and a failure frequency of 0.005 *per connection* will have a total probability of failure of $0.002 + 3 \cdot 0.005 = 0.017$.
4. Enter the mean repair duration.
5. Press **OK** twice to return to the element dialog.

Busbar/Terminal element definition

To define a Stochastic Model for a busbar element follow these steps:

1. Open the dialog for the busbar *element* and navigate to the Reliability tab.
2. Using the 'Element model' selection control click the black triangle and select the option 'New project type'. The dialog for the 'Bar Type Failures' will appear.

3. Enter the failure data and repair time data as described above for the busbar type.
4. Press **OK** to close the element dialog.

Note: If you define a stochastic element model for a busbar/terminal that also has a stochastic type model within its corresponding type, the element model overrules the type model.

44.3.1.2 Line/Cable Stochastic Model (StoTyplne)

It is possible to define a Stochastic Model for every line or cable within the network. The Stochastic Model can be defined either through the object type or through the object element. If you want to use the same Stochastic Model for a number of different lines/cables then you should define it through the object type reliability page. Alternatively, if you want to use a Stochastic Model for only one element, then you should define it through the element reliability page.

Cable type definition

To define a Stochastic Model for a line or cable type follow these steps:

1. Open the dialog for the line *type* and select the Reliability tab.
2. Using the 'Stochastic Model' selection control click the black triangle and select the option 'New project type'. The dialog for the 'Line Type Failures' will appear.
3. Enter the *Sustained Failure Frequency*. Note that the probability of the line failure is determined using this value and the length of the line. For example, a 12 km line with a Sustained failure frequency of $0.032(1/(a \cdot km))$ will have a failure probability of $12 \cdot 0.032 = 0.384(1/(a))$.
4. Enter the mean repair duration in hours.
5. Enter the Transient Fault Frequency. Note this parameter is used for the calculation of the MAIFI index.
6. Press **OK** twice to return to the element dialog.

Cable element definition

To define a Stochastic Model for a line or cable element follow these steps:

1. Open the dialog for the line *element* and navigate to the Reliability tab.
2. Using the 'element model' selection control click the black triangle and select the option 'New project type'. The dialog for the 'Line Type Failures' will appear.
3. Enter the failure data and repair time data as described above for the line type.
4. Press **OK** to return to the element dialog.

44.3.1.3 Transformer Stochastic Model (StoTyptrf)

It is possible to define a Stochastic Model for every transformer within the network. The Stochastic Model can be defined either through the object type or through the object element. If you want to use the same Stochastic Model for a number of different transformers then you should define it through the object type reliability page. Alternatively, if you want to use a Stochastic Model for only one transformer element, then you should define it through the element reliability page.

Transformer type definition

To define a Stochastic Model for a transformer type follow these steps:

1. Open the dialog for the transformer *type* and select the Reliability tab.
2. Using the 'Stochastic Model' selection control click the black triangle and select the option 'New project type'. The dialog for the 'Transformer Type Failures' will appear.
3. Enter the failure frequency data (1/a).
4. Enter the mean repair duration in hours.
5. Press **OK** twice to return to the element dialog.

Transformer element definition

To define a Stochastic Model for a transformer *element* follow these steps:

1. Open the dialog for the transformer *element* and select the Reliability tab.
2. Using the 'element model' selection control click the black triangle and select the option 'New project type'. The dialog for the 'Transformer Type Failures' will appear.
3. Enter the failure data and repair time data as described above for the transformer type.
4. Press **OK** to return to the element dialog.

44.3.1.4 Distribution Transformer Stochastic Model for MV Loads

In *PowerFactory* MV Loads can provide the functionality of a built-in distribution transformer. The fault behaviour of the distribution transformer is the same as for other transformers, except for the fact that the load connected behind the transformer is not supplied until the end of the repair duration.

To define a Stochastic Model for a distribution transformer within the MV Load element or type, open the dialog for the MV Load *element* or *type* and select the Reliability tab. As the failure model is based on the transformer (StoTyptrf), the following steps are equivalent to the ones described in Section 44.3.1.3.

44.3.1.5 Generator Stochastic Model (StoGen)

Within a network, it is possible to define a *Stochastic Model for Generation* (StoGen) for every generator class (synchronous machines, static generators, PV systems, etc.) which can be used by both *Reliability* and *Generation Adequacy*. For further information refer to Section 46.3.1. The Stochastic Model can be defined using the element. The failure model can contain any number of load level states; each state representing the availability of the generator over a year. This way, complete and/or partial outages can be modelled.

Upon execution of Reliability Assessment, *PowerFactory* creates a separate contingency for each defined state. A load flow is calculated considering the reduced availability (including 0 %) of the generator, and depending on constraint violations, load shedding and/or re-dispatch of alternative generators may result.

The *Stochastic Model for Generation* includes an unlimited number of states with each defined according to:

- **State**: Name of the state
- **Availability [%]**: Percentage of the nominal power available
- **Probability [%]**: Probability that this state is valid (the sum of all probabilities must be 100 %)
- **Duration [H]**: Time needed to solve the given failure
- **Frequency [1/a]**: Number of incidents that cause the given state per year
- **Total Duration [h/a]**: Total duration of the given state per year

Generator element definition

To define a Stochastic Model for a generator *element* follow these steps:

1. Open the dialog for the Generator *element* and select the Reliability tab.
2. Using the 'Stochastic Model', click the black triangle and select the option 'Select. . . '. The dialog for the 'Equipment Types' project library will appear.
3. Click the *New Object* button ( ) to create a Stochastic Model for Generation object (StoGen). The dialog for the object should appear.
4. Enter the data according to one of the following:
   - Probability and repair duration
   - Repair duration and frequency per year
   - Probability and frequency per year
5. Press **OK** to return to the element dialog.

44.3.1.6 Common Mode Stochastic Model

A common mode failure (*StoCommon*) involves the simultaneous failure of two or more power system components. An example is a distribution feeder where two lines with different voltages share the same poles. If one or more poles fail, for example a car hits a pole, then both lines will be interrupted simultaneously: these lines have a 'common failure mode'. Such a failure will usually be more likely than the probability of the two lines failing independently at the same time.

In *PowerFactory*, it is possible to define a common mode failure object to consider such failures in the reliability calculation. These Stochastic Models consider the common mode failure probability in addition to the independent failure mode of each component within the model.

