Simple Distribution Networks Reliable Power Electricity

Enkla elnät, säkra elleveranser

Elforsk rapport 10:08

Ying He and Emil Eriksson,
Vattenfall Research and
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ELFORSK

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Förord

Denna rapport är framtagen av projektet ”Enkla elnät, säkra elleveranser'', inom Elforsks FoU program Nätutveckling. Syftet med projektet är att med hjälp av tillförlitlighetssimuleringar undersöka möjlighet att förenkla nätstrukturer och reducera antalet komponenter med bibehållen leveranssäkerhet.

Projektet har genomförts i huvudsak av Vattenfall Research and Development AB med medverkan av Vattenfall Eldistribution AB. Följande personer har bidragit och hjälpt till med projektet:

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Projektets styrgrupp består av följande personer. Styrgruppen har givit värdefulla synpunkter och kommentarer för projektets utförande.

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December 2009

Sammanfattning

Samhällets ökade krav på elleveranssäkerhet och elnätbolagens behov av att kostnadseffektivisera sin verksamhet har lett till ett ökat behov av att rationalisera uppbyggnader av framtida elnät.

Dagens elnät var successivt uppbyggda under lång tid. De tekniska studier och analyser för utvärderingarna vid uppbyggnaderna var framförallt belastningsfördelningar, beräkningar av förluster, livstidskostnader, o dyl., medan elnätstrukturrelaterade tillförlitlighetssimuleringar och utvärderingar inte genomförts lika utbrett. Elleveranssäkerhet kan påverkas av elnätstrukturer, antalet komponenter och komponenternas placeringar. Tillförlitlighetssimuleringar analyserar denna påverkan och kan används som ett verktyg för att rationalisera elnäts uppbyggnader och få största möjliga leveranssäkerhet per satsad investering. Utan sådana analyser kan konsekvenser bli att man bygger för sofistikerat elnät och installerar för många komponenter.

Framtidens elnät kommer att byggas upp baserat på nuvarande elnäts infrastruktur. Elnätsanläggningar som används idag kommer att fortsätta att spela en viktig roll i framtiden. Dagens elnätstrukturer bör förstärkas och uppgraderas. Men en viktig fråga för elnätbolag är hur tillförlitliga framtida elnätsstrukturer ska utvecklas på ett kostnadseffektivt sätt.

Syftet med projektet är att med hjälp av tillförlitlighetssimuleringar undersöka hur man kan förenkla elnät och reducera antalet komponenter med bibehållen leveranssäkerhet. Projektaktiviteter har fokuserat på följande tre delmoment:

- Omvärldsstudier för att utreda trender i elnätstruktur avseende förändringar och utveckling samt vad man gjort i omvärlden när det gäller förenklingar och nya lösningar för elnätstrukturer. Utredningen är för att ge input till projekt och case studier av elnätförenklingar.
- Landsbygdsnät studie.
- Stadsnäts studie.

En serie simuleringar och beräkningar har utförts i projektet för att kvantifiera effekten av olika alternativa förenklingar av tillförlitlighet och undersöka möjligheter att förenkla elnät med bibehållen leveranssäkerhet. Beräkningarna visar att det finns potential att minska antalet elnätkomponenter och förenkla befintliga elnätstrukturer utan att försämra elnäts tillförlitlighet. Det finns möjlighet att bygga framtida elnät med mindre antal komponenter, enklare strukturer och säkrare elleveranser.

Studierna visar att elnätkomponenter kan påverka tillförlitligheten på olika sätt. Att bygga sofistikerat elnät och installera flera komponenter betyder inte att elnätets tillförlitlighet automatiskt höjs. Att investera i flera komponenter kan innebära ett införande av flera aktiva komponentfel och kan eventuellt resultera i försämring av elnäts tillförlitlighet.

Landsbygdsnätsstudier visar att det finns potential att reducera antal lastfrånskiljare och frånskiljare i befintligt elnät utan att påverka elnäts

tillförlitlighet negativt. Det finns möjlighet att minska sektionerings frånskiljare genom optimering av frånskiljarplaceringar.

Resultatet av stadsnätsstudier visar att vissa extra sammankopplingar mellan maskade nätdelar kan tas bort utan att påverka elnätstillförlitlighet negativt.

Rapporten avslutas med en sammanställning av huvudresultat från projektets olika delstudier. Beräknade värde och diskussioner av resultaten dokumenteras i rapporten.

Summary

Distribution systems are becoming increasingly important for electric utilities. The society's increased demand on reliable electricity has resulted in an increased focus on power system reliability. Power supply utilities are taking increasing interest in finding ways to improve the reliability of power supply in a cost effective manner.

Today's power distribution networks were built gradually over time. They were originally set up in the 1940-1950s or even earlier. The technical studies and analyses then for the network buildings were based on basic network design principles and were mainly load flow analysis, power loss calculations, lifetime cost analysis, and suchlike things, while the network structure related reliability simulations and evaluations have not been performed so much.

The distribution systems of the future will be built up based on the present network infrastructure. The power equipments used today will continue to play important roles in the future. The present network structures should be reinforced and upgraded. But, how in a cost effective way to develop a reliable architecture for the future is an important concern of power utilities. It is therefore expected that this project, through reliability evaluations on existing networks, investigates possibilities to simplify the present network structures and component placement, and by doing so to aid future network planning.

The project addresses the important considerations of how to build a reliable distribution network in a cost effective way and how network configurations and network components affect customer reliability indices. The project activities have focused on the following studies:

- The world-around study to identify trends of future network structure development;
- Rural network study;
- Urban network study.

A series of reliability evaluations have been performed to investigate possibilities to simplify network structures while maintaining network reliability. The results of the reliability analyses show that there is potential to reduce the number of network components and simplify the existing network structures without degrading network reliability. It is feasible to build future networks with less components, simpler structures, and reliable customer service.

The studies demonstrate that network components affect the reliability in different ways. It cannot be concluded that installing increased number of components automatically increases the network reliability. Switch devices have potential to improve reliability by allowing faults to be isolated and customers to be restored before the fault is repaired. However, place more switch devices will introduce more active component failures and may eventually result in degradation of system reliability due to the failure probability of each device. It is of great value to consider these effects and

perform reliability quantification in order to obtain the most beneficial solutions of network structures of the future distribution systems.

The rural system analyses show that on existing rural distribution networks some of lateral switches, feeder switches, and certain load-disconnectors can be removed without affecting the network reliability negatively. There is potential to reduce sectionalized switches by optimizing feeder sections.

One feature evident in the results of the urban system study is that some of extra tie interconnections between meshed network parts can be removed without affecting the network reliability negatively.

In the conclusion chapter of the report, the summary of the main results from each part of the project is provided. The detail calculation results, and discussions of the results are described in the different Chapters of case studies.

Contents

1 Introduction

1.1 Background

Power distribution systems are important to modern society. In today's competitive electric market, the economic development and society's increased demand on reliable electricity supply have resulted in an increased focus on power system reliability. Power supply utilities are taking increasing interest in finding ways to improve the reliability of power supply in a cost effective manner.

Today's power distribution networks were built gradually over time. They were originally set up in the 1940-1950s or even earlier. The technical studies and analyses for the network buildings were based on basic network design principles and were mainly load flow analysis, power loss calculations, lifetime cost analysis, and suchlike things, while the network structure related reliability simulations and evaluations have not been performed so much.

Power system behaviour is stochastic in nature and system failures occur randomly. Electricity supply reliability can be affected, among other things, by network structures, number of network components, and component placement. Network reliability analyses simulate system failures and predict network future reliability. It can be used to assess effect of different network designs on system reliability and used as a tool to rationalize network planning. Without such analysis, the consequences may be building too complicated networks or installing too much network components.

The electric distribution systems of the future will be built up based on the present network infrastructure. The power equipments used today such as power lines, cables, stations, and transformers, will continue to play important roles in the future. The present network structures should be reinforced and upgraded. But, how in a cost effective way to develop a reliable architecture for the future is an important concern of power utilities. It is therefore expected that this project, through reliability calculations, performs network structure related analysis and investigates possibilities to simplify the present network structures and component placement, and by doing so to aid future network planning.

1.2 Purpose

The purpose of the project is, through reliability evaluation of different network configurations, to investigate how to simplify the network structures and reduce the number of network components while maintaining the network reliability.

It is desired that by reliability evaluation and quantification this project could spread awareness about that building sophisticated networks and investing too many components do not necessarily imply increasing power supply reliability. Project results could hence be used to support network planning and help rationalizing investment for future network development.

1.3 Project Performance

To perform reliability evaluation requires input data and reliability models that describe the practical systems on which the evaluation is performed. In order to ensure the intended analyses, the project work was divided into four parts:

- The world-around study;
- Network reliability modelling;
- Rural network study;
- Urban network study.

