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Smart Grids and Reliability Analysis in Distribution Networks

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Abstract

In this report four test nets have been reliability analyzed, using the established reliability analysis method RELRAD and in the commercial power grid analysis tool PowerFactory. The RELRAD model approach was established in Excel for the test nets who allowed for it. PowerFactory was deployed for bigger, more complicated nets with distributed generation. These test net analysis were intended to provide practical experience in software analysis of grids. They were also intended to illuminate different aspects of distribution net reliability analysis. Chiefly, this was in regards to how backup cables and distributed generation affects the RELRAD methodology.

The results from analyzing the test nets have been used as a foundation to outline a reliability analysis software solution in MATLAB. This simulation program will be based on RELRAD principles, but enhanced with a load flow capability so that it can properly assess distribution networks with distributed generation.

Sammendrag

I denne oppgaven har fire testnett blitt pålitelighetsanalysert ved hjelp av en etablert pålitelighetsberegningsmetode kalt RELRAD. Deretter har de samme nettene også blitt analysert i det kommersielle kraftnettsanalyseringsprogrammet PowerFactory. Testnettene som tillot det ble etablert i Excel etter RELRAD-prinsipper, mens PF ble brukt først og fremst til større mer avanserte nett med distribuert produksjon. Analysene har vært tiltenkt å gi en praktisk innsikt i software-analyse pålitelighet i kraftnett. De skulle også belyse forskjellige problemstillinger knyttet til pålitelighetsanalyse av distribusjonsnett. I hovedsak på hvilken måte lokal produksjon av strøm og reservetilknytning kunne implementeres i RELRAD-metodikken.

Resultatene fra analysen har blitt brukt som et fundament til å utlede en skisse av et pålitelighetsanalytisk simuleringsprogram. Dette programmet er tenkt implementert i MATLAB og vil være basert på RELRAD-metodikken, men med mulighet til å bruke lastflytanalyse til å bedømme effekten på pålitelighetsanalysen av distribusjonsnett med distribuert produksjon.

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Contents

Introduction.....	0
1 - Methodology	1
1.1 - Reliability Analysis	1
Table 1.1 - Definitions	2
1.2 - Introducing RELRAD	3
Table 1.2 – RELRAD analysis terms and notations	3
Figure 1.1 – RELRAD flowchart (SINTEF, 2010)	5
1.3 – PowerFactory.....	6
Table 1.3 – PF load point indices explained	6
Figure 1.2 – PF reliability analysis flowchart (DlG SILENT GmbH, 2011)	7
Figure 1.3 – User flowchart for reliability analysis in PF	8
2 – Test Nets	9
2.1- Empirical line A.....	9
Fig. 2.1 – Anonymous line A, poor resolution as imposed by confidentiality clause	9
Table 2.1 – Summary PF simulation results	10
2.2 - Empirical line B	11
Fig. 2.2 – Anonymous line B, poor resolution to keep confidentiality agreement .Load points marked with red circles	11
Table 2.3 – LP characteristics from PF simulation of grid B	12
2.3 - Allan and Billinton Test Net Example	13
Fig. 2.3 – Allan and Billinton test net with distributed wind	13
Table 2.2 – Radial distributed wind with separate drift and 100% uptime (disregard cost statistics).....	14
Table 2.2 – Separate operation for wind generation, tripped when interrupted.....	14
2.4 - Extended Billinton Test Net For Educational Purposes (RBTS)	15
Table 2.5 – Bus 2 without backup cables	15
Figure 2.4 – Bus 2 of extended Billinton & Allan test net	16
Table 2.6 – Thermal limits upheld, without backup cables mitigating simulation of RBTS net	17
3 – Software Outline.....	18
3.1 – Software Overall Description.....	18
3.2 – General Architecture of RELRAD	18
Figure 3.1 – Extended RELRAD flowchart.....	19

3.4 – RELRAD Input and Output List	21
4 - Discussion	24
4.1 – Employing external software for power flow analysis	24
4.2 – Implementation Distributed Generation.....	24
4.3 – EMS for Distributed Generators	24
4.4 – Choice of Test Nets.....	25
4.5 – The Layout and Form of the Software Outline	25
Conclusion	26
Works Cited	27
APPENDIX	28
A.1 – Load point PF analysis results from bus 2 in extended test net (RBTS) with backup	28
A.2 – Load point PF analysis results from bus 2 in extended test net (RBTS) , without backup ...	28
A.3 – LP PF analysis results from bus 2 in extended test net (RBTS) , with proper thermal limits	29
A.4 – PF simulation of load point indices for line A.....	30
A.5 – NetBas reference for anonymous line A	32
A.6 - Allan and Billinton Test Net for Educational Purposes with 100% up-time and separate generation for windmill.....	33
A.7 - Allan and Billinton Test Net for Educational Purposes with no distributed generation(wind generation tripped when interrupted).....	34
A.8 – Weighted ENS for results in A.4 and A.5	35
A.9– LP PF analysis results from distributed wind case study, disregard LPEIC values.....	35
A.10 – Excel summary of Extended Alan & Billinton Test Net. Total ENS.	35
A.11 – Reference for no separate wind production for Test Net Example	36
A.12 – Reference for separate generation scenario (1) for Test Net Example	36
A.13 – Reference for separate generation scenario (2) for Test Net Example	37

Introduction

The way energy needs will be supplied in the future and how smart grid functions will change how we monitor grids will impact how reliability analysis is performed on power grids. Distributed generation will for example increase the complexity of analyzing distribution radials greatly. Smart meters can increase the awareness of customers, regulators and grid operators to quality of supply issues. The tools we use to do perform these analyses will have to evolve with the needs arising from change.

At the center of SINTEF Energi AS efforts to develop reliability tools is OPAL. It is a MATLAB based reliability analysis tool for meshed grids. One of the long term goals for OPAL is to implement a distribution net reliability analysis function. This report intends to lay a fundament for implementing the RELRAD methodology in a standalone supplement to OPAL. The RELRAD methodology will be modified to cope with new types of components introduced to distribution nets such as small wind farms and local hydro generators.

The main objectives in this endeavor is considered to be

- Establish different test nets in PowerFactory and to compare the results from reliability analysis of these test grids with results from previous reports done on the same test nets.
- Establish the same test nets in Excel using the RELRAD methodology and compare these reliability analysis results with results from PowerFactory and previous reports.
- Describe the prerequisites and methodological choices behind the different analysis tools and comment on analysis results.
- Establish an outline for implementing RELRAD in MATLAB.

Structure of Report

Chapter 1 takes on the methodology and describes the different methods used to analyze reliability in power grids in this report. Chapter 2 presents the test nets used and discusses their analysis results. Chapter 3 outlines a software which is intended to analyze reliability in distribution grids employing an extended RELRAD method which will be described in the same chapter. Chapter 4 discusses the choices done in the software outline as well as what was learned from the test net analysis.

1 - Methodology

This section will rapidly introduce the concept of reliability analysis itself. Then somewhat bigger introductions to PowerFactory and RELRAD will follow. The reason PowerFactory was chosen for this assignment was that NetBas is fairly common to use for power grid analysis in Norway already. It was considered to be of interest to see how an international, widely used and non-Scandinavian software solution would model the test nets as compared to Scandinavian solutions that had been employed before

1.1 - Reliability Analysis

In the Norwegian energy law (Energiloven) it's stated that "The law shall secure production, transformation, distribution and consumption of energy in an economically rational manner, hereunder public and private interests shall be considered." (OED (Olje- og energidepartementet), 1990)

("Loven skal sikre at produksjon, omforming, overføring, omsetning, fordeling og bruk av energi foregår på en samfunnsmessig rasjonell måte, herunder skal det tas hensyn til allmenne og private interesser som blir berørt.")

In general this means that the following five costs are to be minimized:

- Investment costs
- Operation and maintenance costs
- Transmission loss costs
- Interruption costs
- Bottleneck costs

Since network operators are now incentivized to reduce interruption frequency and duration there is a need to be able to model networks with regards to reliability. Interruption costs require a reliability analysis. The main focus of which is to find the expected frequency of interruptions at load points, the expected duration of these interruptions and the magnitude of the load during the interruptions. These are all needed to estimate the complete interruption costs.

This analysis procedure can be done in different ways and with different methodologies, however this report will only look at one type of methodology and on one software solution. Table 1.1 on the next page will guide you through some of the key definitions used in this report to analyze reliability.

Circuit breaker zone	Area enclosed within circuit breakers. All components within the zone are experiencing the same frequency of outages.	
Component	A device which performs a major operating function and which is regarded as an entity for purposes of recording and analyzing data and outage occurrences.	IEEE Std 859-1987
Connectivity analysis	A simplified reliability analysis where a load point is considered to be supplied if it has a line connection to a power source regardless of load flow restrictions.	See chapter 1.3
Contingency	A contingency is an unplanned outage of one or more component, i.e. one or more components are in the outage state.	This coincides with IEEE Std 859-1987 definition of Outage Event
DG	Distributed Generation is production of power placed in the LV or MV part of the grid	
Distribution analysis	In a reliability analysis this describes a simplified analysis form for distribution nets where mitigating measures only include switching.	See chapter 1.3
Fault type 2	In a protective device this means that the device trips spontaneously even though there is no fault in the line.	(Samdal, Kjølle, & Gjerde, 2006)
Fault type 3	In a protection device this corresponds to the device not tripping properly when a fault occurs in the line.	(Samdal, Kjølle, & Gjerde, 2006)
FEA	Failure Effect Analysis, a PF analytical step in a reliability analysis	
Load flow analysis	This refers to a normal a normal load flow analysis, but in this text it sometimes refers to the option of setting load flow limits for a reliability.	See chapter 1.3
Operational state	Component is fully integrated and operational in the power system.	
Outage state	The component or unit is not in the Operational state. That is, it is partially or fully isolated from the system.	IEEE Std 859-1987
PF	PowerFactory, analytical tool for modeling of power grids.	
Radial net	A radial network is a network with no two unique paths from one node to another.	
Separate operation	When a generator which is cut off from a main grid or another utility which can maintain an acceptable quality of supply can still operate and deliver power to the separated grid.	
SRS	Software requirement specification	
Transmission analysis	In a reliability analysis this describes a form of finding mitigating measures which includes re-distributing generators and load shedding.	See chapter 1.3

Table 1.1 - Definitions

1.2 - Introducing RELRAD

The RELRAD method as defined in depth in “Planleggingsbok for kraftnett” (SINTEF, 2010) is an analytical tool for conducting reliability analysis on a radial network. In a grid without meshed structures reliability analysis can be greatly simplified without significant loss of quality in the resulting data. The concept is to analyze each component in a grid, find its expected outage duration and which load points are affected. RELRAD then uses sectioning as a mitigating measure and calculates the resulting downtime for the set of affected load points during this period. Run the analysis for all components and accumulate the five indices defined in equation (1) to (5). After the process is repeated for all components the sum of the indices produced by each component for a specific load point will represent the complete load point indices. Flow chart for this process is shown in fig. 1.1. The RELRAD method does not require a load flow analysis to be made. For this reason, a RELRAD analysis will not be able to estimate the effects on the reliability indices of a generator in the radial.

Relevant definitions from the reliability chapter of “Planleggingsbok for kraftnett” (SINTEF, 2010) and some definitions used in this report are given in table 1.2.

Interrupted power	The annual power for the load point.	Given as ΔP [MW/a]
Cost of Energy Not Supplied	The lost sales income /mitigation costs expected due to power outages.	Given as K [currency/a]
Failure frequency	The number of sustained failures per year expected from the component.	Given as λ [fault/a].
ENS	“Ikke Levert Energi” (ILE) or “Energy not Supplied”	Given as [MWh] but is sometimes described as Energy Not Supplied (ENS) in PF analysis summary.
Load Point	A network sink for electrical power.	Can occur in two states: In – Has voltage Out – No voltage
Outage duration, expected	The expected outage duration for a component or load point over a year.	Given as U [h/a].
Reparation time	The total downtime of a component due to fault clearance, reparation and reactivation	Given as r [h/fault]
Sectioning/Switching time	Time from the first fault notification to the faulted component is isolated behind the closest switch(es)	

Table 1.2 – RELRAD analysis terms and notations

The Main Reliability Indices in RELRAD

$$\text{Annual outage frequency} \quad \lambda = \sum_j \lambda_j \quad (1)$$

$$\text{Annual expected outage duration} \quad U = \sum_j \lambda_j r_j \quad (2)$$

$$\text{Mean outage duration} \quad r = \frac{U}{\lambda} \quad (3)$$

$$\text{Annual power interrupted} \quad \Delta P = P \sum_j \lambda_j \quad (4)$$

$$\text{ENS} \quad ENS = \sum_j ENS_j \approx P \sum_j \lambda_j r_j \quad (5)$$

Equation symbols

- j is the enumeration variable for components
- λ_j is the failure frequency for component j
- r_j is the summed downtime for a component due to repair and sectioning
- ENS_j is the contribution to load points affected
- P is the average annual load (LE/8760 [MWh/h])
- LE annually supplied energy [MWh]
- In equation (5) the uncertainty in summarizing the ENS with a constant P comes from the fact that the P is varying over time and should thus be integrated over the same time period. Multiplying U with the averaged P is assumed to give a close estimate.