To define a common mode failure Stochastic Model through the single line diagram follow these steps:

1. Mark two or more network objects.
2. Right-click on one of the marked elements and chose *Define* → *Common Mode Failure*.
3. To add a network element, add a cell below the last full cell by right-clicking within an empty area of the dialog and selecting the option 'Append Rows'.
4. Double-click in the first empty cell of the 'Name' column, to open an object selection browser.
5. Use the browser to find the object that is part of the Common Mode Failure that you are trying to define.
6. Click **OK** to return to the Common Mode Failure dialog.
7. Repeat steps 3-6 to add more objects to the Common Mode Failure.
8. Click the 'Failure Data' tab and enter the Sustained Failure Frequency, Mean Outage duration and Transient Fault Frequency data.
9. Click **OK** to save the changes.

To define a common mode failure Stochastic Model through the Data Manager (not suitable for the first Common Mode Stochastic Model) follow these steps:

1. Using the Data Manager, select the 'Common Mode' failures folder within the 'Operational Library'.
2. Click the *New Object* button ( ) to create a Stochastic Common Mode failure object (*StoCommon*). The dialog for the object should appear.
3. Double click in the first empty cell of the 'Name' column, to open an object selection browser.

4. Use the browser to find the object that is part of the Common Mode Failure that you are trying to define.
5. Click **OK** to return to the Common Mode Failure dialog.
6. Add a cell below the last full cell by right-clicking within an empty area of the dialog and selecting the option 'Append Rows'.
7. Repeat steps 3-6 to add more objects to the Common Mode Failure.
8. Click the 'Failure Data' tab and enter the Sustained Failure Frequency, Mean Outage duration and Transient Fault Frequency data.
9. Click **OK** to save the changes.

44.3.1.7 Protection/Switch Failures

PowerFactory can consider the failure of the protection system to clear the fault as a stochastic probability within the reliability calculation. This is enabled by entering a 'Probability of Failure' into the switch object. To enter this data:

1. Open the dialog for the switch object where you want to enter the switch failure probability. Normally switches are accessed by right clicking their containing cubicle and selecting the option 'Edit Devices'.
2. On the Reliability tab of the switch object, enter the 'Fault Clearance: circuit breaker fails to open probability' in percent. For example, a 5 % failure rate means that on average 1 out of 20 attempted fault clearance operations will fail.
3. "Unnecessary backup protection maloperation" gives the probability of the backup protection operating unnecessarily. That is, the backup protection tripping in addition to the main protection device.
4. "Frequency of spurious protection operation" gives the probability of a relay tripping spuriously, without any indication.

Note: *PowerFactory* does not distinguish between a protection system failure and a switch failure. For example, the reason that a switch fails to open could be caused by a faulty relay, a protection mal-grading or a faulty circuit breaker. The cumulative probability of all these events should be entered into the switch failure probability.

44.3.1.8 Double Earth Faults

A double earth fault in *PowerFactory* is defined as follows: a single earth fault on a component followed by a second simultaneous earth fault on another component.

A double earth fault might occur after voltage rises on healthy phases on a feeder following a single phase to earth fault on the feeder, causes a second phase to earth fault on the same feeder.

Double earth faults occur on lines, transformers (2 Winding and 3 Winding transformers) and busbars, and *PowerFactory* supports adding the conditional probability data for double earth faults for Stochastic Models of these components. The reliability calculation automatically generates a contingency event for every double earth fault that meets the following conditions:

- Both objects are in the same part of the network (supplied by the same transformers).
- The star point of the transformers that supply that part of the network is isolated or compensated (both star point grounded and Peterson Coil enabled).

- The frequency of single earth faults of the first object is > 0
- The probability of double earth fault of the second object is > 0.

The frequency for single earth faults and the probability of the second earth fault data can be entered on the 'Earth Fault' page of every Stochastic Model. Follow these steps to enter data for a Line Stochastic Model:

1. Open the Stochastic Failure Model for the line (either through the reliability page of the line type or the line elements).
2. Select the Earth Fault page.
3. Enable the option 'Model Earth Faults'
4. Enter the data for the frequency of single earth faults
5. Enter the data for the conditional probability of a second earth fault
6. Enter the Repair duration in hours.
7. Close the Stochastic Model.

Note: The double earth fault is a conditional probability. Therefore, the probability of one occurring in the network is the probability of an earth fault on component A * probability of an double earth fault on component B

44.3.2 How to Create Feeders for Reliability Calculation

When performing a reliability calculation with the *Distribution* option set under 'Basic Options', *PowerFactory* requires that feeders have been defined in the model.

To create a feeder:

- Right click on the cubicle at the head of the feeder and select the option *Define* $\rightarrow$ *Feeder*; or
- For fast creation of multiple feeders, right click the bus that the feeder/s are to be connected to and select the option *Define* $\rightarrow$ *Feeder*. More information on feeders and feeder creation can be found in Chapter 15: Grouping Objects, Section 15.5(Feeders).

When executing the Reliability Assessment in distribution networks with a focus on optimal power restoration, the meshes within feeders are restricted to be of the following kinds:

1. Mesh within the feeder

In this case, the feeder is supplied from one point and the mesh is within the feeder itself.

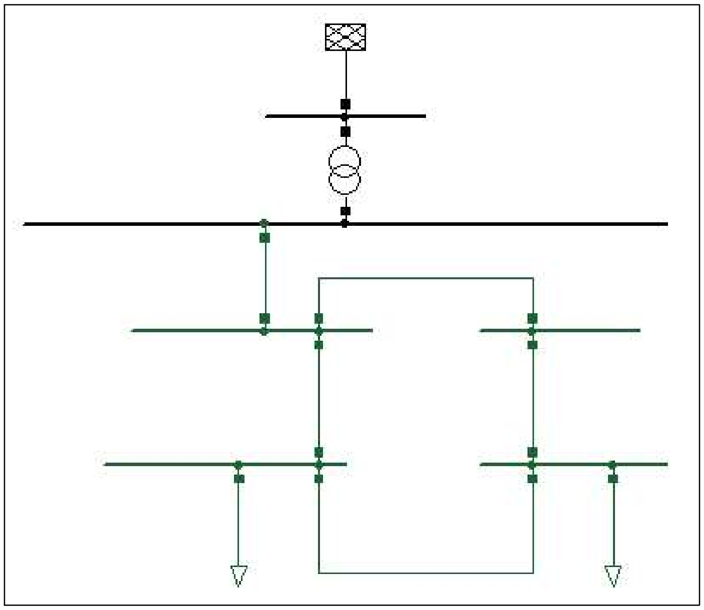

Figure 44.3.1: Mesh within feeder

2. Two feeders, starting from the same terminal, are connected

In this case, the feeders are connected and therefore result in a mesh as shown in figure 44.3.2.