Developing a smart grid of the future has been an active R&D area all over the world during the recent years. The concept of smart grid has emerged in a very broad area and can imply variety of principles and methods for making power systems reliable and smart. In order to get new input from outside the project started with a world-around study. The study inspected the activities and ongoing projects in this area regarding impact of future new technologies on network infrastructures and the work of changing and simplifying existing network structures.

The study was followed by building models of networks in the program NEPLAN for computer simulations. Based on practical distribution systems a set of NEPLAN models of different structural characters was established for reliability simulations.

The main project activities, rural and urban network studies, were performed on two MV distribution networks of Vattenfall Distribution Nordic. A series of cases were analyzed to investigate the possible simplification of the network configurations and the potential to reduce number of components without affecting negatively the network reliability.

2 Reliability Evaluation

Distribution system reliability describes the ability of a system to perform its function and relates to equipment failures and customer interruptions. It is therefore an inherent characteristic of a system and an important design parameter.

Distribution reliability is usually measured in terms of reliability indices. There are two sets of reliability indices: load point indices and system indices. The load point indices reflect reliability at individual customer load point level, while the system indices give a complete reliability at the overall system level.

Reliability evaluation of a system is often referred to quantitative assessment of system reliability by either analytical techniques or simulation methods. Reliability evaluation techniques simulate the random behaviour of a system, deduce the consequences of the failures, and calculate the reliability indices. These numerical values of the indices provide the quantified measure, and can be used to compare and judge the reliability of alternative power systems.

To quantify load point reliability three primary indices are generally used. These indices are average failure rate (λ), average annual unavailability (U) (annual outage time), and average energy not supplied (ENS):

λ = average number of failures per year (f/yr)

U = average annual unavailability (min/yr)

ENS = average energy not supplied (MWh/yr)

Based on load point indices, a number of system reliability indices can be calculated and a complete representation of the system behaviour can then be obtained. The most important system indices are:

SAIFI = System Average Interruption Frequency Index

$$= \frac{total\ number\ of\ customer\ \mathrm{int}erruptions}{total\ number\ of\ customers\ served}$$

$$= \frac{\sum \lambda i \cdot Ni}{\sum Ni} (\mathrm{int}/\ yr.cust)$$

SAIDI = System Average Interruption Duration Index

$$= \frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customers\ served}$$

$$= \frac{\sum Ui \cdot Ni}{\sum Ni} (\min/ yr.cust)$$

ENS_S = Total Energy not Supplied by the System

$$= \sum ENSi$$

where:

λ_i = failure rate of load point i

U_i = annual unavailability of load point i

ENS_i = energy not supplied of load point i

To evaluate system reliability there are two main categories of methods: analytical methods and the simulation methods. The analytical method assesses the reliability of a system mathematically. This technique utilizes a mathematical model to represent a system, and then performs the reliability evaluation directly on the model by solving the mathematical equations. Simulation techniques, on the other hand, estimate the reliability by simulating the actual process and random behaviour of the system. It estimates probability and reliability indices by counting the number of event occurrences.

In order to get fast and efficient solutions of reliability calculations, a number of computer programs are developed. NEPLAN, a PC oriented software developed by Busarello Cott Partner Inc. (BCP), Switzerland, is one of such programs. NEPLAN is a general-purpose program package for power network planning, analysis, simulation, and optimization. It contains more than 30 modules and large component model library. It supports various technical and economic analyses, including static, dynamic, reliability, optimization, maintenance, and investment analysis. NEPLAN reliability module was implemented based on analytical Markov process method and has good reliability modelling capability. It models not only primary networks, but also remote control systems. It simulates the failure events and restoration processes and quantifies their effects on reliability. The program gives good possibilities to perform application studies for evaluating network configurations and therefore was chosen used by the project.

3 Trend and Activity Inspection

In order to provide more input from outside to network structure studies of the project, a world-around study was performed. The objectives of the study are to identify trends in network structure development, and what has been done in the world around regarding simplification and new solutions of network configurations. The study has looked at the following issues:

- How do future distribution systems look like from network structure perspective?
- How will the network structures be affected by the introduction of new technologies?
- How and what has been done in the world around to simplify the grid and modify existing network structures?

The following sections describe briefly the results of the study.

3.1 Network Structures of the Future

Desired functionality

There are a variety of projects and research and development activities around the world to study futuristic distribution systems. Many of the R&D activities share a common vision of desired functionality of distribution networks. Some of these desired functionalities are:

- Automation and self-healing. Automation is the heart of a smart power system of the future. It will play a key role in providing high level of power supply reliability. To a power system operator, automation means a self-healing, self-optimizing smart power system that automatically anticipates and quickly responds to disturbances to minimize their impact and eliminate power interruptions;
- High reliability and power quality. The network would have functions that enable customers to avoid interruptions for most feeder faults.
- Facilitating connection for diverse new generation sources, and integrating a wide variety of distributed generation and storage options;
- Acquiring and processing power system information in a new and effective way. The network monitoring, protection, and control are integrated and implemented in one cost effective system through modern microcomputers, digital signal processors, and communication technologies;
- Distributed intelligence;

- Minimizing operations and maintenance expenses.

Structure characteristics

To achieve the desired functionalities, the networks should be changed and upgraded. The future electric system will be built on the existing electric network infrastructure. The same types of power equipment used today for power delivery, e.g. power lines, cables, stations, and transformers, will continue to play important roles in the future. However, the emergence of new techniques including distributed intelligence and energy resources will increase the efficiency, quality, and reliability of the existing power systems and enable developing a new architecture for the futuristic electric grid.

The grid of the future will be automated power supply network that monitors and controls consumers and network nodes, ensures a two-way power flow and information exchanges between all points of the network. The future power network connects everyone at anytime, anywhere to clean, efficient, and reliable electricity. From architecture perspective its characteristics are:

- Controllable with remote-controlled switch devices. Faster detection of outages and rapid restoration;
- Having compact stations;
- Flexible;
- With back up connections;
- Having local power feeding.

3.2 Impact of New Technologies

Electric distribution systems are undergoing rapid changes due to the penetration of distributed generation and power electronics technologies, and the adoption of efficient computation, communication and control mechanisms.

These new techniques will affect significantly the architecture of future electricity systems. The distribution systems can no longer be considered as a passive appendage to the transmission networks. The entire power network must be designed and used as an integrated and active system.

From the network structure perspective, the technologies that would have biggest impact are distributed energy resources and distribution automation. Their impact is described briefly as follows.

Impact of distributed generation

Distributed generation (DG) is a new model for power system design. It will affect the network technically in a number of ways and bring significant effect on network infrastructure in the future. It is based on integrating into electricity networks small and medium distributed generators with new and renewable energy technologies. All these generators will be interconnected through a fully interactive intelligent electricity network. This integration requires sophisticated control and communication technologies to ensure smooth operation of electric networks. Based on this new electricity service paradigm the conventional electricity distribution grid will be required transformed to two-way power flow, interactive, and unified power supply network.

DG will play a key role in building up futuristic electricity infrastructure. It introduces a broad range of technologies into the power grid, including many renewable techniques supplying small-scale power at sites close to consumers, and providing distributed back-up power resources.

It is believed that to interconnect these decentralized generation resources, small and low-cost underground cables may be used instead of three phase AC lines. Overhead lines are thus shrinking in size in the future, and there is great interest in underground distribution systems.

Impact of automation

Automation technology is an enabling technology. It facilitates the transference of physical requirement into an automated process. Distribution automation extends to three levels, automated devices, substation automation, and distribution system automation.

Automated devices apply automation at network devices, automating such as line sectionalizing devices, switches and disconnects. It upgrades network at component level. Installing remote controlled/automated sectionalizing devices allows quickly identifying a faulted section and remotely/automatically operating switches to restore service, and hence reduce durations of interruption and improve reliability.

The traditional substation has become an ineffective framework for meeting future demand. Automation applied to substation implies producing information, control actions, and managing network operation process. This is generally achieved through computerized processing, the application's interaction with the power system, and communications with other substations. An automated intelligent substation shares all information on apparatus, control, protection, and measurement. Substation automation with integration of protection and control offers an interoperable, capable and timely performance, as well as a compact station framework. Future substation will have compact designs and reduce in size.

Distribution automation is system-wide automation. It means distributed intelligence. Its main benefit is the ability for automatic fault location, isolation, and reconfiguration, and hence reducing outage times and the non-delivered energy and enhancing power supply reliability. The other benefits of distribution automation are: reduction in equipment damage, facilitating monitoring network states, better availability of system information, improved operational planning, and remote load control and shedding.

3.3 Ongoing Work to Modify Network Structures

We are using the grid in the ways that it was not designed for. To integrate DG into the power grid and to meet the future demand requires investments and upgrade of existing network infrastructure. The following describes briefly the work in modifying today's electric infrastructure.

No much work reported about simplifying existing networks

There are not many reports found about work on how to simplify existing distribution networks, nor much found reported regarding how to maintain or improve reliability by simplifying or changing network structures. Rather, the network changes are towards adding new functions and introducing new technologies into the networks to meet the future requirements and achieve the desired functionalities.