Procedure

These indices can be calculated using the flowchart described in figure 1.1 in the next page. The RELRAD analysis described there will start by listing all components j . For every object in the component list a contingency scenario is created by removing the component. All components within the circuit breaker zone will experience an outage until the sectioning is done. Then the faulted component, all affected components and affected load points will be out for the duration of the repair time. The fault frequencies and outage times are calculated at each load point for all components. When all the components have been analyzed the sum of the outage time created by all the components will be equal to the annual outage time for that load point. The results created by this analysis are valid under the following criterias:

- All faults are assumed statistically unrelated. No common mode is possible.
- No two faults occur at the same time. One fault must be repaired before the next one occurs. This is a legitimate simplification because the relationship between repair duration and fault frequency is normally $r\lambda \ll 1$ (ie. if a certain incident happens one hour a year and another statistically unrelated happening happens one hour a year the coincidence of the two overlapping is very small).
- No distributed generation in the radial.

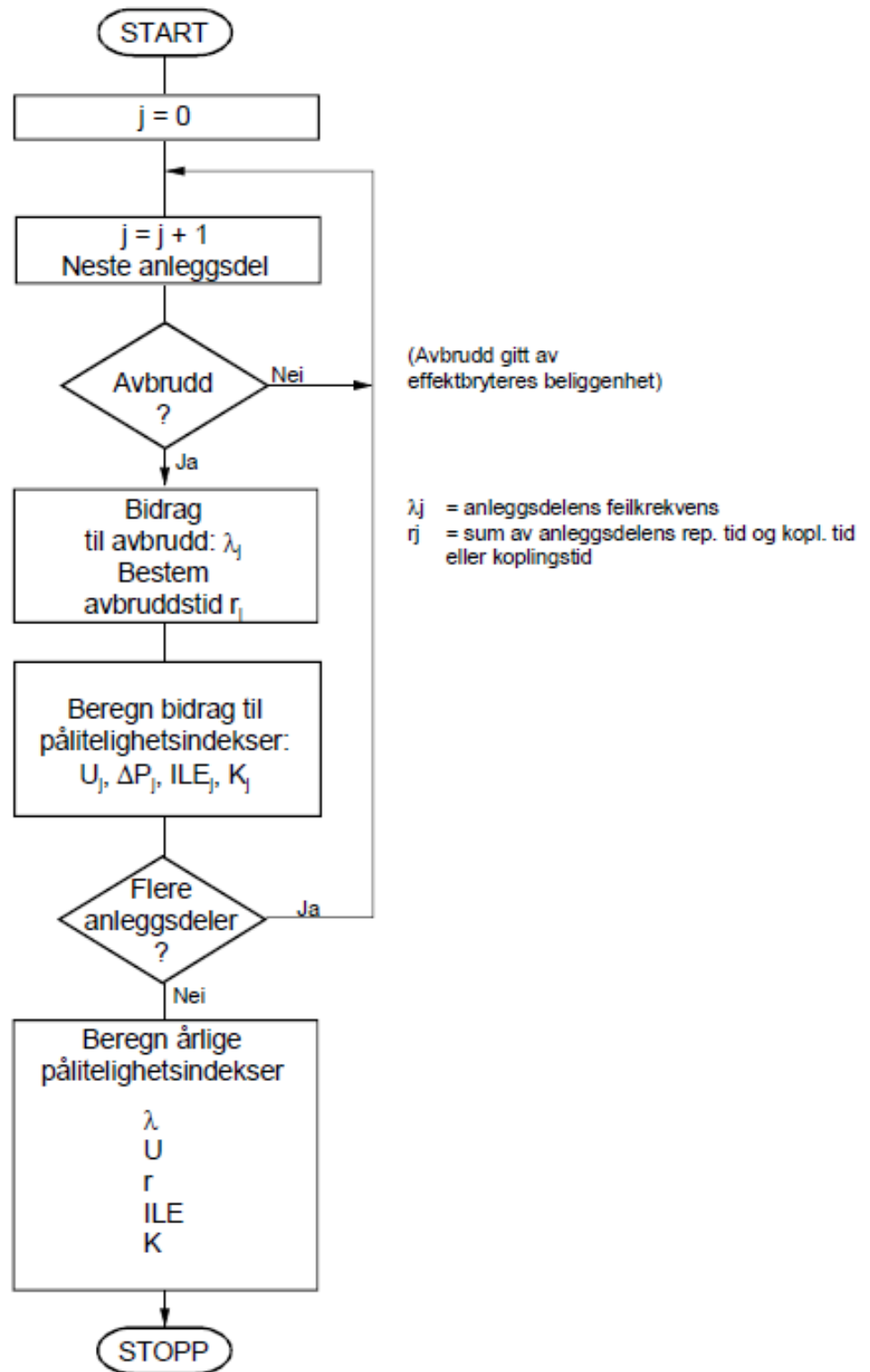


Figure 1.1 – RELRAD flowchart (SINTEF, 2010)

1.3 – PowerFactory

The main setup of how PF does a reliability assessment is somewhat similar to the RELRAD method. When a reliability analysis is conducted PF creates a contingency list which includes contingencies in all components. Each contingency is then generated as a system state with its own topology (System State Generation, in flowchart depicted in fig. 1.2). The main difference is what happens in the System Failure Effect Analysis (FEA). The FEA is conducted to simulate the system reactions to a failure. This includes switch tripping on and off, load shedding, load alleviation, voltage constraint alleviation and re-dispatching generators. This process also includes load flow checks to ensure constraints are satisfied for each mitigation measure. At the end of the FEA, system failure indices are calculated for that specific failure in much the same way as in a RELRAD analysis. The process is described in the flowchart in figure 1.2. The states in this flowchart will be explained in more detail below. Note: PF produces more indices than the ones listed in table 1.3, but explanation for these should be included in the summary tables where they are used.

TCIT	Total Customer Interruption Time
TCIF	Total Customer Interruption Frequency
AID	Average Interruption Duration
LPENS	Load Point Energy Not Supplied
LPEIC	Load Point Energy Interruption Cost
ACIF	Average Customer Interruption Frequency
ACIT	Average Customer Interruption Time

Table 1.3 – PF load point indices explained

Electrical System Model

This is the process of implementing the complete, functioning grid topology and parameters. The key parameters are listed in figure 1.3 showing the user implementation.

Failure Models

This is where the stochastic failure models for components are implemented. For most components this consists of a failure frequency, repair time, frequency of contingencies (passing failures) and maintenance schedule. For protection devices, however, this is modeled as a “failure to open frequency”. After this is implemented, the analysis will create a contingency list where all the components with a failure characteristic are listed.

System State Generation

This part of the analysis goes to the next (or first) object on the contingency list and removes it from the topology. The new topology with the faulted component isolated, is then given to the FEA.

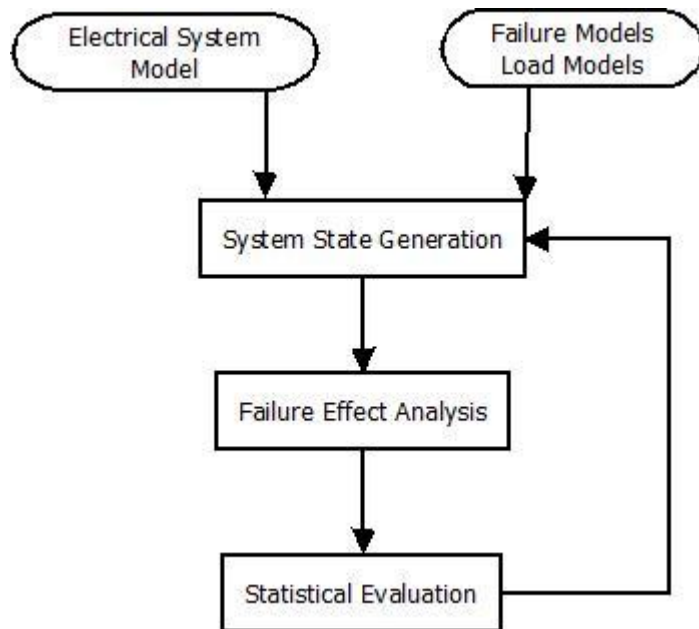


Figure 1.2 – PF reliability analysis flowchart (DIgSILENT GmbH, 2011)

Failure Effect Analysis

In this part of the analysis there are four different main options for how to proceed.

Distribution

The reliability assessment will try to remove overloading at components and voltage violations (at terminals) by optimizing the switch positions in the radial system. If constraints occur in the power restoration process, loads will be shed by opening available switches.

Transmission

Thermal overloads are removed by generator re-dispatch, load transfer and load shedding. First generators are re-dispatched and load transfer is attempted. If this cannot be completed or does 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.

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.

Statistical Evaluation

This part of the analysis adds up the indices in much the same way as in RELRAD, then moves on to the next component or ends the loop.

The flowchart is depicted in fig. 1.3 and provides the most important points to cover for a precise and consistent reliability analysis. All the characteristics mentioned in the flow chart should be present in all the analysis done in this report if not stated otherwise.

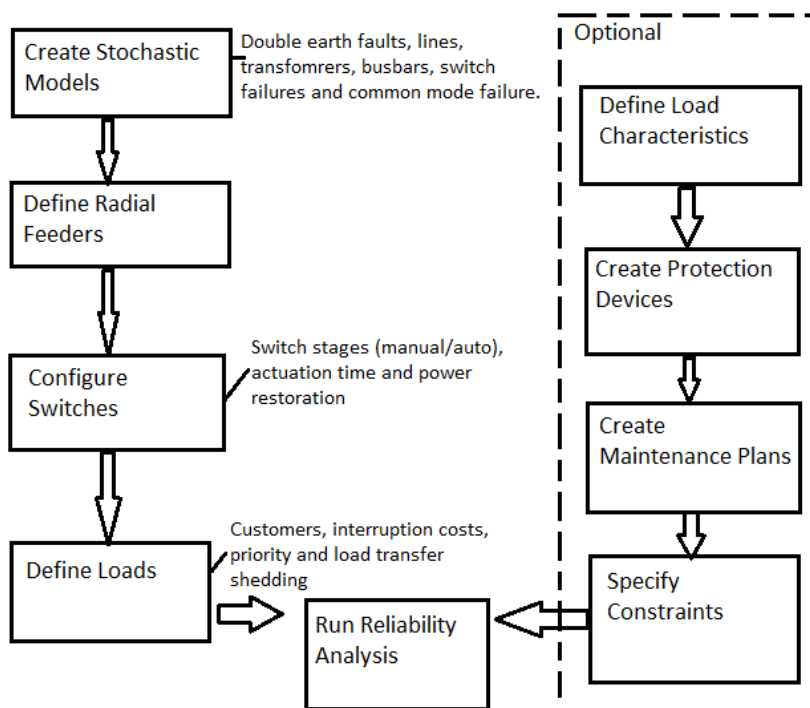


Figure 1.3 – User flowchart for reliability analysis in PF

2 – Test Nets

To have an empirical basis for the software requirement specification, a series of case studies were conducted. These models were constructed in PF for a proper evaluation. The more basic grids were modeled both in PF and Excel using the RELRAD method to make comparisons easier and more reliable. Reliability analysis of generators and switching devices are not directly included in the PF models. This is because a generator representation in PF does not have an included failure representation. Circuit breakers and disconnectors in PF does have a failure rate function implemented, but they are not implemented in the RELRAD form (λ, r) . The main switching device failure characteristic in PF is "failure rate to open". The generator failures can be simulated using a short line with the generators RELRAD failure characteristics to connect it to the grid. The switching devices are more difficult to include correctly.