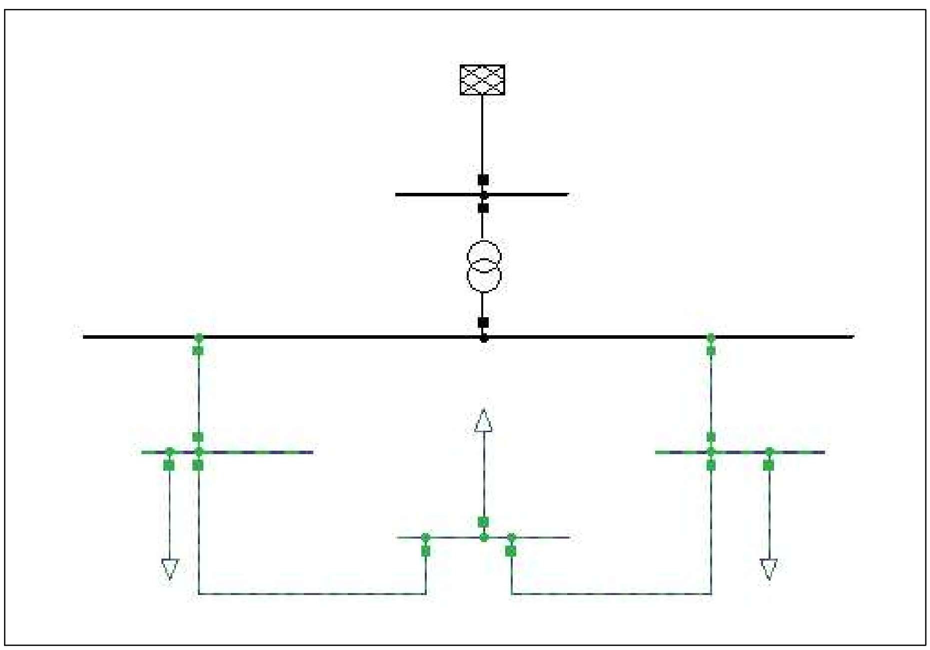

Figure 44.3.2: Mesh containing two feeders starting from the same terminal

44.3.3 Configuring Switches for the Reliability Calculation

A critical component of the Failure Effect Analysis (FEA), is the behaviour of the switches in the network model. Switches in *PowerFactory* are classified into four different categories:

- Circuit Breakers; Typically these are automatic and controlled by relays and through remote communications. They are used for clearing faults and for closing back-feeds for power restoration.
- Disconnectors; Used for isolation and power restoration.
- Load-Break-Switch; Used for isolation and power restoration.
- Switch Disconnector; Used for isolation and power restoration.

All switches in *PowerFactory* are modelled using the *StaSwitch* or *ElmCoup* objects. The switch category (CB, disconnector etc) is selected on the basic data page of the switch. The actions that the FEA analysis takes depends on the configuration of these switches and, optionally, the location of protection devices.

Configuration steps

To configure a switch for reliability analysis follow these steps:

1. Open the dialog for the switch and select the reliability page. This can be done directly by editing switches modelled explicitly on the single line diagram, or for switches embedded within a cubicle, by right-clicking the cubicle and selecting the option 'edit devices', to access the switch.
2. Select the 'Sectionalising' option. The following choices are available:
   - Remote controlled (Stage 1); This option means that the actuation time of this switch is taken from the global 'remote controlled' switch actuation time. The default time is 1 min but this can be adjusted within the reliability command, see Section 44.4.1: How to run the Reliability Assessment.Typically remote controlled switches are circuit breakers controlled by relays or with communications from a control room.
   - Indicator of Short Circuit (Stage 2); This option represents a switch that has an external indication of status on the outside of the switch enclosure. This allows the operator/technician to easily identify the switch status and actuate the switch.
   - Manual (Stage 3); These switches need direct visual inspection to determine their status and therefore take longer to actuate than either stage 1 or stage 2 switches.
3. Select the 'Power Restoration' option. The following choices are available:
   - Do not use for power restoration; If this option is selected the switch can only be used for isolation of equipment or load shedding. It will not be used by the FEA calculation to restore power.
   - From Branch to Node; If this option is selected, the switch will only be used to restore power if the post restoration power flow is in the direction from Branch to Node. The switch will not be used for power restoration in the opposite direction.
   - From Node to Branch; If this option is selected, the switch will only be used to restore power if the post restoration power flow is in the direction from Node to Branch. The switch will not be used for power restoration in the opposite direction.
   - Independent of direction; If this option is selected the switch will be used to restore power flow regardless of the direction of the post restoration power flow.
4. Enter the time to actuate switch (Stage 2 and 3 switches only); This field specifies the time taken by the operator to actuate the switch. Note, this excludes the local access and access time if the switch is within a substation. The total actuation time of such a switch is therefore the switch actuation time + the substation access time + the local access time.

The complete switching times depend on the following settings:

- Switching procedure for fault separation / power restoration (page FEA of reliability command)
- Access time (of terminal for global terminals, of station for terminals inside stations)
- Local access time (of terminal for global terminals, of station for terminals inside stations)
- Time to open remote controlled switches (page FEA of reliability command) for remote controlled switches

- Time to actuate switch (page reliability of switch) for any other switch.

  The final time to actuate a switch is calculated as follows:

  The protection breakers/switches actuate immediately (at 0:00 minutes after the fault was applied).

  Switching procedure for fault separation / power restoration:

  - Concurrently:
    - Remote controlled switches:Are actuated at the time entered in the reliability command.
    - Any other switch: Access Time + Time to actuate switch
  - Sequential (previous switching time is considered):
    - Remote controlled switches: Are actuated at the time entered in the reliability command.
    - Any other switch:
      - If a manual switch was actuated before:
        \- –> If the switch is located in the same station as the switch previously actuated: Last switch time + Time to actuate switch
        \- If switch is in a different substation: Last switch time + Local access time + Time to actuate switch
      - Last switch time + Access time + Time to actuate switch

  A switch however, will never be closed for power restoration before the corresponding area was separated from the fault. If an area can be separated from the fault after 15 minutes and the switch for restoration is remote controlled (time of remote controlled switches is set to 3:00 minutes), it will be restored after 15 minutes

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Note: The Sectionalising options are only considered when the 'Distribution' reliability analysis option is selected under 'Basic Options'. If the 'Transmission' mode is selected, then all switches are assumed to be remote controlled.