Focus on upgrading existing networks with new technologies

To support the desired functions and new demands in future, the grid architecture must be changed. The main work in changing existing networks is related to upgrading and modifying grid architecture by introducing new technologies. The efforts to modernize the grid and incorporate new technologies have been oriented towards:

- Make simple and compact substation. To build next generation of substation that is made up of exchangeable modules with no or little maintenance work in the station. Instead of maintainability, exchangeability and relocate-ability are becoming important issues. Substation will be simple and compact which are mainly enabled by:
  - Simplification of substation lay-out;
  - Reduction of substation apparatus.
- Upgrade from unintelligent to intelligent. To adapting and incorporating communication and control technologies to the network and making the grid smart, so that the grid can be quickly and flexibly reconfigured and becomes more efficient and reliable.
- Change from radial to interconnected and meshed structure. The distribution system of the past is radial. The distribution system of the future is meshed, intelligent, and interconnected with distributed generation and local back-up feedings.
- Upgrade the grid from little control to controllable. Make the restoration of power easy after outages and fully controllable through a combination of high speed communications, switching devices, intelligent controllers, and reconfigured feeders. Upgrade network from manual feeder reconfiguration to remote-controlled or automated. Sectionalisers are automated.

- Optimizing sectionalisation as a means of improving reliability of supply. To minimizing the feeder section that is left without supply after a fault occurrence.
- Optimizing back-up feeder connections.

3.4 Some Network Layouts Reported

The following are some interesting network structures or feeder variations found studied or reported:

Vattenfall vision substation structure for 2010

Vattenfall has proposed a vision structure for transformer station. It is a result of a Vattenfall internal project "Transformatorstation för 2010-talet'' [4]. The station scheme is very simple and has the following characteristics:

- There is only one busbar;
- Swith and circuit breaker are integrated into one unit;
- There is only one transformer;
- There are maximum four outgoing and incoming lines respectively.

Feeder variations

- Place one or more re-closers on a radial feeder.
- Automate switches at feeders having radial or looped topology.

Dual fed LV busbar

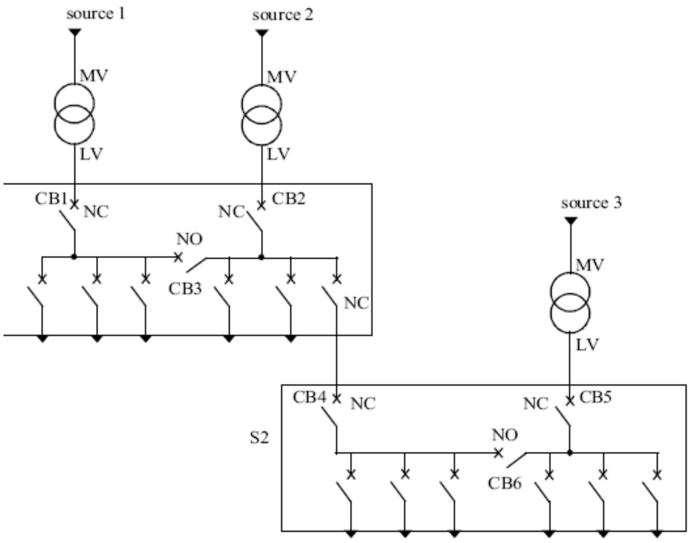


Figure 1-24: dual fed LV switchboards with coupler

Figure 3-1: Dual fed LV switchboards with coupler. Source: [5].

Single transformer and one generator

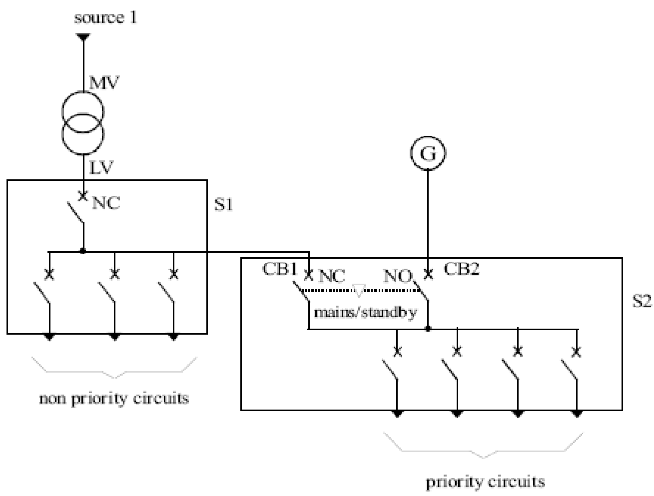


Figure 1-27: 1 transformer and 1 generator

Figure 3-2: One transformer and one generator configuration. Source: [5].

Standard network from Schneider Electric

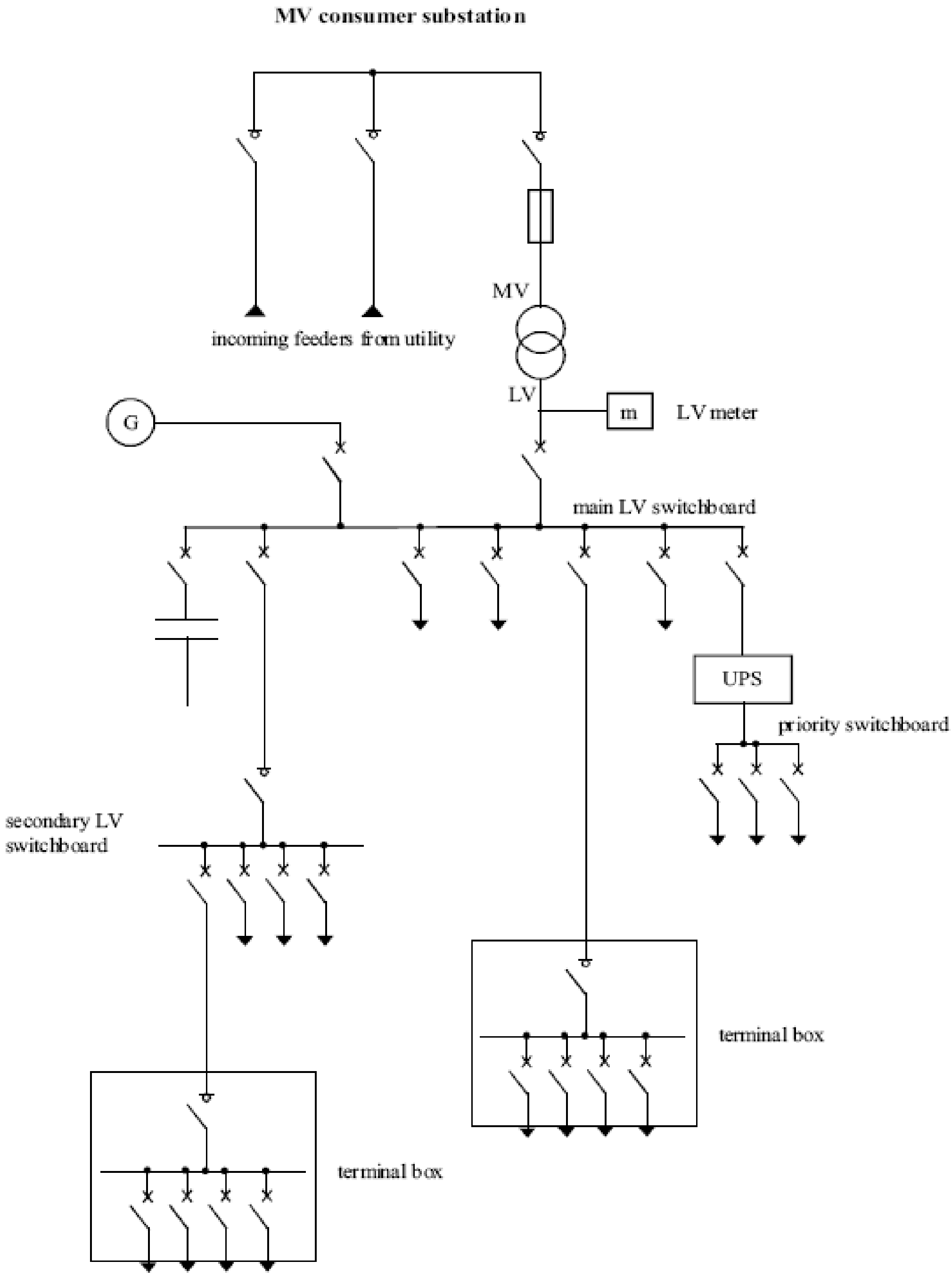


Figure 3-3: An example of standard network structure. Source: [5].

4 Rural System Analysis

Rural power systems are often built with a radial topology. On a radial structure, each component is characterized by its path to a source of power. Load density of a rural system is normally low and most circuit exposure is overhead construction. Most networks, however, are interconnected by normally open tie lines and operated radially. The purpose of these open tie lines is to reduce the amount of equipment exposed to failure on a feeder circuit and to ensure that, in the event of a system failure, the normal open switch can be closed and another opened in order to minimize the total load disconnected.