2.1- Empirical line A

A.4 and A.5 contain load point indices for line A.

To get a better impression of a real life modeling scenario a real life grid was analyzed. This includes checking the analysis against empirical numbers from the site. The chosen network is presented in fig. 1.1 and is a radial net with distributed generation. The grid has been censored in agreement with the network operators. The generators are marked with red circles in figure 2.1. Although, they are not as important since it was later decided to exclude the generators from the analysis.

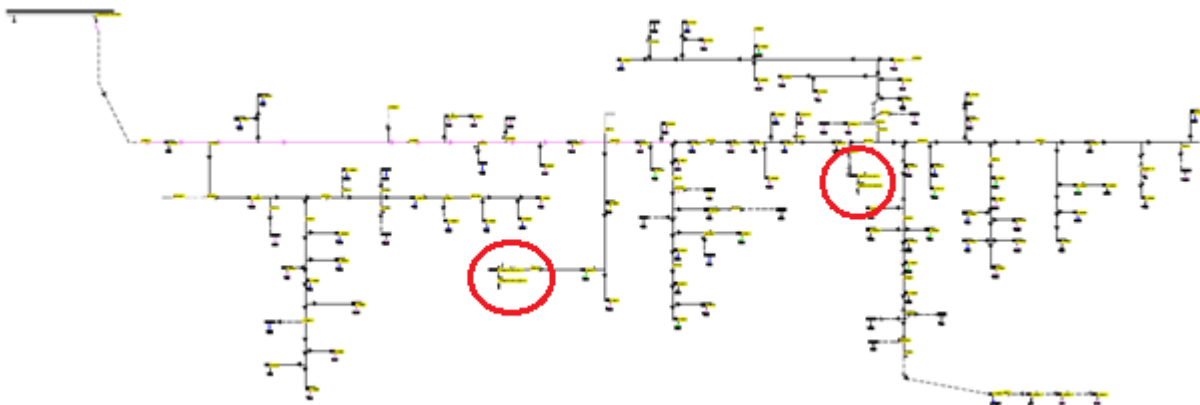


Fig. 2.1 – Anonymous line A, poor resolution as imposed by confidentiality clause

A few of the loads have been left out due to lack of information and parts of the net have been simplified. The loads left out seemed to not be included in the line anymore, are greyed out on sketches and are excluded from the excel tables with measurements received from the operator. The

majority of simplifications consist of leaving out nodes that seemed to be relevant for reliability analysis purposes.

The significant simplifications are as follows.

- Nodes midways in lines between loads with no apparent relevant purpose.
- Nodes with disconnectors in places where they will have no effect on the reliability simulation result. Such as a DC at the beginning and at the end of a feeder line which can be isolated at the bus bar with no implication for the load point failure frequency or downtime.
- The distributed generation cannot run separately. Since there is no apparent problem with voltage in the line and harmonics analysis is outside the scope of this report the generators have been set to zero output.

To leave the generators off was not ideal for the case study, as distributed generation adds a lot of complexity of the analysis. But since the reference analysis from the grid operator was conducted without separate generation there was no reference result to check these simulations against.

System Summary			

System Average Interruption Frequency Index	:	SAIFI	= 5,657076 1/Ca
Customer Average Interruption Frequency Index	:	CAIFI	= 5,657076 1/Ca
System Average Interruption Duration Index	:	SAIDI	= 8,715 h/Ca
Customer Average Interruption Duration Index	:	CAIDI	= 1,541 h
Average Service Availability Index	:	ASAI	= 0,9990051046
Average Service Unavailability Index	:	ASUI	= 0,0009948954
Energy Not Supplied	:	ENS	= 26,037 MWh/a
Average Energy Not Supplied	:	AENS	= 0,260 MWh/Ca
Average Customer Curtailment Index	:	ACCI	= 0,015 MWh/Ca
Expected Interruption Cost	:	EIC	= 0,000 M\$/a
Interrupted Energy Assessment Rate	:	IEAR	= 0,000 \$/kWh
System energy shed	:	SES	= 0,000 MWh/a
Average System Interruption Frequency Index	:	ASIFI	= 5,656966 1/a
Average System Interruption Duration Index	:	ASIDI	= 8,719609 h/a
Momentary Average Interruption Frequency Index	:	MAIFI	= 0,000000 1/Ca

Table 2.1 – Summary PF simulation results

Table 1.1 shows us an ENS of 26 MWh/a. Compared to the 13 MWh/a ENS which is demonstrated in the reference simulation from the net operator this result is far off. This is because variable load was not implemented, and the senior engineer responsible for line A commented that 26MWh/a was very plausible number for a heavy load scenario.

2.2 - Empirical line B

Line B was modeled to further investigate the effects of distributed generation in a line. This grid was a suggestion to a net operator as a complete revamp of an area with big DG potential but little or no existing power grid infrastructure. There is no reference for this model and it is too complicated to replicate in excel, but some simple observations can substantiate the findings. LP 3 from table 2.3 has a delivery failure frequency of 0.32. This is slightly above the 0.316 frequencies which are presented by the lines connecting it to the main grid and the line which is connecting the node to the rest of the grid.

LP 2 and LP 3 are further out in the radial grid and have higher failure frequencies and more downtime. This is due to the radial structure of the grid. Adding all the failure frequencies within the circuit breaker zones leading up from the load point from the main grid provides the exact interruption frequency. This is because a distribution analysis was chosen for the first analysis.

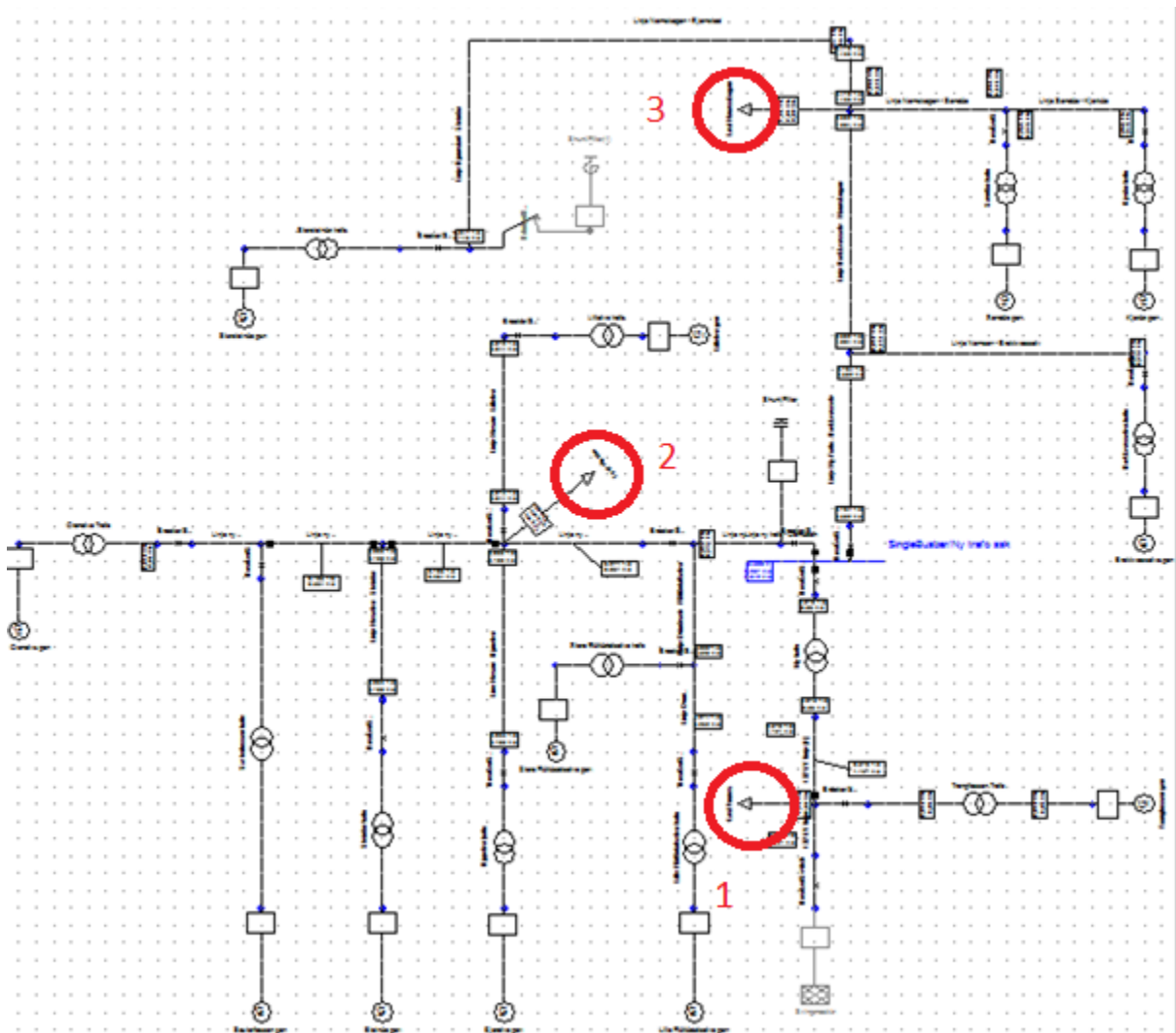


Fig. 2.2 – Anonymous line B, poor resolution to keep confidentiality agreement. Load points marked with red circles

This analysis assumes no separate generation. A transmission analysis resulted in an insignificantly small interruption frequency because of the good coverage of suppliers to all load points.

System		Summary
System Average Interruption Frequency Index	: SAIFI =	1,165344 1/Ca
Customer Average Interruption Frequency Index	: CAIFI =	1,165344 1/Ca
System Average Interruption Duration Index	: SAIDI =	4,151 h/Ca
Customer Average Interruption Duration Index	: CAIDI =	3,562 h
Average Service Availability Index	: ASAI =	0,9995261858
Average Service Unavailability Index	: ASUI =	0,0004738142
Energy Not Supplied	: ENS =	1,747 Mwh/a
Average Energy Not Supplied	: AENS =	0,582 Mwh/Ca
Average Customer Curtailment Index	: ACCI =	0,000 Mwh/Ca
Expected Interruption Cost	: EIC =	0,000 M\$/a
Interrupted Energy Assessment Rate	: IEAR =	0,000 \$/kwh
System energy shed	: SES =	0,000 Mwh/a
Average System Interruption Frequency Index	: ASIFI =	0,532937 1/a
Average System Interruption Duration Index	: ASIDI =	1,896629 h/a
Momentary Average Interruption Frequency Index	: MAIFI =	0,189619 1/Ca

Table 2.2 – Summary PF grid B simulation

A less well connected and less supplied grid would have made a more relevant simulation for load points in the system. With more options in PF when it comes to defining generators states based on time of year etc. might have made a more relevant analysis for load points as well. Also, being able to get some results on how well the generators could supply the central grid would be more relevant for this specific grid. The last proposition will be investigated further later on in the discussion of this report.

Load Inter Name	TCIT Ch/a	TCIF C/a	AID h	LPENS Mwh/a	LPEIC \$/a	ACIF 1/a	ACIT h/a
Last 1	7,04	1,98	3,56	0,05	0,00	1,98	7,04
Last 2	4,29	1,20	3,57	0,91	0,00	1,20	4,29
Last 3	1,12	0,32	3,55	0,79	0,00	0,32	1,12

Table 2.3 – LP characteristics from PF simulation of grid B

2.3 - Allan and Billinton Test Net Example

(Allan & Billinton, Probabilistic Assessment of Power Systems, 2000)

A.9, A.11, A.12 and A.13 contains load point indices and reference for simulation of scenario (2).

As a quality check a test net created by Roy Billinton was implemented in both Excel and PowerFactory. The net had a traditional radial structure, but contained a wind farm in the far end of the radial. The net was then analyzed for two different scenarios listed below as (1) and (2).

- (1) In one scenario the wind farm could not operate without connection to the main grid.
- (2) The second scenario described a wind farm that could operate independently of the main grid, but with either a 25% or 100% uptime.