44.3.4 Load Modelling for Reliability Assessment

This section provides a general description of the load element parameters that are used by the reliability calculation. The first sub-section describes how to input the number of customers that each load represents and how to classify each load. The second sub-section describes how to define load shedding and transfer parameters.

44.3.4.1 Specifying the Number of Customers for a Load

Many of the reliability indices such as SAIFI and CAIFI are evaluated based on the number of customers interrupted. Therefore, for accurate calculation of these indices it is important to specify the number of customers that each load represents. To do this:

1. Open the dialog for the target load element.
2. Select the Reliability page.
3. In the 'Number of connected customers' field, enter the number of customers that this load represents.
4. Repeat this process for each load in the system you are modelling.

Load Classification

Every load can be optionally classified into agricultural, commercial, domestic or industrial load. This option does not affect the calculation of the reliability indices and is provided for categorisation purposes only.

44.3.4.2 Specifying Load Shedding and Transfer Parameters

Load transfer and load shedding are used to alleviate violated voltage or thermal constraints caused by the power restoration process. There is a distinction between load transfer for constraint alleviation, such as described in this section, and load transfer for power restoration. Load transfer by isolating a fault and closing a back-stop switch is considered automatically during the fault separation and power restoration phase of the failure effect analysis.

If a violated constraint is detected in the post-fault system condition, a search begins for the loads contributing to these overloads. The overloads are then alleviated by either:

- Transferring some of these loads, if possible; or
- Shedding some of these loads, starting with the lowest priority loads.

To define the load shedding parameters follow these steps:

1. Open the reliability page of the load element.
2. Enter the number of load shedding steps using the 'Shedding steps' list box. For example, four shedding steps means that the load can be shed to 25%, 50%, 75% or 100% of its base value. Infinite shedding steps means that the load can be shed to the exact value required to alleviate the constraint.
3. Enter the 'Load priority'. The reliability algorithm will always try to shed the loads with the lowest priority first. However, high priority loads can still be shed if the algorithm determines this is the only way to alleviate a constraint.
4. Enter the load transfer percentage in the 'Transferable' parameter. This defines the percentage of this load that can be transferred away from the current network. *PowerFactory* assumes that the transferred load is picked up by another network that is not modelled, hence load transferring in this way is equivalent to load shedding in terms of constraint alleviation. The difference is that transferred load is still considered as supplied load, whereas shed load is obviously not supplied.
5. Optional: Use the selection control next to 'Alternative Supply (Load)' to specify an alternative load that picks up all transferred load.

Note: There is a critical difference between the transmission reliability and distribution reliability functions. In distribution reliability all constraint alleviation is completed using switch actions, so loads can only be fully shed (switched out) or they remain in service. However, by contrast, the transmission reliability option can shed or transfer a percentage of the load.

44.3.5 Modelling Load Interruption Costs

When supply to a load is interrupted, there is a cost associated with the loss of supply. *PowerFactory* supports the definition of cost curves for load elements using Energy Tariffs and Time Tariffs. They can be defined using the 'Tariff' characteristic on the reliability page of the load element, as discussed in Chapter 18: Parameter Characteristics, Load States, and Tariffs, Section 18.5 (Tariffs).

Projects imported from previous versions of *PowerFactory* may include Vector Characteristics for the definition of cost curves, which are discussed in Chapter 18: Parameter Characteristics, Load States, and Tariffs, Section 18.2.5 (Vector Characteristics with Time Scales).

44.3.6 System Demand and Load States

Considering Multiple System Demand Levels

If time-based characteristics for the feeder loads, generators or both are defined so that the demand changes depending on the study case time, these states can be considered in the reliability analysis. Therefore, the load demand for a one year period can be discretised and converted into several so-called 'load states', and a probability of occurrence for each state. The Reliability Command does not automatically generate the load states. One possibility is the specification of load characteristics for individual loads and generators, and the second is by specification of load distribution states for substations. The procedures for each method is described in Chapter 18: Parameter Characteristics, Load States, and Tariffs; Sections 18.3 (Load States) and 18.4 (Load Distribution States).

44.3.7 Fault Clearance Based on Protection Device Location

The Reliability Calculation has two options for fault clearance:

- Use all circuit breakers; or
- Use only circuit breakers controlled by protection devices (fuses or relays).

The second option is the more realistic option, because only locations within the network that can automatically clear a fault will be used by the reliability calculation to clear the simulated faults.

Note: If there is no protection device entered in the network model, there is the possibility to define a circuit breaker to be considered as switch with protection device for reliability calculations. This setting can be found within the circuit breakers reliability tab. "Fault Clearance: Consider as switch with protection device"

44.3.8 How to Consider Planned Maintenance

The *PowerFactory* reliability calculation supports the definition and automatic inclusion of planned network maintenance. Maintenance is implemented with a planned outage object. These objects are found within the 'Outages' sub-folder within the project 'Operational Library'. The following steps describe the procedure for creating a planned outage:

1. On the single line diagram (or within the Data Manager), select the object (or objects) that you would like to define an outage for.
2. Right-click the selected object/s and from the menu that appears choose the option *Define* $\rightarrow$ *Planned Outage*. The dialog box for the planned outage will appear.
3. Using the Start Time selection control '...', enter the time that the outage begins.
4. Using the End Time selection control '...', enter the time that the outage ends.
5. Optional: Adjust the Outage Type. Typically you would leave this on the default 'Outage of Element' option, but if you wanted to model a generator derating, then you would choose the 'Generator Derating' option.

Note: When the reliability calculation considers outages it creates a unique contingency case for every contingency with the outage applied and also without the outage. For example, for a network with two planned outages and six contingencies there will be a total of $6 \cdot 3 = 18$ contingency cases.

44.3.9 Specifying Individual Component Constraints

The reliability calculation can automatically consider voltage and thermal constraints for the power restoration process. There are two options for specifying constraints applied to branch, terminal, and feeder objects as follows:

Global Constraints; All network constraints are based on the constraints specified on the constraints tab of the Reliability Command dialog.