Outage statistics shows that rural distribution systems still make considerable contribution to the unavailability of customer supply. The increasing demand on reliable power supply and ongoing change on power networks toward future smart grid driver utilities to search a solution of future reliable rural systems with low overall cost. This has resulted in an increased focus on system reliability. In order to reduce customer interruptions, more effort is being given to optimizing system design and enhancing system construction of the future rural systems.

This Chapter and subsequent Chapters 5-10 carry out the reliability evaluations on a rural distribution system. The evaluation focuses on the possibilities of simplifying network structure without degrading the reliability. The reliability quantification is related to alternative modifications of system configuration. The analyses intend to give contribution to the development of economical, and reliable rural distribution systems.

4.1 Rural System Studied

A Vattenfall rural distribution network was used in the project. Figure 4-1 gives an overview of the system. The system is a typical network in rural area in Sweden. It has a radial structure and consists of a primary substation and 54 secondary substations spread along the feeders. The total length of the overhead lines in the network is approximately 67 km, and 37 km underground cables are used. In the secondary substations, distribution transformers step down the voltage from 11 kV to 0.4 kV. A total of 313 customers are connected to the system. The power consumption at the load points ranges from 1 to 123 kW. The total load demand of the network is approximately 2.5 MW. Table 4-1 gives an overview of the network objects.

At the primary substation, a main feeder begins with a disconnect-switch, which is then connected to a feeder circuit breaker. Figure 4-2 shows the layout of the primary substation. The main feeder is routed around the feeder service area and is connected to other feeders through tie points. The lateral branches tap off from the main feeder and cover the feeder service territory.

At two different locations the network is connected to neighbouring distribution networks through normally open disconnectors. The reserve feeding power from each of these normally open points is able to cover the load of the network in the failure event of the primary substation.

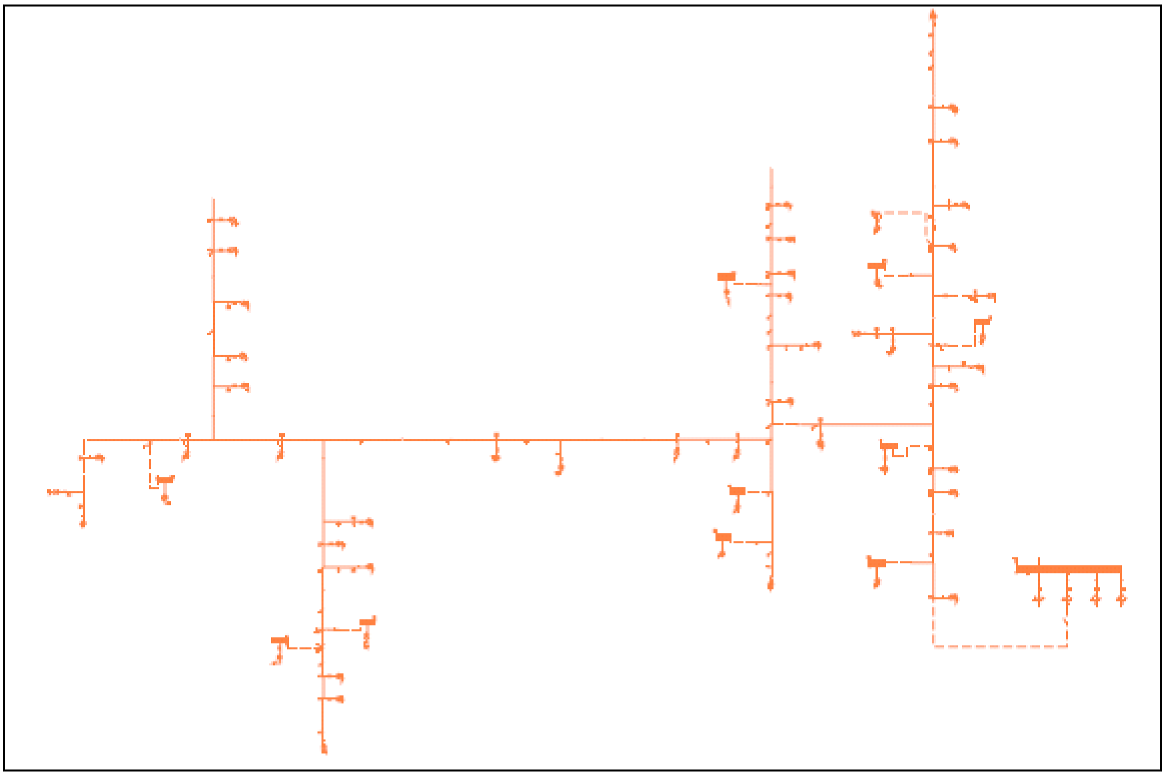


Figure 4-1: Overview of the rural network studied.

Table 4-1: Summary of the network objects.

Items	Number
Primary substation	1
Secondary substation	54
Overhead line	67 km
Underground cable	37 km
Distribution transformer	54
Circuit breaker	4
Fuse	54
Load-switch	8
Disconnect-switch	26
Customer	313
Customer load	2458 kW

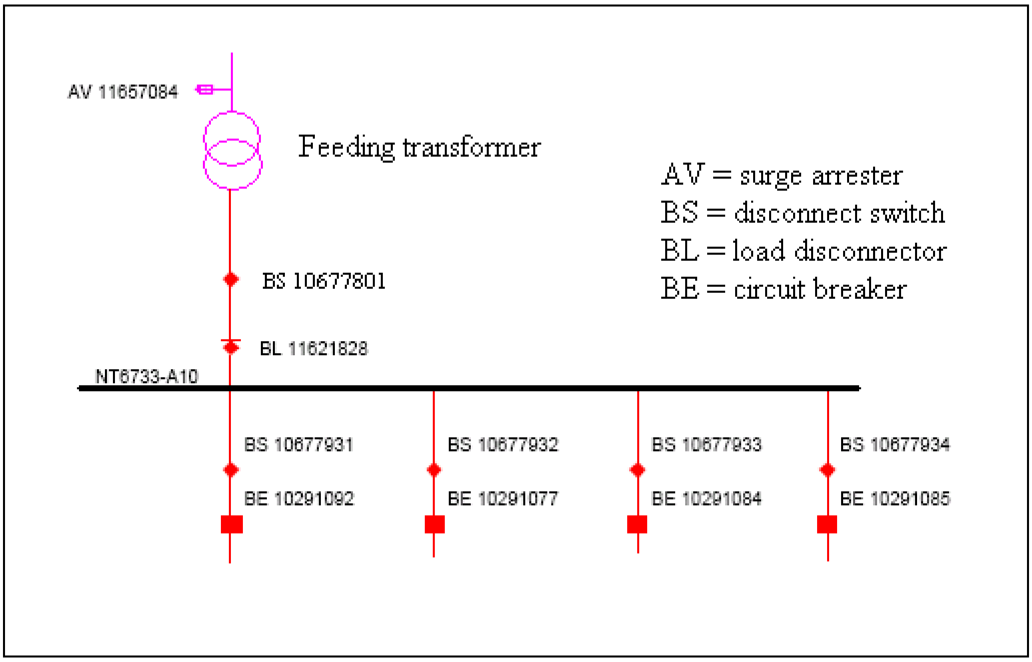


Figure 4-2: The layout of primary substation.

4.2 Reliability Data

A distribution system consists of network components. Component failures can lead to system failure, and the component outages are the root cause of a system failure. The reliability of network components is described by their reliability data and failure characteristics. The data relates to two main aspects of the component behaviour, that is, the failure process and the restoration process.

Good component parameters for reliability calculations are the data related to the system studied. The reliability data used in the rural network study are based on failure statistics from Vattenfall Distribution Nordic. Table 4-2 summarized the data used in analyses.

The switch time is average time for operation of switch devices in fault isolation and restoration. It is system specific and is affected by many factors. The manual switch time can normally vary from 30 minutes to a couple of hours, and remote switch time from a few minutes to 15 minutes. The switch time was set to 1-2 hours for manual switches and 3-15 minutes for remote controlled switches in the different case calculations. The length of switch time affects the duration related reliability indices, like SAIDI and ENSs. Increasing the switch time may increase the values of such indices.

Using these data, the subsequent Chapters 5-10 analyse the possibilities to simplify the rural distribution system. A series of case studies were performed on alternative network configurations.

Table 4-2: Component reliability data used for rural system analysis.