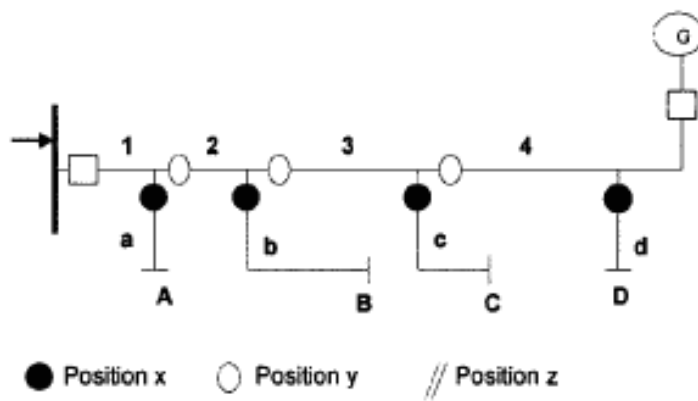


Fig. 2.3 – Allan and Billinton test net with distributed wind

The first scenario implemented in PF gave the results shown in table 2.2. From a strict reliability perspective this scenario accumulates to a scenario with no distributed generation at all. The reference result of this analysis (Allan & Billinton, Probabilistic Assessment of Power Systems, 2000) shows in table 11 an ENS of 14,675MWh. The 15,75MWh ENS we can see from table 2.2 is the result of PFs simulation. The 1MWh difference in ENS is somewhat difficult to explain. Excel calculation of the same scenario in A.8 suggests a slightly lower ENS of 13.95 MWh. It is important to note that the report did not provide an exact description of how the total load (7.5 MW) is distributed between the load points. I estimated the load distribution to be about 1.875 MW on each LP, but there is room for error here. However, a relatively quick sensitivity analysis of the load distribution showed no big difference in results except when the total load of LP D and C became lower than the wind generation. A.7 and A.8 (calculations in appendix) also shows that the annual outage frequency and outage times were identical for the excel analysis, the PF analysis and the reference analysis. It is difficult to be cocksure about the reason for the discrepancy in ENS, but from playing around with generator settings in PF it seems that the PF ILF calculation is surprisingly sensitive to changes in generator data. A very detailed generator representation in PF could be the source of the ENS anomalies.

System Summary			
System Average Interruption Frequency Index	: SAIFI =	1,150000	1/Ca
Customer Average Interruption Frequency Index	: CAIFI =	1,150000	1/Ca
System Average Interruption Duration Index	: SAIDI =	2,763	h/Ca
Customer Average Interruption Duration Index	: CAIDI =	2,402	h
Average Service Availability Index	: ASAI =	0,9996846461	
Average Service Unavailability Index	: ASUI =	0,0003153539	
Energy Not Supplied	: ENS =	15,750	MWh/a
Average Energy Not Supplied	: AENS =	3,938	MWh/Ca
Average Customer Curtailment Index	: ACCI =	4,935	MWh/Ca
Expected Interruption Cost	: EIC =	13,950	M\$/a
Interrupted Energy Assessment Rate	: IEAR =	885,714	\$/kwh
System energy shed	: SES =	0,000	MWh/a
Average System Interruption Frequency Index	: ASIFI =	0,893333	1/a
Average System Interruption Duration Index	: ASIDI =	2,100000	h/a
Momentary Average Interruption Frequency Index	: MAIFI =	0,000000	1/Ca

Table 2.2 – Radial distributed wind with separate drift and 100% uptime (disregard cost statistics)

Scenario number two is not possible to implement directly in PF. DigSILENT has not added many reliability analysis features for generation and protection devices. Since there is an estimated linear relationship between ENS and outage time it should be possible to do a reliability analysis of a scenario with and without a generator at the end of the radial. These results was then weighted (with 25% and 75%) and added together. The analysis results from a pure radial are shown below in table 2.3. In A.8 the weighted results from the excel RELRAD calculations A.6 and A.7 are added together. The resulting ENS is 18.825 MWh, which is very close to the 18.23 MWh ENS value in the reference.

System Summary			
System Average Interruption Frequency Index	: SAIFI =	0,824812	1/Ca
Customer Average Interruption Frequency Index	: CAIFI =	0,824812	1/Ca
System Average Interruption Duration Index	: SAIDI =	2,600	h/Ca
Customer Average Interruption Duration Index	: CAIDI =	3,152	h
Average Service Availability Index	: ASAI =	0,9997032313	
Average Service Unavailability Index	: ASUI =	0,0002967687	
Energy Not Supplied	: ENS =	20,397	MWh/a
Average Energy Not Supplied	: AENS =	8,099	MWh/Ca
Average Customer Curtailment Index	: ACCI =	3,130	MWh/Ca
Expected Interruption Cost	: EIC =	0,000	M\$/a
Interrupted Energy Assessment Rate	: IEAR =	0,000	\$/kwh
System energy shed	: SES =	0,000	MWh/a
Average System Interruption Frequency Index	: ASIFI =	0,756990	1/a
Average System Interruption Duration Index	: ASIDI =	2,314044	h/a
Momentary Average Interruption Frequency Index	: MAIFI =	0,000000	1/Ca

Table 2.2 – Separate operation for wind generation, tripped when interrupted

2.4 - Extended Billinton Test Net For Educational Purposes (RBTS)

(Billinton, 1991)

A.1, A.2 and A.3 contains more indices from PF simulations of this grid.

The extended test net was introduced to give an analysis with several branches and backup cables. The backup cables were implemented as faultless since they will only be utilized when an error occurs in the feeders. Each branch from the main bus (F1, F2, F3 and F4) is a circuit breaker zone.

System Summary				
System Average Interruption Frequency Index	:	SAIFI	=	0,189505 1/Ca
Customer Average Interruption Frequency Index	:	CAIFI	=	0,189505 1/Ca
System Average Interruption Duration Index	:	SAIDI	=	3,226 h/Ca
Customer Average Interruption Duration Index	:	CAIDI	=	17,024 h
Average Service Availability Index	:	ASAI	=	0,9996317172
Average Service Unavailability Index	:	ASUI	=	0,0003682828
Energy Not Supplied	:	ENS	=	59,465 MWh/a
Average Energy Not Supplied	:	AENS	=	2,703 MWh/Ca
Average Customer Curtailment Index	:	ACCI	=	0,000 MWh/Ca
Expected Interruption Cost	:	EIC	=	0,000 M\$/a
Interrupted Energy Assessment Rate	:	IEAR	=	0,000 \$/kWh
System energy shed	:	SES	=	0,000 MWh/a
Average System Interruption Frequency Index	:	ASIFI	=	0,185472 1/a
Average System Interruption Duration Index	:	ASIDI	=	2,973169 h/a
Momentary Average Interruption Frequency Index	:	MAIFI	=	0,000000 1/Ca

Table 2.4 – Bus 2 with backup cables

The first thing to note about this case is that the two main transformers connecting the main 11kV bus to the grid seem to be in the same circuit breaker zone (judging from the drawing shown in figure 2.4). With this setup a single fault in one of the transformers would leave the whole grid without voltage for three hours a year. This alone would accumulate to a 2x60MWh ENS per year. In my PF analysis I assumed that the main transformers could be separated with circuit breakers on each side so that at least one transformer could continue to feed the grid while the other was being repaired. The results with and without backup cables are shown in table 1.4 and 1.5. The ENS of 59,465 MWh and 74,047 MWh respectively from the PF simulation suggests that the reference values have been calculated not using the backup cables. In the reference the sum of ENS is given as 73,6 MWh.

System Summary				
System Average Interruption Frequency Index	:	SAIFI	=	0,189505 1/Ca
Customer Average Interruption Frequency Index	:	CAIFI	=	0,189505 1/Ca
System Average Interruption Duration Index	:	SAIDI	=	3,980 h/Ca
Customer Average Interruption Duration Index	:	CAIDI	=	21,000 h
Average Service Availability Index	:	ASAI	=	0,9995457093
Average Service Unavailability Index	:	ASUI	=	0,0004542907
Energy Not Supplied	:	ENS	=	74,047 MWh/a
Average Energy Not Supplied	:	AENS	=	3,366 MWh/Ca
Average Customer Curtailment Index	:	ACCI	=	0,000 MWh/Ca
Expected Interruption Cost	:	EIC	=	0,000 M\$/a
Interrupted Energy Assessment Rate	:	IEAR	=	0,000 \$/kWh
System energy shed	:	SES	=	0,000 MWh/a
Average System Interruption Frequency Index	:	ASIFI	=	0,185472 1/a
Average System Interruption Duration Index	:	ASIDI	=	3,702220 h/a
Momentary Average Interruption Frequency Index	:	MAIFI	=	0,000000 1/Ca

Table 2.5 – Bus 2 without backup cables

This is plausible as the case study itself does not mention anything about backup cables except in the figure describing the topology. I included backup cables so that I could check if the results produced matched one of the two scenarios.

The excel calculation that was done to verify the results estimated the total ENS be 63,5 MWh with backup cables and an ENS of 72,3 MWh without backup cables. However, these excel calculations do not take into account the main transformer couple and their failure ratings. The transformers are dimensioned to 16 MVA. The calculations here deal with a power factor of 1, so the transformers are able to handle about 16MW of power transfer. This means that if one transformer is faulted and isolated, there would be a deficit of roughly 4 MW over the whole system during the repair duration (averaged to 3 hours a year per transformrer). In PF you have the option to stretch the thermal limits of the components beyond a 100%.

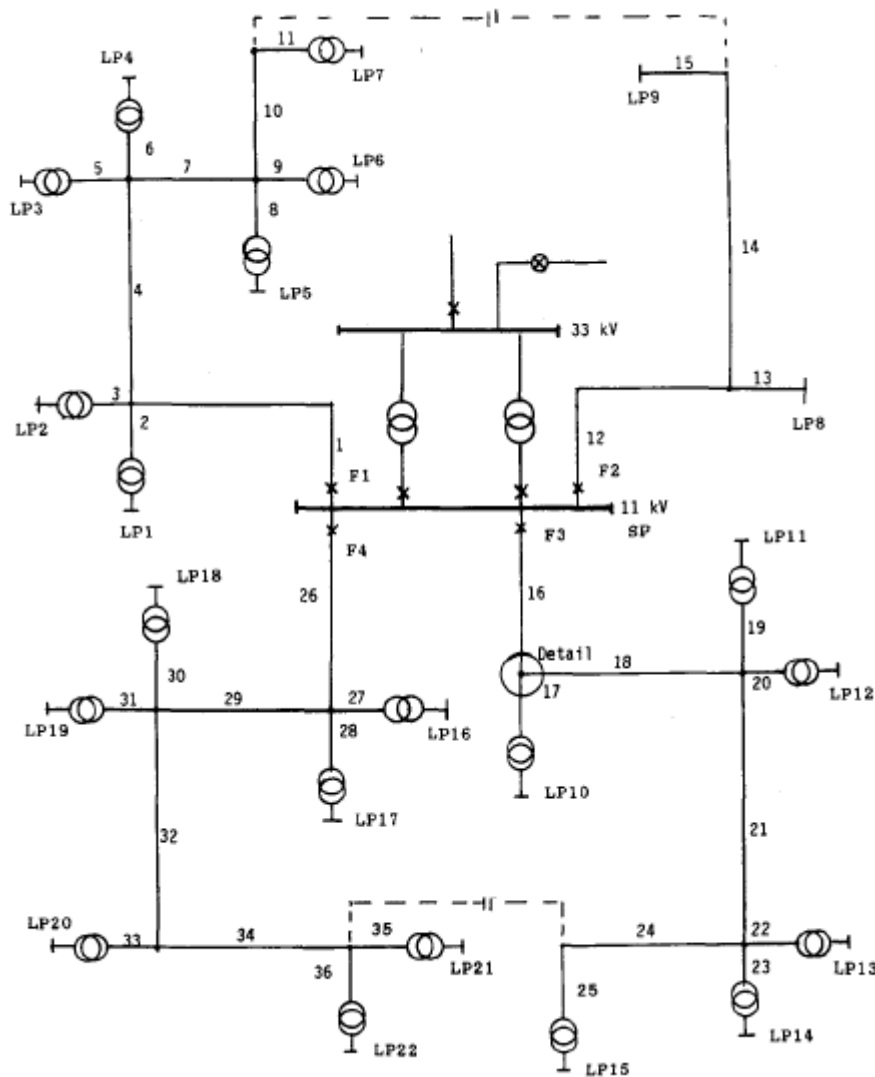


Figure 2.4 – Bus 2 of extended Billinton & Allan test net

I tried several times to run the analysis with all thermal limits set to 100%. During most of the project period I never managed to implements a thermal limit which properly impacting the summary ENS.

However, the first modeling period I was working in PF version 14.0. The later version 14.1 which I received at the end of my analysis working period has a more orderly way of setting thermal limits and analysis constraints. My final results from the 14.1 analysis are printed in table 2.5.