Individual Constraints; If Individual Constraints are selected for branches, terminals, and / or feeders, constraints should be defined by the user for each relevant object by taking the following steps:

1. Open the reliability page of the target terminal, branch (line/transformer), or feeder.
2. Enter the Max and Min Voltage limits, max loading, or voltage drop/rise for the terminal, branch, or feeder respectively.
3. Click **OK** to close the dialog and save the changes.

44.3.10 Consider switching rules

Reliability Analysis in *PowerFactory*allows the user to consider predefined switching rules within substations according to chapter 11.2.7.4. Switching-rules are executed directly after protection operation.

44.4 Running The Reliability Assessment Calculation

The procedure for using the *PowerFactory* Reliability Assessment tool and analysing the results generated by the tool is described in this section.

44.4.1 How to run the Reliability Assessment

In *PowerFactory* the network Reliability Analysis is completed using the *Reliability Assessment* command (*ComRel3*). This command is found on the 'Reliability Analysis' toolbar.

Alternatively, the commands can be executed for a single element by right-clicking the element and selecting *Calculate* → *Reliability Assessment* or → *Optimal Power Restoration*. The options for the reliability command that are presented within its dialog are described in the following sub-sections.

A reliability assessment is started when the **Execute** button is pressed. The calculation time required for a reliability assessment can range from a few seconds for a small network only considering n-1 contingencies, to several hours for a large network considering n-2 contingencies. A reliability assessment calculation can be interrupted by clicking on the *Break* icon () on the main toolbar.

44.4.1.1 Basic Options

The following options are available on the Basic Options page Reliability Assessment Command dialog.

Load Flow

This button is a link to the load-flow calculation command used for the analysis. The load demand is calculated using this load-flow. In addition, its settings are used for the constraint evaluation load-flows.

Method

- **Connectivity analysis:** this option enables failure effect analysis without considering constraints. A load is assumed to be supplied if it is connected to a source of power before a contingency, and assumed to undergo a loss of supply if the process of fault clearance separates the load from all power sources. Because constraints are not considered, no load-flow is required for this option and hence the analysis will be faster than when using the alternative load-flow analysis option.

- **Load flow analysis:** this option is the same as the connectivity analysis, except that constraints are considered by completing load-flows for each contingency. Loads might be disconnected to alleviate voltage or thermal constraints. For the transmission analysis option, Generator re-dispatch, load transfer and load shedding are used to alleviate overloads.

Calculation time period

- **Complete year:** the reliability calculation is performed for the current year specified in the 'Date/-Time of the Calculation Case'. This can be accessed and the date and time changed by clicking the → button.
- **Single Point in Time:** the Reliability Calculation is completed for the network in its current state at the actual time specified by the 'Date/Time of the Calculation Case'.

Note: If load states or maintenance plans are not created and considered, then these options make no difference because the reliability calculation is always completed at the single specified time.

Network

- **Distribution:** the reliability assessment will try to remove overloading at components and voltage violations (at terminals) by optimising the switch positions in the system. If constraints occur in the power restoration process, loads will be shed by opening available switches. This option is the recommended analysis option for distribution and medium voltage networks.

Note: The reliability command optimises switch positions based on load shedding priorities, and not network losses.

- **Transmission:** thermal overloads are removed by generator re-dispatch, load transfer and load shedding. First generator re-dispatch and load transfer is attempted. If these cannot be completed or do not remove the thermal overload, load shedding actions will occur. Generator re-dispatch and load transfer do not affect the reliability indices. However, by contrast, load shedding leads to unsupplied loads and therefore affects the reliability indices.

Automatic Contingency Definition

If the checkbox is selected, new contingencies will be created. If it is unchecked, existing contingencies from previous calculations will be used for reliability assessment.

The 'Selection' list presents two possible options for the contingency definition. These are:

- Whole system: *PowerFactory* will automatically create a contingency event for every object that has a Stochastic Model defined.
- User Defined: Selecting this option shows a selection control. Now you can select a set of objects (*SetSelect*), and contingencies will be created for each of these objects that has a Stochastic Model defined.

In addition to the above contingency definition options, the automatic contingency definition can be further controlled with the following checkboxes:

- Busbars/Terminals; This flag should be enabled for *PowerFactory* to create Busbar and terminal contingencies.
- Lines/Cables; This flag should be enabled for *PowerFactory* to create Line/Cable contingencies.
- Transformers; This flag should be enabled for *PowerFactory* to create transformer contingencies.
- Generators; This flag should be enabled for *PowerFactory* to create generator contingencies (Load flow analysis only).
- Common Mode; This flag should be enabled for *PowerFactory* to create Common Mode contingencies. See section 44.3.1.6 (Common Mode Stochastic Model) for more information.

- Independent second failures; This flag should be enabled for *PowerFactory* to consider n-2 outages in addition to n-1 outages. Caution: n-2 outages for all combinations of n-1 outages are considered. This means that for a system of n contingencies there are $(n \cdot (n-1))/2) + n$, contingencies to consider. This equation is quadratic, and so to minimise the required time for computation this option is disabled by default.
- Double-earth faults; This flag should be enabled for *PowerFactory* to consider double-earth faults. See section 44.3.1.8 (Double Earth Faults) for more information.
- Protection/switching failures; This flag should be enabled for *PowerFactory* to consider the failure to operate of protection devices or circuit breakers. See section 44.3.1.7 (Protection/Switch Failures) for more information.
- Spurious protection operation; as explained in section 44.3.1.7.
- Backup protection maloperation; as explained in section 44.3.1.7.

44.4.1.2 Outputs

The following options are available on the *Outputs* tab of the Reliability command.

Results

This option allows the selection of the result element (*ElmRes*) where the results of the reliability analysis will be stored. Normally, *PowerFactory* will create a results object within the active study case.

Perform Evaluation of Results File

The Reliability Analysis automatically writes all simulation results to a results object specified above. After completing the Reliability Calculation, *PowerFactory* automatically evaluates the results object to compute the reliability indices. This button allows you to re-evaluate a results file that has previously been created by this or another reliability calculation command. The benefit of this is that you do not have to re-run the reliability calculation (which can be time consuming compared with the results object evaluation) if you only want to recalculate the indices from an already completed calculation.

Report

Displays the form used for the output report. Report settings can be inspected and the format selected by clicking on the → button.

Show detailed output of initial load flow and top level feeders

If this option is checked, a detailed report of the initial load flow will be printed to the output window.