Equipment	For data from	Failure rate (f/yr.unit), (f/yr.km)	Outage duration (h/f)	Unavailability (%)
MV open wire conductor lines	Vattenfall	0,050	6,0	0,003
MV underground cables		0,020	5,9	0,001
MV aerial cables		0,021	6,0	0,001
Distribution transformers 10-20/0.4 kV		0,010	5,0	0,001
Power transformer 44/11 kV		0,002	1,7	0,000
Circuit breakers	Elforsk report [8]	0,020	4,0	0,001
Switches 10-20 kV		0,05	4,0	0,002
Load switches 10-20 kV		0,05	4,0	0,002
Fuse	Vattenfall	Stuck probability: 5%		

5 Case Study S1: Effect of Reducing Lateral Disconnect Switches

Rural distribution systems consist of feeders that deliver power from primary substations to distribution transformers. A main feeder goes from a substation and is routed to service area. Lateral branches that tap off from a main feeder are used to extend through the load area to service territory.

At tee-junction of lateral branch an isolating protective device such as fuses is normally installed to prevent feeder outages from faults occurring on the lateral. In a fault event on a lateral branch the fault causes the fuse to blow. This causes disconnection of the lateral branch but does not cause disconnection of any other load point on the main feeder.

Figures 5-1, 5-2, and 5-3 show the examples of lateral arrangement on the Vattenfall distribution system.

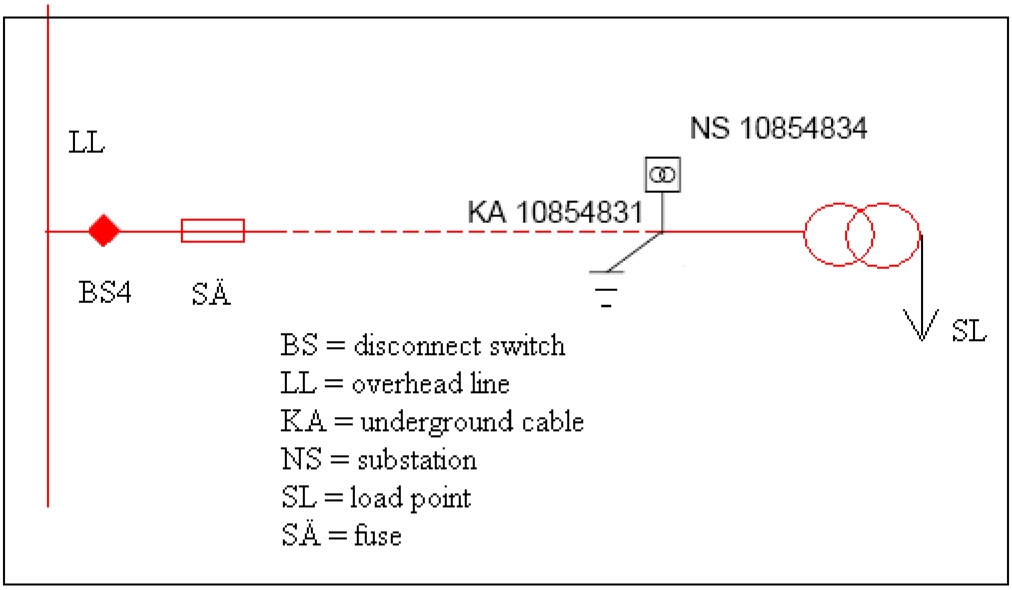


Figure 5-1: A lateral branch of the Vattenfall distribution system.

On these lateral branches, the lateral feeder taps off from the main feeder, and the lateral disconnect-switch may be located directly at the lateral tap point as shown in Figure 15-1, or placed after fuse as shown in Figure 15-2. Figure 15-3 shows another possibility of lateral tap, where there is no lateral switch only a fuse is used as the isolating protective device.

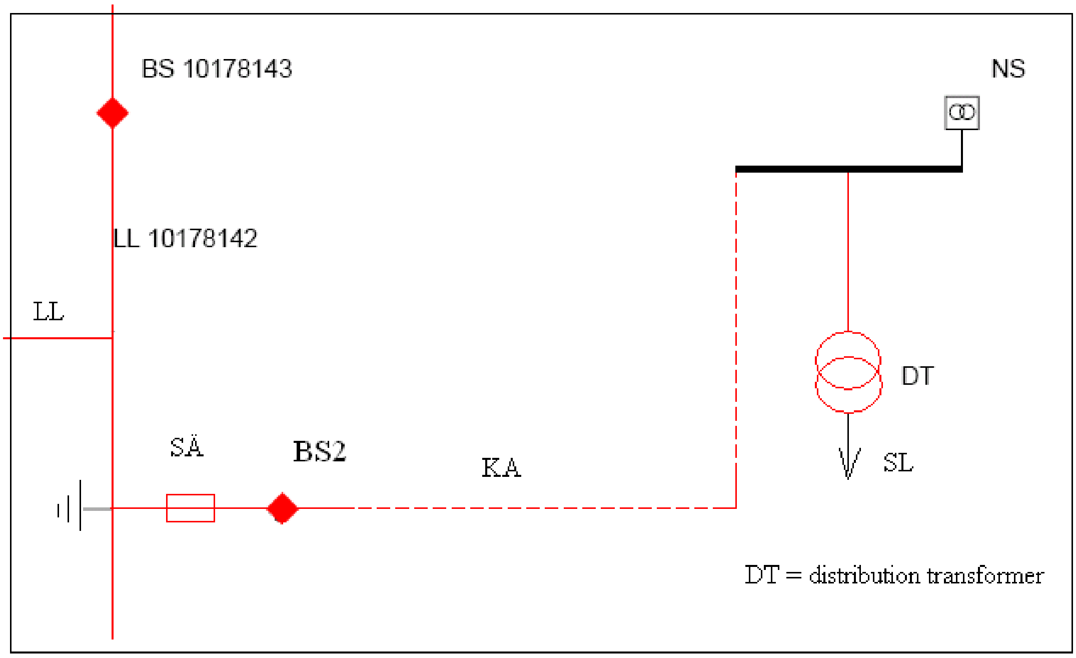


Figure 5-2: A lateral branch of the Vattenfall system.

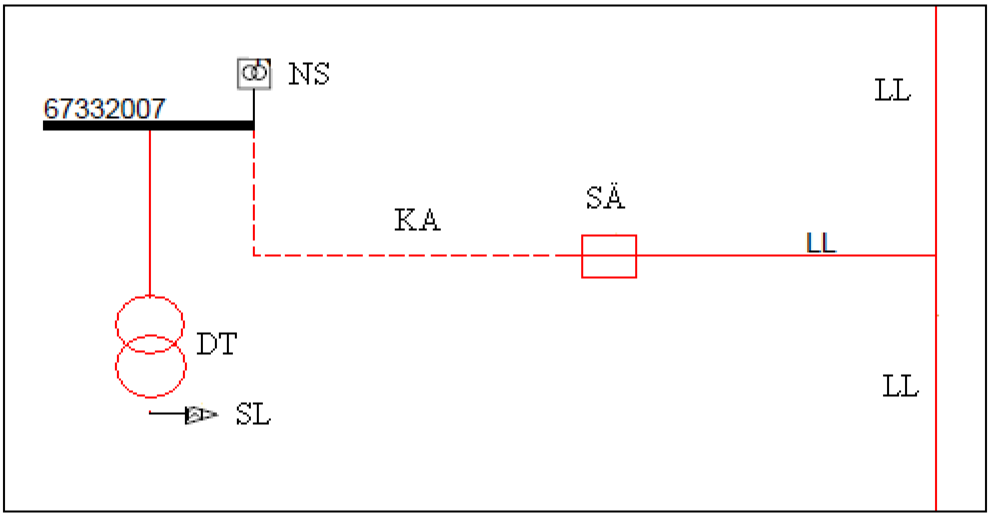


Figure 5-3: A lateral branch of the Vattenfall system.

In order to quantify the effect of reducing lateral disconnect-switches on system reliability, the following four cases were calculated:

- Base case: the present existing network without modifications;

- Case S1-1: same as Base case but remove the lateral disconnect-switch BS4_m (BS10854832) shown in Figure 5-1;
- Case S1-2: same as Base case but remove the lateral disconnect-switch BS2_m (BS11032799) shown in Figure 5-2;
- Case S1-3: same as Base case but remove both the lateral disconnect switch BS4_m and BS2_m.

The system and load point indices are calculated. In this calculation only the results for feeders shown in Figure 5-4 are presented but the similar results would be given for all the other feeders of the system. Since this portion of the network has structure characteristics typical of the distribution system studied and is therefore representative for illustrating the evaluation results.