System		Summary
System Average Interruption Frequency Index	: SAIFI =	0,193218 1/Ca
Customer Average Interruption Frequency Index	: CAIFI =	0,193218 1/Ca
System Average Interruption Duration Index	: SAIDI =	4,421 h/Ca
Customer Average Interruption Duration Index	: CAIDI =	22,879 h
Average Service Availability Index	: ASAI =	0,9994953590
Average Service Unavailability Index	: ASUI =	0,0005046410
Energy Not Supplied	: ENS =	84,540 MWh/a
Average Energy Not Supplied	: AENS =	3,843 MWh/Ca
Average Customer Curtailment Index	: ACCI =	0,001 MWh/Ca
Expected Interruption Cost	: EIC =	0,000 M\$/a
Interrupted Energy Assessment Rate	: IEAR =	0,000 \$/kwh
System energy shed	: SES =	14,415 MWh/a
Average System Interruption Frequency Index	: ASIFI =	0,160617 1/a
Average System Interruption Duration Index	: ASIDI =	4,226872 h/a
Momentary Average Interruption Frequency Index	: MAIFI =	0,000000 1/Ca

Table 2.6 – Thermal limits upheld, without backup cables mitigating simulation of RBTS net

Here the 24MWh of lost power due to failures in the main transformers seems to be added properly to the 60MWh from the original. This makes me fairly confident in assuming that the reference analysis did not include these transformers in their original analysis. This is even though the RBTS report prints reliability analysis characteristics for these transformers as well as for the distribution transformers.

3 – Software Outline

This software sketch is loosely based on *IEEE Recommended Practices for Software Requirement Specification* (Tripp, 2009) and drawing from the experiences from analyzing the test nets. This software outline will very roughly outline an analytical tool for reliability analysis of distribution networks which is based on the RELRAD methodology. The working title for this software outline will be “RELRAD”.

The OPAL tool for power systems reliability analysis is looking to implement a coherent Nordic standard for logging and reporting failures in power systems. A tool for analyzing meshed networks is being developed, but a simpler tool for analyzing radial networks is also needed. The RELRAD is intended to be a part of the OPAL software cluster. Here it will serve as an analysis tool which operates well with Nordic standards for logging power system data. The tools intention is to make gathering of standardized Nordic data more easily analyzed and the results more relevant to companies who wants use them. Getting consistent data and analysis results will also make the results more appropriate for regulatory and decision making purposes.

It is also important to note that this software outline is by no means complete. It outlines the core changes and functions that are intended for RELRAD at this point. More on this is commented in the discussion.

3.1 – Software Overall Description

The RELRAD tool will be modeled to take on data provided in a FASIT form. This data will then be analyzed according to the RELRAD method described in chapter 1.2. However, a major addition to RELRAD will be the introduction of a power flow analysis which gives the software the possibility to analyze how distributed generation will affect the network. This function will have to be introduced under the “Avbrudd?” tile of the original RELRAD flow chart from fig. 1.1 but will also affect the other parts of the analysis. This will be described in more detail later. The analysis results will be outputted as the five basic RELRAD indices, probably a few customer indices which will be decided on later and a short analysis on how reliably the radial can operate as a power supplier to the surrounding grid.

3.2 – General Architecture of RELRAD

As mentioned before the main functionality of RELRAD will be centered on the RELRAD analysis method for radials. But since reliability analysis of DG can’t be done without some form of load flow analysis this will have to be implemented either through external software or programmed as a part of the software itself. The load flow enhanced RELRAD method proposed is shown in the flowchart presented in figure 4.1 below. The added “mitigation measures” is to check if the DG can supply parts of the grid after a sectioning has occurred behind the fallout of the circuit breaker zone.

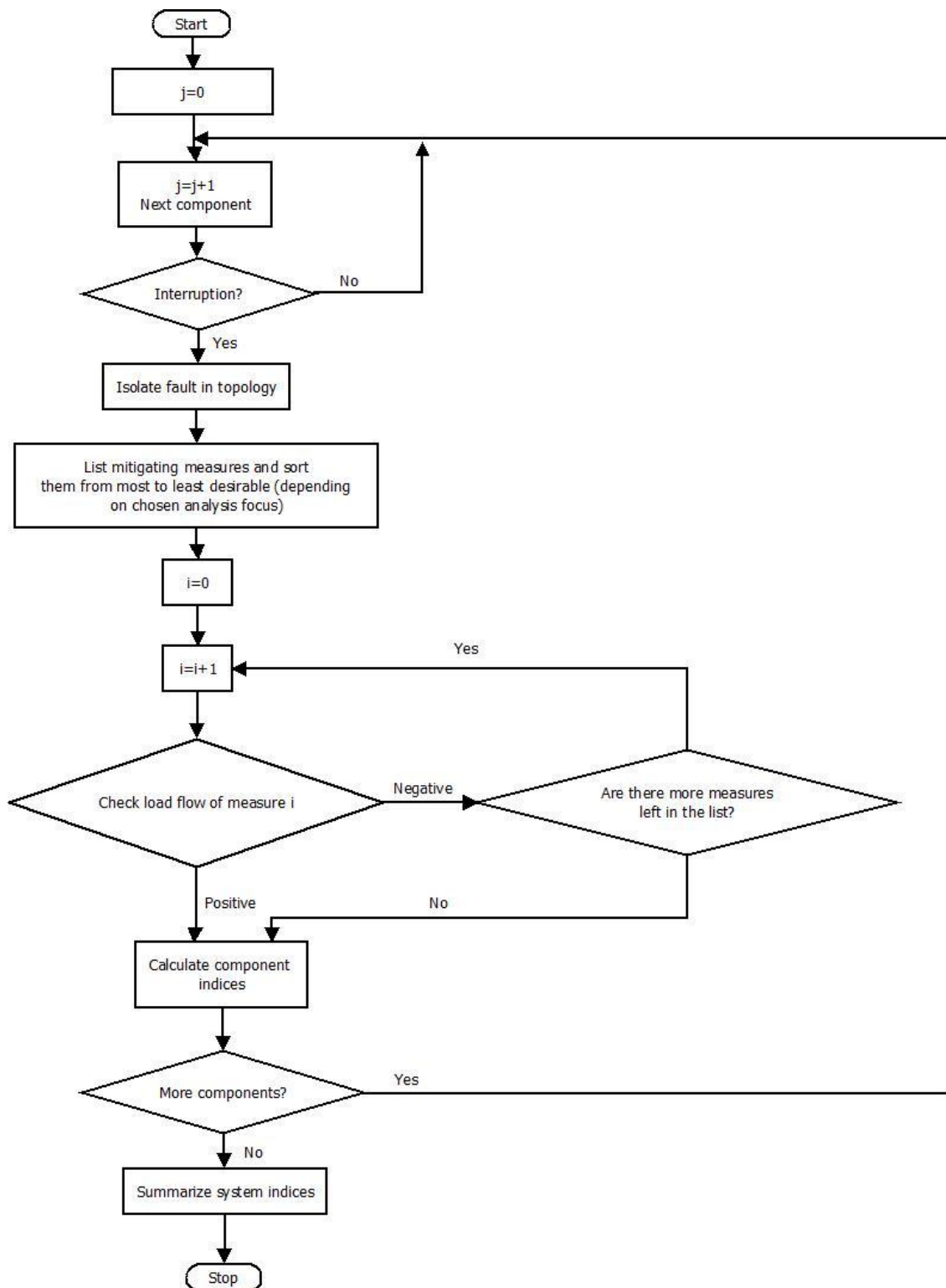


Figure 3.1 – Extended RELRAD flowchart

This mitigation will also include the old RELRAD measures such as sectioning off faulted branches and open reserve supply connections. Next step is to list all the accumulated mitigation measures. A simple connectivity analysis will check measures on the list against an objective function (minimize loss, minimize load shed, minimize costs etc.). The order in the flowchart in which the “list mitigation” box and the “load flow check” box is chosen to what is perceived to require the smallest run time by reducing the amount of load flow analysis the program will have to compute. The architecture is not necessarily optimized from an algorithm point of view, and the runtime has a potential of growing exponentially with the number of components. This is not desirable, but optimizing the algorithm for runtime purposes is outside the scope of this report.

Topology

The topology implementation is done will depend on what kind of load flow alternative is used. An extended external load flow code will potentially impose a certain form on which it demands the topology it’s analyzing. If the power flow analysis is to be performed by the RELRAD itself then an adjacency matrix of the components might be sufficient. Ideally the format on which the topology is implemented in should be compatible with OPAL.

Checks

The methodology used by the RELRAD comes with conditions to the input. It is important to have a robust set of control measures to ensure you are analyzing a grid that is entered in an analyzable format and which is within the constraints and assumptions of the extended RELRAD methodology.

List Mitigating Measures

The mitigating measures box from flowchart 4.1 is difficult to be very specific about. The mitigating options after sectioning out a fault in a radial net are the following:

- Section of feeder to an isolated load if the feeder is faulted thus restoring the rest of the grid.
- If a fault is isolated such that a part of the radial connected to a backup cable is left unpowered the backup cable could restore power.
- If a fault is isolated such that a part of the radial containing some sort of separate generation this could try to supply the whole disconnected part of the grid or parts of it.
- A combination of the above, especially for a second order analysis.

Load Flow Check

Initially, this step was intended solely to check whether or not the grid components were within their load flow limits. There is, however, a case to be made for including small tap changing mechanism. This mechanism would check to see if a good mitigating measure discarded because it’s not within suggested voltage levels can be used with a tap change on a transformer. The possibility of doing this will be looked at more closely at a later state in the process. If OPAL itself can provide a load flow analysis this would be the ideal option.

3.3 – Software Functions

The vital functions which must be performed by the program

- a) The system shall compute and present the five indexes defined in equation (1) to (5) in chapter 1 for all load points in the system. The analysis will be performed according to the extended RELRAD methodology depicted in the flowchart in figure 4.1.
- b) The system shall check the provided topology and find out if it describes a radial net as defined in table 1.1 (*Definitions*). If not an error message will be displayed highlighting the parallel connections.
- c) The system shall check all parameters for validity
 - a. All non-cost related parameters must be positive and on the correct form.
 - b. Check if lines and nodes are belonging to the same voltage subset.
- d) The system shall be able to perform a load flow analysis and check if results are within specified limits.
- e) The system shall be able to determine the optimal mitigating measures if given a proper objective function.
- f) The system shall be able produce an orderly interface for inputting variables and reading analysis results.

3.4 – RELRAD Input and Output List

The list of RELRAD input and output suggestions. Generators are left to be implemented in as basic a form as possible, but this could change if a more realistic model of the generator is needed. The protection devices are intended to be defined with a type 2 fault (definitions table 1.1) statistics. Type 3 faults in protective devices could be relevant to an analysis

Inputs:

- Topology (placement)
 - Circuit breakers
 - Disconnectors
 - Transformers
 - Load points
 - Supply points
 - Generators
 - Lines
 - Nodes/Busbars
 - Main grid

- Component
 - Line
 - Fault frequency [1/a]
 - Repair cost [currency]
 - Repair duration [hours]
 - Line length [km]
 - Thermal limits [MVA]
 - Impedance [Ω /km]
 - Rated voltage [kV]
 - Transformer
 - Fault frequency [1/a]
 - Repair cost [currency]
 - Repair duration [hours]
 - Thermal limits [MVA]
 - Impedance [Ω /km]
 - HV/LV voltage levels [kV/kV]
 - Load
 - Load [MW]
 - Power Factor
 - Amount of customers
 - Customer type [Agriculture, Industry, Household, etc.]
 - ENS cost [currency/MWh]
 - Priority (optional)
 - Power factor (optional)
 - Load states (optional)
 - Generators
 - Fault frequency [1/a]
 - Repair cost [currency]
 - Repair duration [hours]
 - Output voltage [kV]
 - Dispatch [MW, MVAR]
 - Operational limits [MW, MVAR]
 - Generation cost [currency/MWh]
 - Shutdown/startup cost (optional) [currency]
 - Minimum up-time/minimum downtime (optional) [currency]
 - Priority (optional)
 - Grid
 - Short circuit impedance (optional) [Ω]
 - Capacity [MW, MVAR]
 - Rated voltage [kV]
 - Repair cost [currency]
 - Repair duration [hours]

- Protection devices
 - Type 2 fault frequency [1/a]
 - Repair duration [1/a]
 - Repair cost [currency]
- Nodes/Busbars
 - Fault frequency [1/a] (optional)
 - Repair cost [currency] (optional)
 - Repair duration [hours] (optional)
- Analysis
 - Sectioning time [h]
 - Basic options
 - Connectivity analysis
 - Load flow analysis
 - Distribution analysis
 - Transmission analysis
 - Load flow options (to be determined)
 - Order of fault analysis
 - Select components which are to be included in the reliability analysis

Output:

- Topology
 - Load flow analysis of lines
 - Validity check
- Load point
 - Interruption frequency [1/a]
 - ENS [MWh]
 - Expected outage duration, U [h]
 - Interrupted power [MW]
 - Mean outage duration [h]
- Generator
 - ENS to grid (optional) [MWh]
 - Possibly some sort of supply index indicating how much the generator contributes to reducing load point ENS (calculated from some base scenario) (optional)

4 - Discussion

The main points of discussion in this section will be with regards to the outline of the eventual RELRAD software. This outline is very rough and a lot will probably be changed once the actual implementation is started. However, these are discussion points that I mean are relevant to the development process.