44.4.1.3 Protection

Fault Clearance Breakers

- **Use all circuit breakers:** all switches in the system whose *Usage* is set to *Circuit Breaker* can be used for fault clearance.
- **Use only circuit breakers with protection device:** all circuit breakers in the system which are controlled by a protection device (fuse or relay) can be used for fault clearance. Circuit breakers which are set to have a protection device are also considered.

Create Contingencies

These settings are the same as in "Automatic Contingency Definition", described in section 44.4.1.1. For convenience they are displayed within this tab as well.

44.4.1.4 Restoration

Automatic Power Restoration

The options described below will only be available if Automatic Power Restoration is selected.

Load/Generator Priorities

The two settings will be used to evaluate the element's priority value, entered by the user.

- **Lowest priority number refers to most critical load/generator:** this means that higher priorities are shed first.
- **Highest priority number refers to most critical load/generator**

Switching procedures for fault separation/power restoration

- **Concurrent Switch Actions:** it is assumed that the switching actions can be performed immediately following the specified switching time. However, a switch can be closed for power restoration only after the faulted element was disconnected. The analogy for this mode is if there were a large number of operators in the field that were able to communicate with each other to coordinate the switching actions as quickly as possible. Therefore, this option gives an optimistic assessment of the 'smart power restoration'.
- **Sequential Switch Actions:** it is assumed that all switching actions are performed sequentially. The analogy for this mode is if there were only a single operator in the field, who was required to complete all switching. The fault separation and power restoration is therefore slower when using this mode compared with the 'concurrent' mode.
- **Consider Sectionalising (Distribution analysis only):** if enabled, the FEA considers the switch sectionalising stage when attempting fault separation and power restoration.

Time to open remote controlled switches

The time (in minutes) taken to open remote controlled switches.

Power restoration

After the isolation of failures, parts of the network may be unsupplied. However, the network can be reconfigured by moving the tie open point in order to restore as much power as possible (partial power restoration). This reconfiguration might lead to violations of constraints (e.g. overloading), which should be avoided. For each sectionalising stage of switches, the optimisation method offers three power restoration modes:

- Disabled (no movement of tie open points)
- Enabled without load transfer (tie open points can only be moved between the feeder and a directly-bordering feeder)
- Enabled with load transfer (tie open points can be moved between a bordering feeder and a second-level bordering feeder)

First sectionalising is attempted using only stage 1 switches, if this is not successful then stage 1 and 2 switches are used. Finally, if this is not successful, then stage 1, 2 and 3 switches are used.

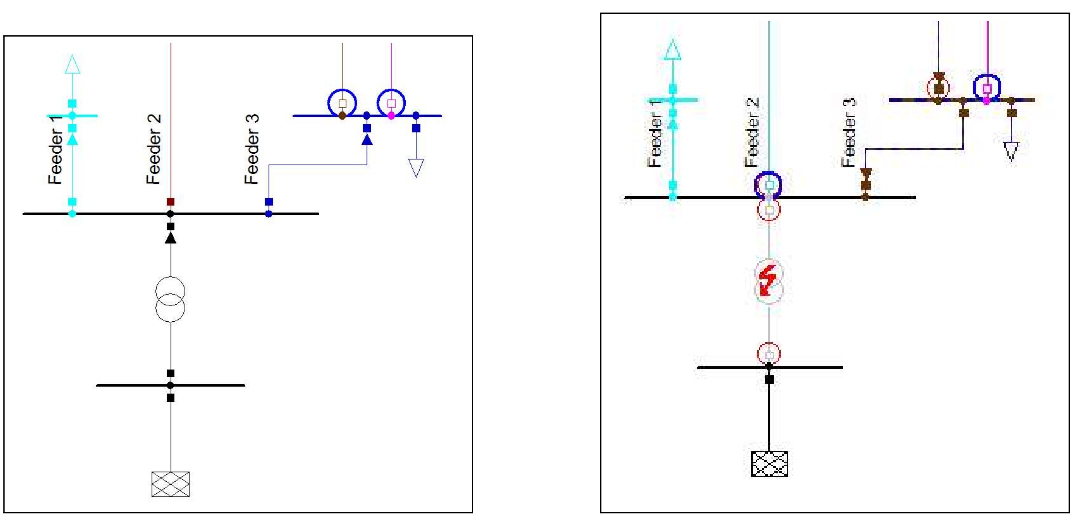
If *Consider Sectionalising Actions* is disabled, the stage of each switch is ignored and all switches will be considered equally with one of the above mentioned methods.

Enhanced restoration

If this checkbox is enabled, the restoration uses a more precise algorithm to solve load flow convergence issues during the restoration process. Setting this option can decrease the performance of the Reliability assessment.

Consider a possible backward recovery of a feeder in a primary substation

Whenever the start point of a feeder is de-energised after a fault (e.g. on a HV/MV-transformer), backward recovery can be used to resupply this feeder. Backward recovery allows the restoration through a substation. It is started in a case where the standard recovery could not resupply all loads after the first stage of the recovery, e.g. because of constraint violations or because of de-energised isolated feeders. The algorithm finds the best feeder for resupplying the substation and the interrupted feeders. This can improve the restoration quality for a loss of a substation significantly, especially, for example, for dedicated low-load feeders between substations or isolated feeders (see figure below).



(a) Initial State

(b) Resupply of Feeder 1

Figure 44.4.1: Example of Backward Recovery

The Backward recovery option, located within the “Restoration” Option, can be set as follows.

- Do not allow: no backward recovery will be used for restoration
- Allow but prefer standard recovery: backward recovery is allowed, but standard recovery will be preferred for restoration.
- Allow with user-defined preference: substations, where Backward recovery is allowed can be selected here.
- Allow and prefer: whenever possible, backward recovery will be preferred.

44.4.1.5 Costs

Costs for energy not supplied

If this option is selected, an Energy Tariff can be selected. Energy Tariffs are discussed in Chapter 18: Parameter Characteristics, Load States, and Tariffs, Section 18.5.2(Defining Energy Tariffs).

Costs for loads

If this option is selected, a Global cost curve for all loads can be selected. Alternatively, 'Individual cost curve per load' may be selected, allowing the user to define tariffs for individual loads. In both cases, a Time Tariff or Energy Tariff may be defined, as discussed in Chapter 18: Parameter Characteristics, Load States, and Tariffs, Section 18.5 (Tariffs).

44.4.1.6 Constraints

The settings for global constraints are defined within this page. The options are as follows:

Consider Thermal Constraints (Loading)

If this option is enabled, thermal constraints are considered by the FEA.