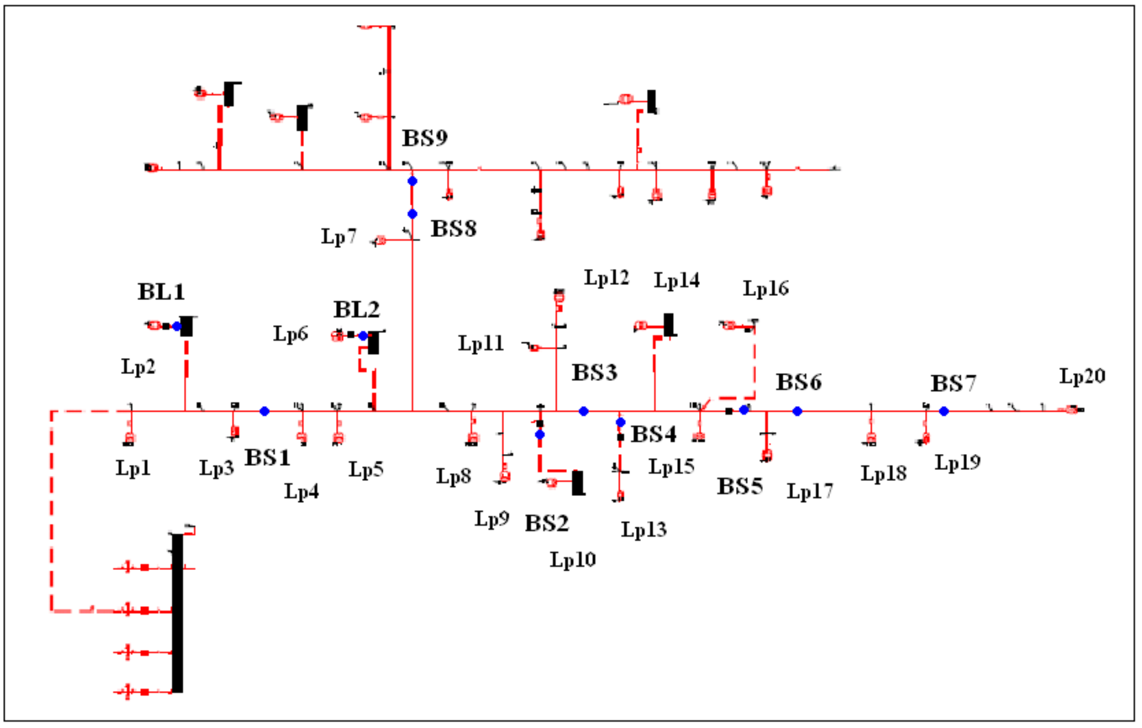


Figure 5-4: The feeders for which the calculated results are presented.

The results of the calculations are presented in Figures 5-6 ~ 5-11 and Tables 5-1 ~ 5-4. These results represent the effect on the system reliability when lateral switches are reduced. As expected failure rates decrease both on system and load point levels when the number of lateral switches is reduced, which is shown clearly in Figures 5-6 and 5-7.

Comparing the results of Case S1-1 with that of Case S1-2, it is interesting to notice that removing BS4_m in Case S1-1 results in more positive impact on reliability than removing BS2_m in Case S1-2. The disconnect switch BS4_m is installed at the lateral tap end before the protective fuse. In this case a short circuit on the switch BS4_m will cause the main circuit breaker on primary substation to open and disconnect all the load points on the main feeder. The switch BS2_m is however located behind the fuse. A short circuit on it will be protected by the fuse and will not cause the main breaker to trip when the fuse functions. The removal of the switch BS4_m gives therefore more positively effect on reliability than removing the switch BS2_m.

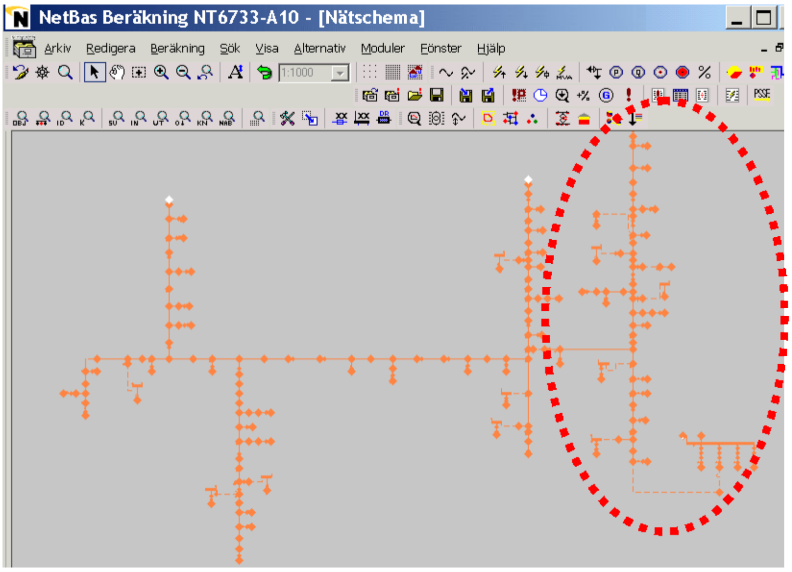


Figure 5-5: The feeder portion for which the calculated results are presented.

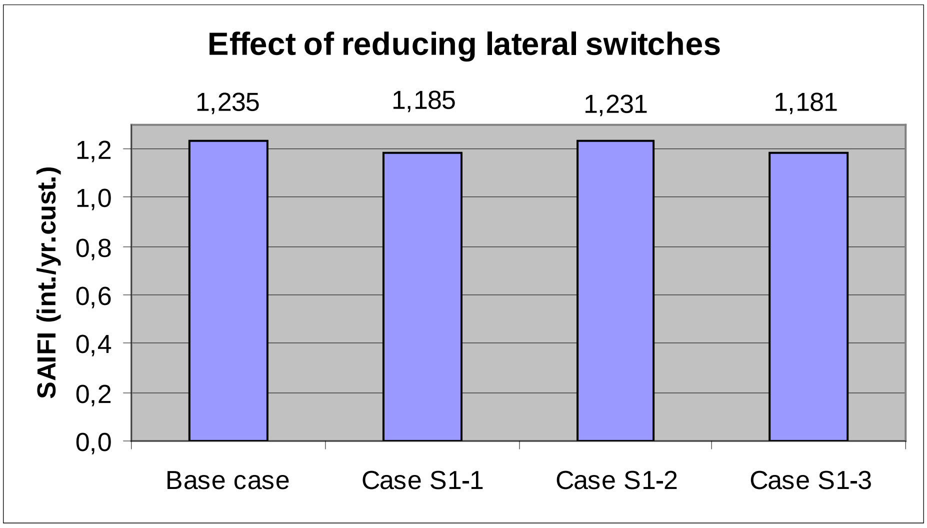


Figure 5-6: Results of Case study S1.

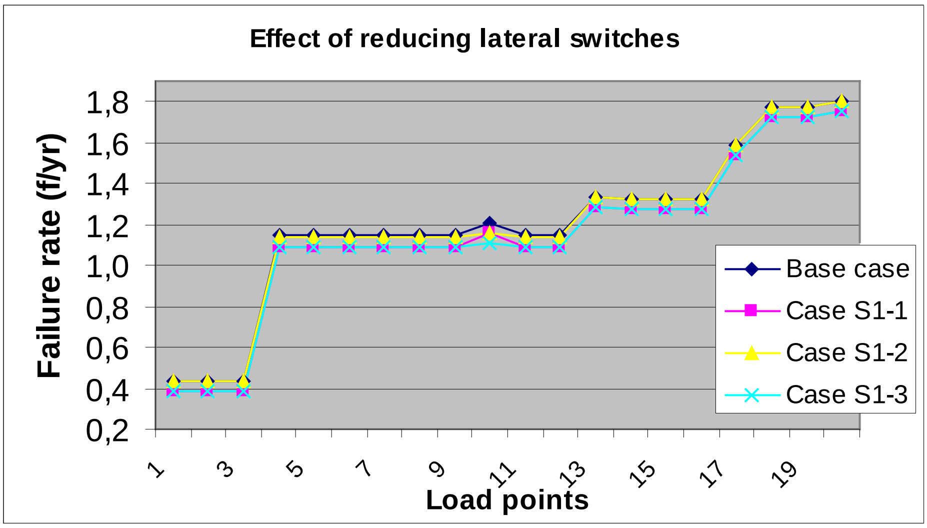


Figure 5-7: Results of Case study S1.

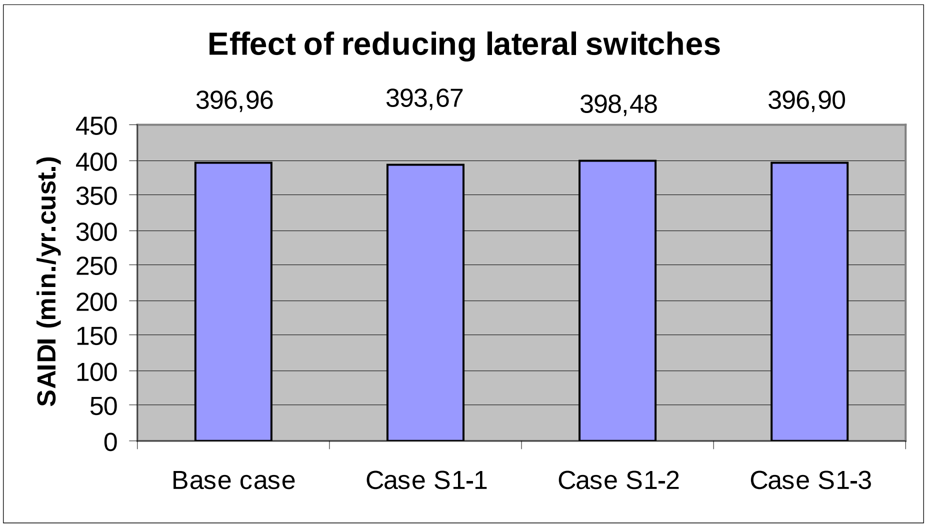


Figure 5-8: Results of Case study S1.