4.1 – Employing external software for power flow analysis

After modeling grids with more than 30 nodes the amount of calculations taking place soon becomes substantial. In PF this appears to be due to optimal power flow algorithms and power flow analysis which is performed at every instance in the contingency list. This list itself grows exponentially if second order fallouts are to be considered. Finding an algorithm which does this effectively could therefore determine whether or not the software can be utilized in practice. As a side note to this it should be mentioned that if OPAL could be used to perform load flow analysis this would ease the eventual process of merging the two.

The drawback with implementing an external analysis tool is that it might require a standardized input. This could be especially challenging for implementation of topology in RELRAD.

4.2 – Implementation Distributed Generation

A subject which is discussed in the original Sintef software outline (Samdal, Kjølle, & Gjerde, 2006), but is not included in the RELRAD method defined in “Planleggingsbok for kraftnett” (SINTEF, 2010) is the behavior of the distributed generation in radial networks. After the sectioning is conducted in the RELRAD model mitigating measures has to be considered. If the generator can’t produce separately a straight forward RELRAD analysis can be done. However, if the generator is able to maintain a sufficient quality of supply while the radial is cut off from the main grid the analysis becomes more complicated. This scenario makes introducing some sort of load flow analysis necessary.

4.3 – EMS for Distributed Generators

In general a common Scandinavian distribution radial is not intended, structured or dimensioned for power production placed throughout the line. The radials will also, in general, have prospects of diminishing load due to emigration and an increase in DG suppliers who are interested in selling electricity to the central grid. Given such an environment a reliability analysis could not only be performed to check if the customers in the radial will be receiving a proper quality of supply, but also to check what kind of reliability the DG in the radial can supply the transmission grid with. This could easily be implemented as the analysis will be broadly the same as with analyzing load points.

4.4 – Choice of Test Nets

The test nets presented in this report are chosen from a few grids that were available. In hindsight there is a case to be made for including one or more larger grids with more load, less connectivity and only some production. This would give a better understanding of the problems related to implementing a reliability analysis with DG options. A better selection of grids was difficult to spot at the beginning of the project when the impact of including distributed generation was not known. The inclusion of load flow in the RELRAD software was not thought of either.

4.5 – The Layout and Form of the Software Outline

The software outline included in this report is by no means a complete SRS as according to the IEEE report (Tripp, 2009). First it was intended to create an overall SRS for RELRAD, but a good SRS for the RELRAD method already exists in “Planleggingsbok for kraftnett” (SINTEF, 2010). Judging from this, it seemed more constructive to focus on the specific changes from the original RELRAD and how these were going to be implemented. Also, including the few specifics that was possible to be somewhat certain about such as input values and imperative functions. This is why a software outline was chosen instead

4.6 – Providing a Transparent Analysis

One of the major problems I encountered when operating PF was to get clear view of whether the parameters I implemented were being used or not used for and in what part of the analysis they were being used. An example from PF is how thermal ratings were being utilized. In the “Basic Data” implementation window for a component (i.e. transformer or line) a thermal limit was set for a certain type of equipment. In the “Load Flow” window for the same component a limit could be set on to what extent the component could be over thermally overloaded (i.e. “limited to max. 120% of thermal rating”). This same limit can be defined in the “Constraints” window for the reliability assessment and set as a time dependent vector (i.e. can handle a 120% overload for 1h or 130% for 0,5h). At the same time a constraint can be set on maximum amount of current allowed through the same component which could be interpreted as the same thing in a fixed voltage line. Knowing which limit was trumping which was very difficult to clarify when modeling. The extended Allan & Billinton test net is the best example I have for this problem. The two transformers became major bottlenecks in the two contingency cases where one of them was faulted. I tried a sensitivity analysis of thermal ratings for the 33/11kV-type transformers, but very few of the analysis throughputs came out as expected (i.e. a rapid increase in ILE for low thermal ratings). These kind of problems often manifested themselves. A single power flow analysis with a component overloaded 110% could turn out as not valid. The same case could apparently be counted as valid (using other thermal limits) in the reliability power flow analysis conducted as a part of the contingency list run through.

There has been sent a lot of emails to DigSILENT about this subject, and in the later version 14.1 there is a more extensive explanation of the technicalities behind the reliability analysis in the manual. There is also done some changes with regard to how limits are presented in the analysis option in the new PF 14.1. The importance of maintaining a clear connection between inputs and where these inputs are used later will be an emphasis in the RELRAD.

Conclusion

This report first tried to discover how big discrepancies there were between different methods of doing reliability analysis and why these discrepancies occurs. The chosen methods were RELRAD and the software solution PowerFactory. For most of the simulations the results matched sufficiently after enough work was put into the models. The discrepancies that were found were given reasonable explanations. The Allan & Billinton test net with distributed wind had some exceptions, but considering the uncertainty surrounding the load point data the results were accepted. This was particularly due to the Excel RELRAD simulations that turned produced an almost identical ENS in the end.

After considering the different reliability analysis methods a software outline was created for the purpose of creating a MATLAB based reliability analysis tool which was given the working title RELRAD. It was suggested that distributed generation was one of the biggest new problems when it comes to analyzing reliability in distribution nets. For this reason it was decided that the RELRAD software had to be able to include distributed generation in its analysis in order to be relevant in the future. In order to do this in a satisfactory, some form or other of load flow analysis would inevitably have to be included. A new algorithm was devised to add this feature to the software.

Finally, a discussion was conducted on why transparency is important to analysis software. The benefits of adding more indices describing distributed generator performance reliability wise were also explored.

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APPENDIX

Name	TCIT Ch/a	TCIF C/a	AID h	LPENS Mwh/a	LPEIC \$/a	ACIF 1/a	ACIT h/a
LP22	3,58	0,25	14,37	2,68	0,00	0,25	3,58
LP21	3,58	0,25	14,37	3,28	0,00	0,25	3,58
LP13	3,58	0,25	14,37	3,28	0,00	0,25	3,58
LP14	3,58	0,25	14,37	3,28	0,00	0,25	3,58
LP7	3,58	0,25	14,37	2,68	0,00	0,25	3,58
LP6	3,58	0,25	14,37	2,68	0,00	0,25	3,58
LP5	3,58	0,25	14,37	3,28	0,00	0,25	3,58
LP3	3,54	0,21	16,85	3,07	0,00	0,21	3,54
LP12	3,53	0,20	17,62	2,57	0,00	0,20	3,53
LP11	3,53	0,20	17,62	3,06	0,00	0,20	3,53
LP15	3,50	0,24	14,63	2,62	0,00	0,24	3,50
LP19	3,49	0,16	21,64	2,54	0,00	0,16	3,49
LP20	3,49	0,16	21,64	3,20	0,00	0,16	3,49
LP2	3,49	0,16	21,64	3,02	0,00	0,16	3,49
LP4	3,46	0,20	17,28	3,17	0,00	0,20	3,46
LP16	3,44	0,11	30,58	2,58	0,00	0,11	3,44
LP18	3,41	0,15	22,52	2,49	0,00	0,15	3,41
LP1	3,41	0,15	22,51	2,96	0,00	0,15	3,41
LP17	3,36	0,10	32,72	2,45	0,00	0,10	3,36
LP10	3,36	0,10	32,72	2,91	0,00	0,10	3,36
LP9	0,48	0,14	3,50	0,90	0,00	0,14	0,48
LP8	0,48	0,14	3,50	0,78	0,00	0,14	0,48

A.1 – Load point PF analysis results from bus 2 in extended test net (RBTS) with backup

Load Name	TCIT Ch/a	TCIF C/a	AID h	LPENS Mwh/a	LPEIC \$/a	ACIF 1/a	ACIT h/a
LP22	4,87	0,25	19,57	3,65	0,00	0,25	4,87
LP7	4,87	0,25	19,57	3,65	0,00	0,25	4,87
LP21	4,87	0,25	19,57	4,47	0,00	0,25	4,87
LP15	4,79	0,24	20,05	3,60	0,00	0,24	4,79
LP6	4,60	0,25	18,48	3,45	0,00	0,25	4,60
LP5	4,60	0,25	18,48	4,22	0,00	0,25	4,60
LP14	4,53	0,25	18,20	4,15	0,00	0,25	4,53
LP13	4,53	0,25	18,20	4,15	0,00	0,25	4,53
LP3	4,22	0,21	20,10	3,66	0,00	0,21	4,22
LP12	4,21	0,20	21,03	3,07	0,00	0,20	4,21
LP11	4,21	0,20	21,03	3,65	0,00	0,20	4,21
LP19	4,17	0,16	25,87	3,04	0,00	0,16	4,17
LP20	4,17	0,16	25,87	3,82	0,00	0,16	4,17
LP4	4,14	0,20	20,69	3,80	0,00	0,20	4,14
LP18	4,09	0,15	27,02	2,98	0,00	0,15	4,09
LP2	3,83	0,16	23,75	3,32	0,00	0,16	3,83
LP16	3,78	0,11	33,61	2,84	0,00	0,11	3,78
LP1	3,75	0,15	24,77	3,25	0,00	0,15	3,75
LP17	3,70	0,10	36,04	2,70	0,00	0,10	3,70
LP10	3,70	0,10	36,04	3,21	0,00	0,10	3,70
LP9	1,09	0,14	8,00	2,04	0,00	0,14	1,09
LP8	0,82	0,14	6,00	1,33	0,00	0,14	0,82

A.2 – Load point PF analysis results from bus 2 in extended test net (RBTS) , without backup

Smart Grids and Reliability Analysis in Distribution Networks

LoadInt Name	TCIT Ch/a	TCIF C/a	AID h	LPENS Mwh/a	LPEIC \$/a	ACIF l/a	ACIT h/a
LP1	3,75	0,15	24,77	3,23	0,00	0,15	3,75
LP2	3,83	0,16	23,75	3,30	0,00	0,16	3,83
LP3	4,22	0,21	20,10	3,26	0,00	0,21	4,22
LP4	4,14	0,20	20,69	3,78	0,00	0,20	4,14
LP5	4,60	0,25	18,48	4,20	0,00	0,25	4,60
LP6	4,60	0,25	18,48	3,44	0,00	0,25	4,60
LP7	4,87	0,25	19,57	3,64	0,00	0,25	4,87
LP8	4,41	0,17	26,47	7,12	0,00	0,17	4,41
LP9	4,69	0,17	28,10	7,47	0,00	0,17	4,69
LP10	3,70	0,10	36,04	2,93	0,00	0,10	3,70
LP11	4,21	0,20	21,03	3,30	0,00	0,20	4,21
LP12	6,72	0,22	33,82	4,87	0,00	0,22	6,72
LP13	4,53	0,25	18,20	3,79	0,00	0,25	4,53
LP14	4,53	0,25	18,20	4,10	0,00	0,25	4,53
LP15	4,79	0,24	20,05	3,59	0,00	0,24	4,79
LP16	3,78	0,11	33,61	2,54	0,00	0,11	3,78
LP17	3,70	0,10	36,04	2,68	0,00	0,10	3,70
LP18	4,09	0,15	27,02	2,74	0,00	0,15	4,09
LP19	4,17	0,16	25,87	3,02	0,00	0,16	4,17
LP20	4,17	0,16	25,87	3,80	0,00	0,16	4,17
LP21	4,87	0,25	19,57	4,09	0,00	0,25	4,87
LP22	4,87	0,25	19,57	3,64	0,00	0,25	4,87

A.3 – LP PF analysis results from bus 2 in extended test net (RBTS) , with proper thermal limits