- **Global constraints for all components:** constraints specified in 'Max thermal loading of components' apply to all components in percent value.
- **Individual constraint per component:** the maximum thermal loading limit is considered for each component separately. This loading limit can be found on the Reliability tab of each component.

Consider Voltage Limits (Terminals)

If this option is enabled terminal voltage limits are considered by the FEA.

- **Global Constraint for all terminals:** constraints specified in Lower and Upper Limit of allowed voltage in p.u. that will apply to all terminals.
- **Individual Constraint per terminal:** voltage constraints are considered for each terminal separately. These constraints can be found on the Reliability tab of each terminal.

Consider Voltage Drop/Rise

If this option is enabled feeder voltage limits are considered by the FEA.

- **Global Constraint for all feeders:** constraints specified in Maximum Voltage Drop and Rise in percent value that will apply to all feeders.
- **Individual Constraint per feeder:** voltage Drop/Rise constraints are considered for each feeder separately. These constraints can be found on the Reliability tab of each feeder.

Consider Boundary Constraints outside feeders

If this option is set, the boundary constraints, applied on the boundaries "Reliability" settings are considered during restoration.

Ignore all constraints for

Constraints are ignored for all terminals and components below the entered voltage level.

- **Nominal voltage below or equal to:** the voltage level in kV is specified here if 'Ignore all constraints for...' is enabled.

Note: Voltage constraints are only available when the 'Distribution' analysis option is selected under 'Basic Options'. Thermal constraints are available when either the 'Transmission' or 'Distribution' analysis option is selected.

44.4.1.7 Maintenance

This tab allows you to enable or disable the consideration of Maintenance based on the Planned Outages you have defined. See Section 44.3.9, for more information on defining planned outages. The following options are available on this page:

Consider Maintenance

If enabled, all maintenance that falls in the selected time period, whether it's a year or a single point in time, is considered.

- **Show used planned outages:** when clicked, this button will show a list of all planned outages that will be considered by the calculation.
- **Show all planned outages:** when clicked, this button will show a list of all planned outages created in the project, including those not considered by the analysis because they fall outside of the selected time period.

44.4.1.8 Load Data

If the Reliability Calculation option 'Complete Year' is selected on the basic options page, then the following options are available on the Load Data page.

Load Variations

Enable the relevant flag to consider load states, load distribution states or Load and Generator States according to section 44.3.6 in the reliability calculation. The reliability calculation does not create load states automatically. If this flag is enabled but the states have not been created, then an error will be printed to the output window and the reliability calculation will stop. Otherwise the following two buttons are available.

Update/creation of States

- **Manually:** if selected, a button 'Create load states' will be available. When clicked, it launches the 'Load state creation' command after closing the reliability command (see Chapter 18 for more information on load state creation).
- **Automatically before running reliability calculation:** when selected, a pointer to the load state creation command is available.

44.4.1.9 Advanced Options

Events created during restoration

- **Only store them in the results file:** events will only be stored in the results file and not be saved as separate events in the contingency. This minimises the number of objects created in the database while performing calculations with many contingencies in large networks (e.g if independent second failures or double earth faults are enabled).
- **Also save them in the corresponding contingency:** switch events will be saved in the corresponding contingency.

Stop calculation if base case is overloaded

If this option is set, the reliability assessment will stop if the base case is overloaded. If not, a user defined threshold can be specified.

Calculation of SAIFI/SAIDI according to IEEE 1366

- **Do not consider interruptions shorter than or equal to:** this option enables the possibility to not consider interruptions shorter than a user defined duration for the calculation of SAIFI/SAIDI according to section 44.2.3.3.

Trace Functionality (Jump to Last Step)

A user-defined 'Time delay in animation' can be entered to delay the animation of power restorations when the *Jump to Last Step* icon ⏭ is pressed.

Switch/Load events

- **Delete switch events:** removes all switch events associated with the contingencies stored inside the command.
- **Delete load events:** removes all load events associated with the contingencies stored inside the command.

Failures, correction of forced outage rate

This option performs an automatic correction/normalisation of the reliability indices to allow for the fact that not all unlikely but possible contingencies have been considered in the analysis. For instance, n-3 contingencies have a non-zero probability.

Note: 'Forced outage' refers to the unplanned removal of a primary component from the system due to one or more failures in the system.

44.4.1.10 Parallel Computing

Parallel calculation of the *Reliability Assessment* is possible and can be activated on the Parallel Computing page of the *Reliability Assessment* command dialog. The options provided on this page are described below.

Parallel computation of contingencies: if the checkbox is ticked, the Reliability Assessment is executed in parallel. Otherwise, the calculation is run sequentially.

Minimum number of contingencies: this parameter defines the minimum number of contingencies necessary to start a parallel calculation. This means, if the number of contingencies is less than the entered number, the calculation is run sequentially.

Parallel Computing Manager: the parallel computation settings are stored in a *Parallel Computing Manager* object (*SetParalman*). Further information on the particular configuration is found in Section 22.4.

44.5 Results of the Reliability Analysis

44.5.1 Contribution to Reliability Indices

Contribution means the effects of the calculated contingencies to the reliability indices of all loads or a selection of loads. This chapter describes an optional post processing step, which can be useful to analyse the influence of a particular component or group of components on the calculated reliability indices. This enables the identification of components that can be targeted for upgrade to improve reliability, or to examine the impact of improved switch automation for example. This sub-section describes the post-processing functionality that can be used for these purposes.

To analyse the contributions to the following indices

1. SAIFI,
2. SAIDI,
3. ASIFI,
4. ASIDI,
5. ENS,
6. EIC,

the Reliability Assessment Calculation has to be executed once, or it has to be ensured that the currently activated study case contains results of a previously executed reliability analysis.

- Choose the *Contributions to Reliability Indices* button () in the Reliability Analysis toolbar menu.
- Choose between the contribution to all loads or to a user defined selection of loads. Loads can be selected according to the following groupings.
  - Grids,
  - Feeders,
  - Zones,
  - Areas.
  - and General Selections.
- Furthermore, it is possible to analyse the contribution of network elements to reliability indices of one Load, which can be a General Load, LV-Loads or MV-Load.
- After setting the required set, the user can execute the post process.

Note: The Contributions to Reliability Indices is a post-processing command. Once calculated the contributions for a selection, it is possible to change the selection or re-run the command for all Loads without executing the Reliability Assessment once again.