Figure 5-9: Results of Case study S1.

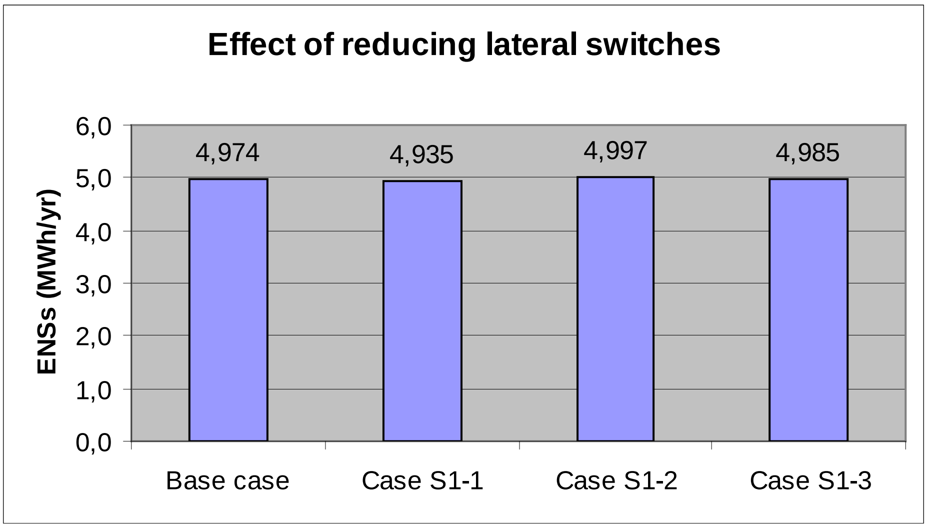


Figure 5-10: Results of Case study S1.

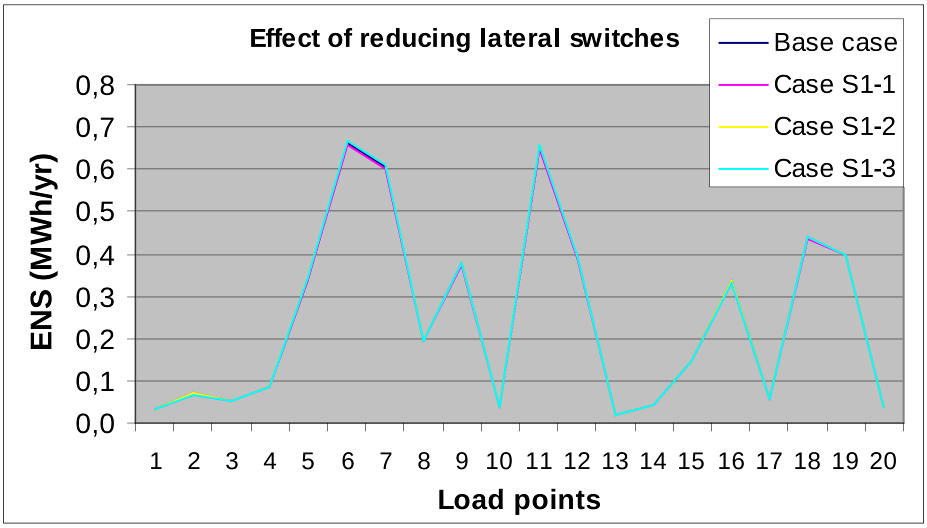


Figure 5-11: Results of Case study S1.

The indices calculated in Case S1-2 show that the removal of the switch BS2_m leads to marginal increase of outage duration and energy not supplied compared with the Base case. When this lateral (of load point 10) should be isolated in the, for example, failure occurrence on this lateral branch, if removing the lateral switch BS2_m, the adjacent sectionalizing switches on main feeder BS1 and BS3 should then be used to isolate the fault. This causes the load points 4-10 disconnected until the fault is repaired, and this results in slightly longer outage duration.

After changing the network in Cases S1-1, S1-2, and S3-3, the reliability calculated remains almost on the same level. The modifications in the indices due to the changes in the network are only marginal. This illustrates that the reduction of the lateral disconnect-switches made in these three cases does not affect the system reliability negatively.

Table 5-1: Results of Base case.

Case: S1-Base				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,437	126,9	4,84	0,0350
2	0,437	127,0	4,85	0,0690
3	0,437	126,9	4,84	0,0510
4	1,143	369,0	5,38	0,0840
5	1,143	369,0	5,38	0,3380
6	1,143	369,2	5,38	0,6630
7	1,143	369,0	5,38	0,6060
8	1,143	369,0	5,38	0,1940
9	1,143	369,0	5,38	0,3770
10	1,210	387,0	5,33	0,0400
11	1,143	369,0	5,38	0,6530
12	1,143	369,0	5,38	0,3910
13	1,336	429,2	5,35	0,0190
14	1,324	425,1	5,35	0,0420
15	1,324	425,0	5,35	0,1470
16	1,324	425,0	5,35	0,3340
17	1,591	512,2	5,37	0,0570
18	1,776	572,6	5,38	0,4400
19	1,776	572,6	5,38	0,3980
20	1,806	583,4	5,39	0,0360
SAIFI (int./yr.cust.	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,235	396,96	4,974		

Table 5-2: Results of Case S1-1

Case: S1-1 Remove BS at load point 13				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,387	126,1	5,43	0,0349
2	0,387	126,3	5,44	0,0684
3	0,387	126,1	5,43	0,0502
4	1,093	366,0	5,58	0,0830
5	1,093	366,0	5,58	0,3355
6	1,093	366,2	5,58	0,6579
7	1,093	366,0	5,58	0,6009
8	1,093	366,0	5,58	0,1928
9	1,093	366,0	5,58	0,3740
10	1,160	384,0	5,52	0,0397
11	1,093	366,0	5,58	0,6473
12	1,093	366,0	5,58	0,3880
13	1,286	418,4	5,42	0,0188
14	1,274	421,3	5,51	0,0416
15	1,274	421,3	5,51	0,1453
16	1,274	421,3	5,51	0,3314
17	1,541	508,4	5,50	0,0568
18	1,726	568,9	5,49	0,4371
19	1,726	568,9	5,49	0,3954
20	1,756	579,6	5,50	0,0357
SAIFI (int./yr.cust.)	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,185	393,67	4,935		

Table 5-3: Results of Case S1-2.

Case: S1-2 Remove BS at load point 10				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,435	126,8	4,87	0,0351
2	0,435	127,0	4,87	0,0688
3	0,435	126,8	4,87	0,0505
4	1,141	371,1	5,42	0,0841
5	1,141	371,1	5,42	0,3401
6	1,141	371,2	5,42	0,6669
7	1,141	371,1	5,42	0,6092
8	1,141	371,1	5,42	0,1954
9	1,141	371,1	5,42	0,3791
10	1,160	376,6	5,41	0,0389
11	1,141	371,1	5,42	0,6562
12	1,141	371,1	5,42	0,3933
13	1,334	431,2	5,39	0,0194
14	1,322	427,1	5,39	0,0421
15	1,322	427,1	5,39	0,1473
16	1,322	427,1	5,39	0,3359
17	1,589	514,2	5,40	0,0574
18	1,774	574,6	5,40	0,4415
19	1,774	574,6	5,40	0,3994
20	1,804	585,4	5,41	0,0361
SAIFI (int./yr.cust.)	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,231	398,48	4,997		

Table 5-4: Results of Case S1-3.

Case: S1-3 Remove BS:s at load point 10 and 13				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,385	126,1	5,47	0,0349
2	0,385	126,2	5,47	0,0684
3	0,385	126,1	5,47	0,0502
4	1,091	371,1	5,67	0,0841
5	1,091	371,1	5,67	0,3401
6	1,091	371,2	5,67	0,6669
7	1,091	371,1	5,67	0,6092
8	1,091	371,1	5,67	0,1954
9	1,091	371,1	5,67	0,3791
10	1,110	376,6	5,65	0,0389
11	1,091	371,1	5,67	0,6562
12	1,091	371,1	5,67	0,3933
13	1,284	420,4	5,46	0,0189
14	1,272	423,4	5,55	0,0418
15	1,272	423,3	5,55	0,1460
16	1,272	423,3	5,55	0,3330
17	1,539	510,4	5,53	0,0570
18	1,724	570,9	5,52	0,4386
19	1,724	570,9	5,52	0,3968
20	1,754	581,6	5,53	0,0359
SAIFI (int./yr.cust.)	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,181	396,90	4,985		

6 Case Study S2: Effect of Reducing Feeder Sectionalizing Switches

On distribution networks sectionalizing switch devices are normally installed on feeders. They may be either load break separable devices or switches. They are provided at different locations for isolation of faulted sections from un-faulted portions of the system. After fault occurrence, the fault is located, and the relevant sectionalizing switches are subsequently opened or closed to isolate the fault. The un-faulted sections of the system can then be restored. In the network reconfiguration and restoration process, the sectionalizing switch devices play an important role, and are applied widely on distribution networks to avoid extended customer interruptions and thus to enhance service reliability.