LoadInt Name	TCIT Ch/a	TCIF C/a	AID h	LPENS Mwh/a	LPEIC \$/a	ACIF l/a	ACIT h/a
L63040	9,44	5,77	1,64	0,39	0,00	5,77	9,44
L63050	9,21	5,74	1,60	0,54	0,00	5,74	9,21
L63060	9,06	5,72	1,58	0,14	0,00	5,72	9,06
L78300	8,85	5,69	1,55	0,48	0,00	5,69	8,85
L63070	8,82	5,69	1,55	0,26	0,00	5,69	8,82
L78030	8,82	5,68	1,55	0,05	0,00	5,68	8,82
L78305	8,82	5,69	1,55	0,04	0,00	5,69	8,82
L63080	8,80	5,68	1,55	0,27	0,00	5,68	8,80
L78010	8,80	5,68	1,55	0,50	0,00	5,68	8,80
L78290	8,80	5,68	1,55	0,01	0,00	5,68	8,80
L80450	8,79	5,67	1,55	0,18	0,00	5,67	8,79
L78020	8,78	5,68	1,55	0,32	0,00	5,68	8,78
L78050	8,78	5,68	1,55	0,04	0,00	5,68	8,78
L80230	8,77	5,68	1,55	0,09	0,00	5,68	8,77
L78140	8,77	5,68	1,55	0,45	0,00	5,68	8,77
L63020	8,77	5,68	1,55	0,05	0,00	5,68	8,77
L78165	8,77	5,68	1,55	0,26	0,00	5,68	8,77
L63170	8,77	5,66	1,55	0,66	0,00	5,66	8,77
L78200	8,77	5,67	1,55	0,41	0,00	5,67	8,77
L78160	8,77	5,67	1,55	0,50	0,00	5,67	8,77
L80490	8,77	5,67	1,55	0,40	0,00	5,67	8,77
L78490	8,77	5,67	1,54	0,31	0,00	5,67	8,77
L78350	8,76	5,67	1,54	0,25	0,00	5,67	8,76
L80390	8,76	5,67	1,54	0,11	0,00	5,67	8,76
L78080	8,76	5,67	1,54	0,18	0,00	5,67	8,76
L63030	8,75	5,67	1,54	0,16	0,00	5,67	8,75
L78210	8,75	5,67	1,54	0,32	0,00	5,67	8,75
L78090	8,75	5,67	1,54	0,46	0,00	5,67	8,75
L63090	8,75	5,67	1,54	0,14	0,00	5,67	8,75
L80430	8,75	5,67	1,54	0,12	0,00	5,67	8,75
L78040	8,75	5,67	1,54	0,03	0,00	5,67	8,75
L78190	8,75	5,67	1,54	0,28	0,00	5,67	8,75
L78270	8,75	5,67	1,54	0,31	0,00	5,67	8,75
L80290	8,75	5,67	1,54	0,17	0,00	5,67	8,75
L78130	8,74	5,67	1,54	0,08	0,00	5,67	8,74
L78070	8,73	5,67	1,54	0,10	0,00	5,67	8,73

Smart Grids and Reliability Analysis in Distribution Networks

L78100	8,73	5,66	1,54	0,37	0,00	5,66	8,73
L80455	8,73	5,66	1,54	0,28	0,00	5,66	8,73
L78180	8,73	5,66	1,54	0,17	0,00	5,66	8,73
L78060	8,73	5,66	1,54	0,27	0,00	5,66	8,73
L80200	8,72	5,66	1,54	0,08	0,00	5,66	8,72
L80210	8,72	5,66	1,54	0,50	0,00	5,66	8,72
L63110	8,72	5,66	1,54	0,05	0,00	5,66	8,72
L80360	8,72	5,66	1,54	0,32	0,00	5,66	8,72
L78170	8,72	5,66	1,54	0,73	0,00	5,66	8,72
L78110	8,71	5,66	1,54	0,27	0,00	5,66	8,71
L78760	8,71	5,66	1,54	0,27	0,00	5,66	8,71
L78440	8,71	5,66	1,54	0,13	0,00	5,66	8,71
L78120	8,71	5,66	1,54	0,19	0,00	5,66	8,71
L63120	8,71	5,66	1,54	0,22	0,00	5,66	8,71
L78150	8,70	5,66	1,54	0,11	0,00	5,66	8,70
L78750	8,70	5,66	1,54	0,39	0,00	5,66	8,70
L78730	8,70	5,65	1,54	0,74	0,00	5,65	8,70
L80190	8,69	5,65	1,54	0,04	0,00	5,65	8,69
L78770	8,69	5,65	1,54	0,31	0,00	5,65	8,69
L63010	8,69	5,65	1,54	0,05	0,00	5,65	8,69
L78670	8,69	5,65	1,54	0,10	0,00	5,65	8,69
L78500	8,69	5,65	1,54	0,35	0,00	5,65	8,69
L78745	8,68	5,65	1,54	0,07	0,00	5,65	8,68
L78700	8,68	5,65	1,54	0,37	0,00	5,65	8,68
L80480	8,68	5,65	1,54	0,10	0,00	5,65	8,68
L78740	8,68	5,65	1,54	0,17	0,00	5,65	8,68
L63100	8,67	5,65	1,54	0,18	0,00	5,65	8,67
L78710	8,67	5,65	1,54	0,05	0,00	5,65	8,67
L78890	8,67	5,64	1,54	0,83	0,00	5,64	8,67
L78570	8,66	5,64	1,53	0,31	0,00	5,64	8,66
L78720	8,66	5,64	1,53	0,25	0,00	5,64	8,66
L78990	8,66	5,64	1,53	0,27	0,00	5,64	8,66
L78880	8,65	5,64	1,53	0,21	0,00	5,64	8,65
L78660	8,65	5,64	1,53	0,22	0,00	5,64	8,65
L80180	8,65	5,64	1,53	0,16	0,00	5,64	8,65
L78870	8,65	5,64	1,53	0,21	0,00	5,64	8,65
L78810	8,65	5,64	1,53	0,30	0,00	5,64	8,65
L80400	8,65	5,64	1,53	0,28	0,00	5,64	8,65
L80220	8,64	5,63	1,53	0,41	0,00	5,63	8,64
L78780	8,64	5,64	1,53	0,57	0,00	5,64	8,64
L78860	8,64	5,64	1,53	0,13	0,00	5,64	8,64
L78800	8,63	5,64	1,53	0,35	0,00	5,64	8,63
L63140	8,63	5,64	1,53	0,14	0,00	5,64	8,63
L78930	8,63	5,64	1,53	0,18	0,00	5,64	8,63
L63130	8,63	5,63	1,53	0,22	0,00	5,63	8,63
L80320	8,63	5,64	1,53	0,23	0,00	5,64	8,63
L78830	8,63	5,63	1,53	0,40	0,00	5,63	8,63
L80350	8,63	5,64	1,53	0,16	0,00	5,64	8,63
L78920	8,63	5,63	1,53	0,16	0,00	5,63	8,63
L78850	8,62	5,63	1,53	0,18	0,00	5,63	8,62
L78820	8,62	5,63	1,53	0,16	0,00	5,63	8,62
L80300	8,62	5,63	1,53	0,26	0,00	5,63	8,62
L80470	8,61	5,63	1,53	0,18	0,00	5,63	8,61
L80370	8,61	5,63	1,53	0,47	0,00	5,63	8,61
L78910	8,61	5,63	1,53	0,22	0,00	5,63	8,61
L78640	8,61	5,63	1,53	0,37	0,00	5,63	8,61
L78900	8,61	5,63	1,53	0,28	0,00	5,63	8,61
L80420	8,61	5,63	1,53	0,11	0,00	5,63	8,61
L80260	8,61	5,63	1,53	0,18	0,00	5,63	8,61
L78980	8,61	5,63	1,53	1,05	0,00	5,63	8,61
L78840	8,60	5,63	1,53	0,22	0,00	5,63	8,60
L80250	8,60	5,63	1,53	0,35	0,00	5,63	8,60
L78940	8,59	5,63	1,53	0,29	0,00	5,63	8,59
L63180	8,58	5,62	1,53	0,01	0,00	5,62	8,58

A.4 – PF simulation of load point indices for line A

Smart Grids and Reliability Analysis in Distribution Networks

punkt	avbrudd	varighet	avbr.tid	effekt	energi	
navn.	pr. år	timer/avbr.	timer	<kw>	<kwh>	<kk>
T78980	5.616	1.20	6.73	352.409	422.293	28.373
T78170	5.617	1.72	9.65	241.032	414.207	19.002
T78830	5.618	1.26	7.09	131.724	166.189	9.468
T78110	5.604	1.60	8.97	89.860	143.825	8.150
T80210	5.604	1.44	8.10	163.289	235.926	6.789
T78730	5.620	1.44	8.12	245.942	355.176	6.660
T78300.2	5.604	1.74	9.75	45.547	79.206	5.689
T80370	5.604	1.31	7.33	154.324	201.908	5.101
T80455	5.641	1.74	9.82	94.146	163.835	4.289
T78750	5.604	1.50	8.41	92.655	138.992	3.487
T78670	5.616	1.44	8.08	30.392	43.736	3.191
T80400	5.604	1.34	7.51	91.400	122.447	3.066
T80360	5.604	1.60	8.99	107.526	172.390	2.989
T78160	5.604	1.72	9.63	163.300	280.687	2.844
T63050	5.705	1.84	10.50	171.113	314.994	2.841
T63170	5.616	1.46	8.21	217.517	318.099	2.726
T78300.1	5.604	1.74	9.75	110.719	192.541	2.605
T78745	5.616	1.44	8.06	24.027	34.486	2.516
T78010	5.616	1.77	9.93	164.715	291.371	2.462
T78200	5.604	1.72	9.63	136.880	235.276	2.458
T78920	5.604	1.25	6.98	52.887	65.888	2.431
T78900	5.616	1.20	6.71	90.776	108.528	2.415
T78080	5.604	1.71	9.57	60.613	103.473	2.363
T80470	5.604	1.26	7.06	61.125	76.966	2.338
T78140	5.604	1.77	9.92	145.916	258.287	1.961
T63070	5.628	1.76	9.88	87.099	152.963	1.930
T80450	5.641	1.73	9.75	57.016	98.578	1.893
T78090	5.604	1.71	9.57	143.066	244.228	1.799
T63040	5.705	1.84	10.50	119.927	220.769	1.776
T78100	5.604	1.60	8.97	120.309	192.559	1.763
T80490	5.604	1.77	9.92	129.081	228.487	1.735
T78990	5.604	1.31	7.33	90.424	118.304	1.672
T80350	5.604	1.31	7.33	52.525	68.721	1.661
T78890	5.626	1.20	6.76	277.403	333.375	1.595
T78440	5.604	1.72	9.63	43.342	74.498	1.464
T80190	5.604	1.45	8.11	13.690	19.799	1.444
T78780	5.604	1.34	7.51	189.536	253.918	1.438
T78490	5.604	1.77	9.92	101.238	179.200	1.415
T78020	5.604	1.77	9.92	102.557	181.536	1.378
T78210	5.604	1.72	9.63	106.488	183.036	1.359
T78710	5.604	1.45	8.11	18.250	26.394	1.335
T80300	5.604	1.26	7.06	85.680	107.884	1.328
T78500	5.604	1.45	8.11	114.902	166.179	1.302
T78940	5.604	1.17	6.56	97.497	114.085	1.242
T78060	5.604	1.71	9.57	88.797	151.584	1.195
T63080	5.617	1.74	9.79	90.663	158.034	1.187
T78190	5.604	1.72	9.63	91.873	157.916	1.172
T78700	5.604	1.45	8.11	125.179	181.042	1.131
T78270	5.604	1.60	8.99	100.047	160.399	1.117
T78165	5.604	1.72	9.63	87.342	150.126	1.114
T78350	5.604	1.72	9.63	82.623	142.015	1.054
T78770	5.604	1.44	8.07	102.940	148.172	0.921
T78760	5.604	1.50	8.41	88.201	132.311	0.862
T63120	5.604	1.60	8.97	72.389	115.862	0.806
T78150	5.604	1.51	8.44	36.721	55.332	0.786
T78800	5.604	1.26	7.06	119.164	150.047	0.774
T78570	5.604	1.34	7.51	101.884	136.492	0.773
T80220	5.604	1.20	6.71	135.792	162.641	0.772
T78720	5.604	1.45	8.11	84.337	121.973	0.762
T63060	5.705	1.84	10.50	50.675	93.286	0.750
T78180	5.604	1.72	9.63	57.674	99.132	0.736
T80310	5.604	1.26	7.06	95.792	120.617	0.718
T80290	5.604	1.71	9.57	54.448	92.948	0.685
T63030	5.604	1.71	9.57	53.203	90.823	0.669
T78640	5.617	1.17	6.58	122.953	144.095	0.654
T78810	5.604	1.26	7.06	99.715	125.558	0.648
T78120	5.604	1.51	8.44	63.191	95.219	0.623
T80430	5.604	1.72	9.63	40.176	69.056	0.604
T80250	5.604	1.12	6.28	118.935	133.294	0.599
T63090	5.604	1.71	9.57	46.476	79.340	0.584