44.5.2 Viewing Results in the Single Line Diagram

You can view the Reliability Assessment Load Point Indices in three ways: in the load result boxes in single line graphic, in the data browser (Data Manager or load filter) or according to the diagram colouring. This sub-section describes the first two of these methods. The third method is described in chapter 44.5.2.2.

44.5.2.1 Result Boxes

After you have executed the Reliability Assessment Calculation, all loads within the Network Single Line Graphic, will show the following load point indices:

- AID: Average Interruption Duration.
- LPIF: Load Point Interruption Frequency.
- LPIT: Load Point Interruption Time.
- LPIC: Load Point Interruption Costs.

As usual, with *PowerFactory* result boxes, you can hover the mouse pointer over the result box to show an enlarged popup of the results. This is demonstrated in Figure 44.5.1

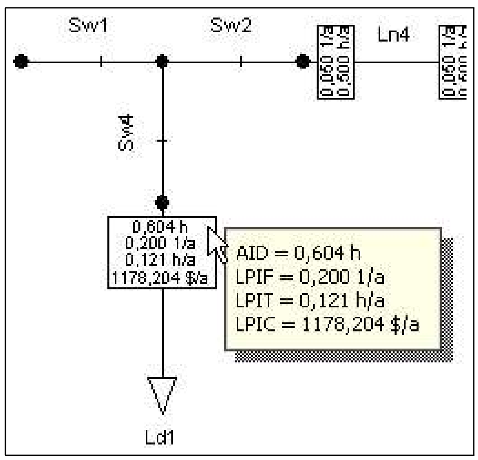


Figure 44.5.1: Single Line Diagram Graphic Showing the Load Point Indices Results

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Note: You can show any of the calculated load point indices in the load result boxes. To do this modify the displayed variables as described in Chapter 19: Reporting and Visualising Results, Section 19.3 (Variable Selection)

44.5.2.2 Diagram Colouring

For further analysis, which element contributes most to the reliability of a certain selection of customers, it is possible to use the diagram colouring.

The colouring is according to results of the whole system or the selection that has been chosen as described in chapter 44.5.1. The diagram colouring, especially for branches, terminals, MV Loads and generators can be according to

- contribution to EIC,
- contribution to ENS,

- contribution to SAIDI,
- and contribution to SAIFI.

The colouring, especially for Loads, can be according to

- average interruption duration,
- load point energy not supplied,
- yearly interruption frequency,
- and yearly interruption time.

In addition, there are several colouring modes that can aid you when using the reliability assessment functions. These are:

- Colouring according to *Feeders*; Use this to identify each Feeder and to see which feeder picks up load when back-feed switches are closed.
- Colouring according to *Connected Grid Components*; Use this to identify de-energised sections of the network during the fault isolation, separation and power restoration.
- Switches, type of usage. Use this mode to check the type of switches in the system when they are not modelled explicitly in the single line diagram.

To Colour According to Feeders

1. Click the *Diagram Colouring* button. The Diagram colouring dialog will appear.
2. Select the tab for the function you want to show the colouring mode for. For example, if you want the feeder colouring to appear before a calculation, then select the *Basic Data* tab. If you want the colouring to appear after a load-flow choose the load-flow tab.
3. Check the *3. Other* box and select *Topology* from the drop down list.
4. Select *Feeders* in the second drop down box.
5. Optional: To change the feeder colour settings click the *colour settings* button. You can double click the displayed colours in the colour column and select a different colour for each feeder as desired.
6. Click OK to close the Diagram Colouring dialog and save your changes.

To Colour According to Connected Grid Components

The *Connected Grid Components* colouring mode displays all the network components that are electrically connected together in the same colour. Other components are not coloured. To enable this mode:

1. Click the *Diagram Colouring* button. The diagram colouring dialog will appear.
2. Select the load-flow tab.
3. Check the *3. Other* box and select *Topology* from the drop down list.
4. Select *Connected Grid Components* in the second drop down box.
5. Click **OK** to close the Diagram Colouring dialog and save your changes.

To Colour According to Switch Type

The *Switches: type of usage* colouring mode displays all switches in the network with a different colour depending on their *switch type*. For instance circuit breakers will be displayed in a different colour to disconnectors. To enable this mode:

1. Click the *Diagram Colouring* button. The diagram colouring dialog will appear.

2. Select the tab for the function you want to show the colouring mode for. For example, if you want the switch type colouring to appear before a calculation, then select the *Basic Data* tab. If you want the colouring to appear after a load-flow choose the load-flow tab.
3. Check the *3. Other* box and select *Secondary Equipment* from the drop down list.
4. Select *Switches, Type of Usage* in the second drop down box.
5. Optional: To change the switch colour settings, click the *colour settings* button. You can double click the displayed colours in the colour column and select a different colour for each switch type as desired.
6. Click **OK** to close the Diagram Colouring dialog and save your changes.

44.5.3 Viewing Results in the Data Browser

To view the load point and system reliability indices in the Data Browser (as a selectable spreadsheet list), follow these steps:

1. Select the element or grouping element icon from the *Network Model Manager* button.
2. Choose the *Flexible Data* tab.
3. Click the *Define Flexible Data* button, to show all available variables.
4. Add more variables to the *Selected Variables* by double-clicking the variable in the *Available Variables* window.
5. Click **OK** to view the result variables in the data browser.

Note: Steps 3-5 are only required the first time you want to view the system reliability indices, or if you want to change the displayed variables. *PowerFactory* 'remembers' these settings within each project.

44.5.4 Reliability Reports

The Report can be accessed through the *Reliability Reports* button ( ) within the Reliability Analysis toolbar. The Report is based on the whole system or the selection that has been chosen as described in chapter 44.5.1. The report offers the following functionalities.

ASCII Report

This report is writing the results into the output window.

- **System Summary:** reports a calculation summary of the Reliability Assessment together with calculated system indices.
- **Load Interruptions:** reports the following indices for all Loads within the selection.
  - TCIT
  - TCIF
  - AID
  - LPENS
  - LPIC
  - ACIF
  - ACIT
- **Node Interruptions:** reports the following indices, focused on nodes.

  - AIT
  - AIF
  - AID

- **Contribution of Component Classes:** reports the contribution of Lines, Cables, Transformers, Terminals, Generators, Common Mode Failures and Double-Earth Faults to the system-indices, that are available for contributions mentioned in 44.5.1.

Tabular report of Contributions

This Report returns the contribution of one single element to the overall system-indices in a tabular form. This contribution is given as absolute value and in per-cent.