Smart Grids and Reliability Analysis in Distribution Networks

T78660	5.604	1.34	7.51	72.925	97.696	0.553
T78740	5.604	1.44	8.07	57.864	83.289	0.518
T78870	5.617	1.31	7.36	69.795	91.403	0.502
T80320	5.604	1.25	6.98	78.902	98.298	0.498
T80390	5.604	1.72	9.63	38.824	66.732	0.495
T78880	5.604	1.31	7.33	67.657	88.518	0.485
T78840	5.604	1.12	6.28	74.163	83.117	0.483
T63130	5.618	1.26	7.08	71.087	89.653	0.464
T80260	5.604	1.31	7.33	60.659	79.362	0.434
T63100	5.604	1.44	8.07	48.241	69.438	0.432
T78850	5.604	1.31	7.33	59.356	77.657	0.425
T78910	5.604	1.19	6.68	71.673	85.400	0.400
T78070	5.604	1.71	9.57	30.732	52.462	0.386
T80230	5.604	1.72	9.64	28.446	48.914	0.378
T78930	5.604	1.25	6.98	59.673	74.341	0.377
T80180	5.604	1.31	7.33	51.738	67.690	0.371
T63140	5.604	1.34	7.51	45.764	61.309	0.347
T78820	5.604	1.26	7.06	52.296	65.849	0.340
T80200	5.604	1.60	8.99	26.561	42.583	0.297
T80480	5.604	1.45	8.11	30.312	43.838	0.294
T78860	5.604	1.31	7.33	39.444	51.605	0.283
T78130	5.604	1.60	8.99	24.758	39.692	0.276
T78030	5.604	1.80	10.10	18.612	33.530	0.258
T63180	5.604	1.12	6.28	2.956	3.313	0.248
T80420	5.604	1.26	7.06	37.610	47.357	0.244
T63020	5.604	1.77	9.92	16.259	28.781	0.219
T78305	5.616	1.74	9.76	15.065	26.193	0.196
T63110	5.604	1.60	8.97	17.056	27.299	0.190
T78050	5.604	1.77	9.92	13.414	23.745	0.180
T63010	5.604	1.50	8.41	16.072	24.110	0.157
T78040	5.604	1.77	9.92	10.320	18.268	0.139
T78290	5.604	1.74	9.77	2.964	5.167	0.039
XXXXXX-22A	0.006	2.08	0.01	0.000	0.000	0.000

Sum	5.556	1.51	8.38	8712.252	12969.163	198.347

A.5 – NetBas reference for anonymous line A

Smart Grids and Reliability Analysis in Distribution Networks

Load [MW]		2	2	1,5	2
		LP A	LP B	LP C	LP D
Section 1	Outage Freq. [f/y]	0,2	0,2	0,2	0,2
Section 2		0,1	0,1	0,1	0,1
Section 3		0,3	0,3	0,3	0,3
Section 4		0,2	0,2	0,2	0,2
Lateral a		0,2	0,2	0,2	0,2
Lateral b		0,6	0,6	0,6	0,6
Lateral c		0,4	0,4	0,4	0,4
Lateral d		0,2	0,2	0,2	0,2
Sum		2,2	2,2	2,2	2,2

		LP A	LP B	LP C	LP D
Section 1	Repair/Sectioning [h/f]	4	4	0,5	0,5
Section 2		0,5	4	0,5	0,5
Section 3		0,5	0,5	4	0,5
Section 4		0,5	0,5	0,5	4
Lateral a		2	0	0	0
Lateral b		0	2	0	0
Lateral c		0	0	2	0
Lateral d		0	0	0	2
Sum		7,5	11	7,5	7,5

		LP A	LP B	LP C	LP D
Section 1	Avrg. Outage [h/y] Out Freq*Out Time	0,8	0,8	0,1	0,1
Section 2		0,05	0,4	0,05	0,05
Section 3		0,15	0,15	1,2	0,15
Section 4		0,1	0,1	0,1	0,8
Lateral a		0,4	0	0	0
Lateral b		0	1,2	0	0
Lateral c		0	0	0,8	0
Lateral d		0	0	0	0,4
Sum		1,5	2,65	2,25	1,5
ENS [MWh]		3	5,3	2,65	3
Sum ENS [MWh]		13,95			

A.6 - Allan and Billinton Test Net for Educational Purposes with 100% up-time and separate generation for windmill

Smart Grids and Reliability Analysis in Distribution Networks

Load [MW]		2	2	1,5	2
		LP A	LP B	LP C	LP D
Section 1	Outage Freq. [f/y]	0,2	0,2	0,2	0,2
Section 2		0,1	0,1	0,1	0,1
Section 3		0,3	0,3	0,3	0,3
Section 4		0,2	0,2	0,2	0,2
Lateral a		0,2	0,2	0,2	0,2
Lateral b		0,6	0,6	0,6	0,6
Lateral c		0,4	0,4	0,4	0,4
Lateral d		0,2	0,2	0,2	0,2
Sum		2,2	2,2	2,2	2,2

		LP A	LP B	LP C	LP D
Section 1	Repair/Sectioning [h/f]	4	4	4	4
Section 2		0,5	4	4	4
Section 3		0,5	0,5	4	4
Section 4		0,5	0,5	0,5	4
Lateral a		2	0	0	0
Lateral b		0	2	0	0
Lateral c		0	0	2	0
Lateral d		0	0	0	2
Sum		7,5	11	14,5	18

		LP A	LP B	LP C	LP D
Section 1	Avrg. Outage Freq*Out Time [h/y]	0,8	0,8	0,8	0,8
Section 2		0,05	0,4	0,4	0,4
Section 3		0,15	0,15	1,2	1,2
Section 4		0,1	0,1	0,1	0,8
Lateral a		0,4	0	0	0
Lateral b	0	1,2	0	0	
Lateral c	0	0	0,8	0	
Lateral d	0	0	0	0,4	
Sum		1,5	2,65	3,3	3,6
ENS		3	5,3	4,95	7,2
Sum ENS		20,45			

A.7 - Allan and Billinton Test Net for Educational Purposes with no distributed generation(wind generation tripped when interrupted)

Smart Grids and Reliability Analysis in Distribution Networks

	LP A	LP B	LP C	LP D
Weighted ENS	3	5,3	4,375	6,15
Sum weighted ENS	18,825			

A.8 – Weighted ENS for results in A.4 and A.5

LI Name	TCIT Ch/a	TCIF C/a	AID h	LPENS Mwh/a	LPEIC \$/a	ACIF l/a	ACIT h/a
lateral d	3,60	1,00	3,60	4,00	7196910,32	1,00	3,60
lateral c	3,30	1,20	2,75	3,75	6748755,13	1,20	3,30
lateral b	2,65	1,40	1,89	5,00	0,00	1,40	2,65
lateral a	1,50	1,00	1,50	3,00	0,00	1,00	1,50

A.9– LP PF analysis results from distributed wind case study, disregard LPEIC values

With backup cables		W/O backup cables	
LP1	3,264369	LP1	3,433395
LP2	3,309442	LP2	3,478468
LP3	3,309442	LP3	3,647494
LP4	3,452292	LP4	3,809805
LP5	3,309287	LP5	3,845557
LP6	2,85375	LP6	3,2925
LP7	2,8635	LP7	3,41925
LP8	0,650753	LP8	1,222146
LP9	0,748372	LP9	1,405479
LP10	3,206293	LP10	3,375319
LP11	3,240098	LP11	3,409124
LP12	2,734854	LP12	3,028681
LP13	3,426625	LP13	3,93906
LP14	3,438542	LP14	3,950977
LP15	2,77425	LP15	3,33975
LP16	2,85375	LP16	3,00975
LP17	2,745791	LP17	2,897443
LP18	2,745791	LP18	3,039618
LP19	2,783704	LP19	3,077531
LP20	3,499961	LP20	4,048147
LP21	3,488044	LP21	4,179235
LP22	2,8635	LP22	3,429
SUM =	63,56241	SUM =	72,27773

A.10 – Excel summary of Extended Alan & Billinton Test Net. Total ENS.

Table 10
Reliability Indexes with Embedded Generation (Tripped When Supply is Interrupted)

failure	Load point A			Load point B			Load point C			Load point D		
	λ	r	U	λ	r	U	λ	r	U	λ	r	U
section												
1	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8
2	0.1	0.5	0.05	0.1	4	0.4	0.1	4	0.4	0.1	4	0.4
3	0.3	0.5	0.15	0.3	0.5	0.15	0.3	4	1.2	0.3	4	1.2
4	0.2	0.5	0.1	0.2	0.5	0.1	0.2	0.5	0.1	0.2	4	0.8
lateral												
a	0.2	2	0.4	-	-	-	-	-	-	-	-	-
b	-	-	-	0.6	2	1.2	-	-	-	-	-	-
c	-	-	-	-	-	-	0.4	2	0.8	-	-	-
d	-	-	-	-	-	-	-	-	-	0.2	2	0.4
Total	1.0	1.5	1.5	1.4	1.89	2.65	1.2	2.75	3.3	1.0	3.6	3.6

Security = 115 interruptions/100 customers

Availability = 155 minutes/yr

Average duration = 2.25 h/interruption

Expected energy not supplied = 19400 kWh or 3.23 kWh/customer

Energy delivered by BSP = 39.4 GWh

Energy delivered by embedded generation = 26.3 GWh, i.e. import reduction

A.11 – Reference for no separate wind production for Test Net Example

Table 11
Reliability Indexes with Embedded Generation (Available Continuously, Can Run Independently)

failure	Load point A			Load point B			Load point C			Load point D		
	λ	r	U	λ	r	U	λ	r	U	λ	r	U
section												
1	0.2	4	0.8	0.2	4	0.8	0.2	0.5	0.1	0.2	0.5	0.1
2	0.1	0.5	0.05	0.1	4	0.4	0.1	0.5	0.05	0.1	0.5	0.05
3	0.3	0.5	0.15	0.3	0.5	0.15	0.3	4	1.2	0.3	0.5	0.15
4	0.2	0.5	0.1	0.2	0.5	0.1	0.2	0.5	0.1	0.2	4	0.8
lateral												
a	0.2	2	0.4	-	-	-	-	-	-	-	-	-
b	-	-	-	0.6	2	1.2	-	-	-	-	-	-
c	-	-	-	-	-	-	0.4	2	0.8	-	-	-
d	-	-	-	-	-	-	-	-	-	0.2	2	0.4
Total	1.0	1.5	1.5	1.4	1.89	2.65	1.2	1.88	2.25	1.0	1.5	1.5

Security = 115 interruptions/100 customers

Availability = 117.4 minutes/yr

Average duration = 1.70 h/interruption

Expected energy not supplied = 14675 kWh or 2.45 kWh/customer

A.12 – Reference for separate generation scenario (1) for Test Net Example

Table 12

Reliability Indexes with Embedded Generation (Available for 25% of Time, Can Run Independently)

wind farm status	Load point A			Load point B			Load point C			Load point D		
	λ	r	U	λ	r	U	λ	r	U	λ	r	U
Avail	1.0	1.5	1.5	1.4	1.89	2.65	1.2	1.88	2.25	1.0	1.5	1.5
Unav	1.0	1.5	1.5	1.4	1.89	2.65	1.2	2.75	3.3	1.0	3.6	3.6
Total	1.0	1.5	1.5	1.4	1.89	2.65	1.2	2.53	3.04	1.0	3.08	3.08

Security = 115 interruptions/100 customers
 Availability = 145.8 minutes/yr
 Average duration = 2.11 h/interruption
 Expected energy not supplied = 18230 kWh or 3.04 kWh/customer

A.13 – Reference for separate generation scenario (2) for Test Net Example