It is however an unfortunate fact that a sectionalizing switch is subject to possible failures in the same way as all other types of network components. When it fails, for example, a short circuit on it, the fault causes the feeder circuit breaker to trip and disconnects all load points on the feeder. Placing more sectionalizing switches may introduce more active equipment failures to the network, and does not automatically increase system reliability.

In distribution system planning the number and location of sectionalizing switches is an important consideration. To ensure customer service reliability, it is essential to install reasonable number of sectionalizing switches at proper places.

Study the feeders of Vattenfall network shown in Figure 5-4. Five sectionalizing switches are installed on the main feeder, two of which are manual (BS3 and BS5) and three remote-controlled. These switches divide the feeder to six sections. To evaluate the impact of reducing the number of sectionalizing switches, define the following cases:

- Case S2-1: same as Base case but remove the manual feeder switch BS5_m (BS10178143).
- Case S2-2: same as Base case but remove the remote-controlled feeder switch BS7_r (BS10178155).
- Case S2-3: same as Base case but remove both the switch BS5_m and BS7_r.

Figures 6-1, 6-2, and 6-3 gives more details about these switches. The results of reliability calculations of these three cases are compared with Base case defined in Case study S1 and presented in Figures from 6-4 to 6-9. The detailed values of reliability indices of the case studies are given in Tables 6-1, 6-2, and 6-3.

The failure rates shown in Figures 6-4 and 6-5 confirm again that reducing the number of components decreases active component failure events and results in improvement in SAIFI and even the failure rates of certain load points.

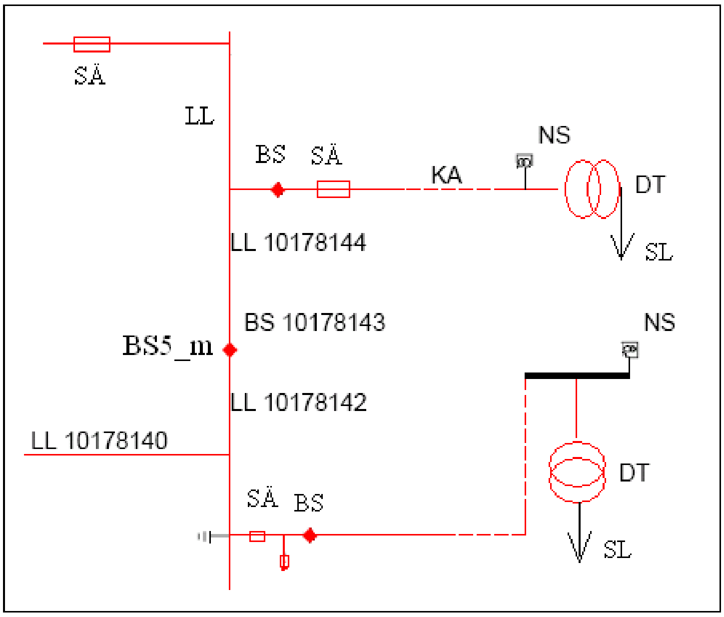


Figure 6-1: The manual sectionalizing switch BS5_m.

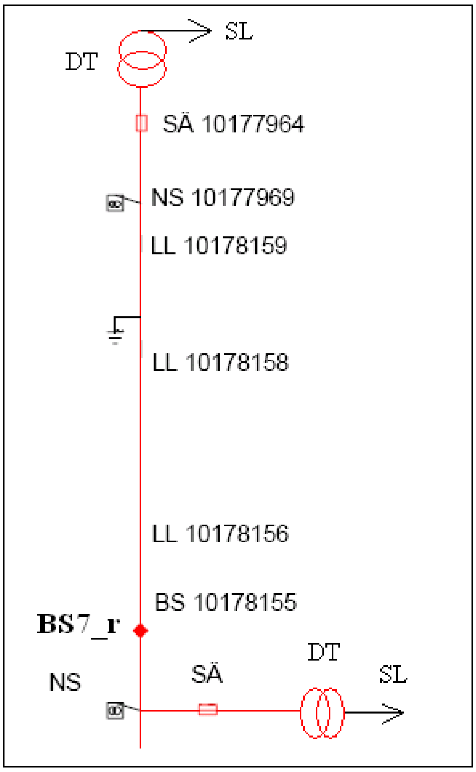


Figure 6-2: The remote-controlled sectionalizing switch BS7_r.

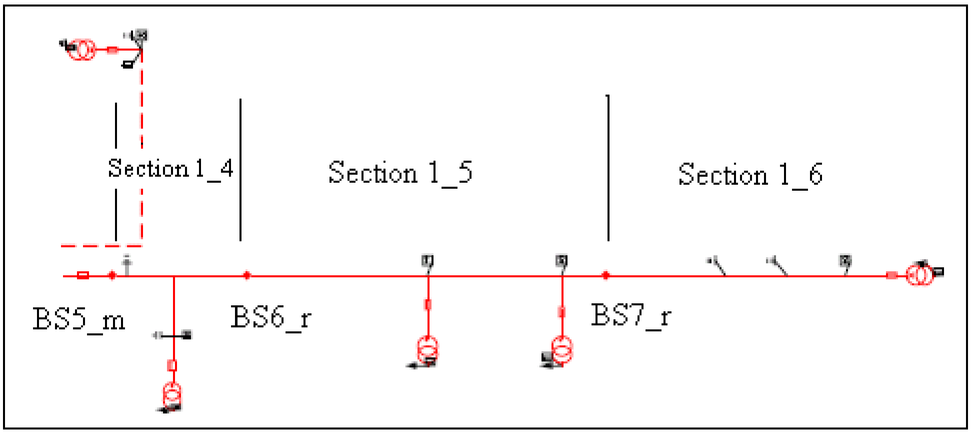


Figure 6-3: The sections divided by the switches BS5 and BS7.

The main feeder has a total length of approximately 15,5 km. The removal of the switches BS5_m and BS7_r reduces the sections from six to four. As observed in Figures 6-6 and 6-8, this reduction would not degrade SAIDI and ENSs.

The allocation of sectionalizers affects the system reliability. On radial feeder distribution system, sectionalizers are placed in order to improve the system reliability. They isolate the failed portion of the network while the rest of the system is supplied. However it cannot be concluded that an increased number of feeder sectionalizing switches automatically increases the reliability. The calculations of Case study S2 illustrate that installing more sectionalizers than that are needed does not give extra benefits in reliability improvement.

The failure rate of overhead lines used in the calculations includes both short circuit faults and line-to-ground faults that could trip circuit breakers. For the line-to-ground faults on the network part protected by a fuse, their effect on tripping the circuit breaker is considered by the stuck probability of the fuse.

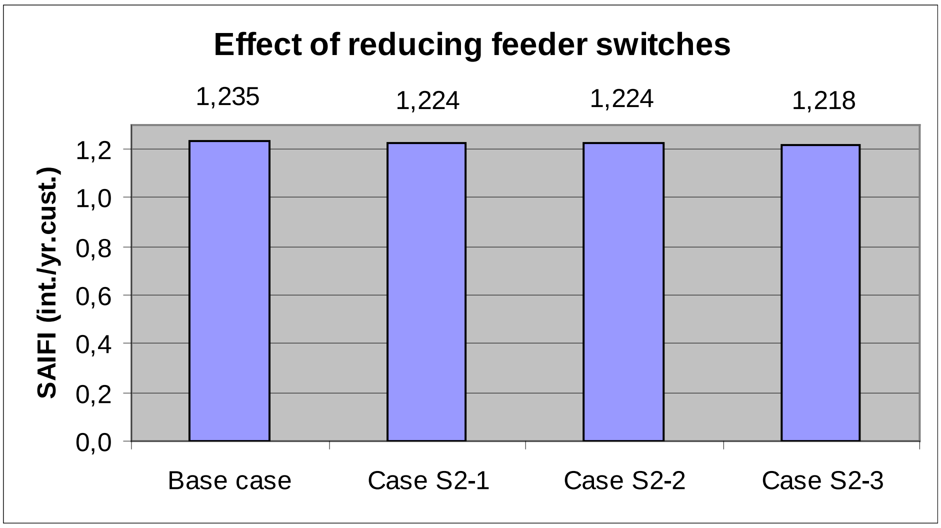


Figure 6-4: The results of Case study S2.

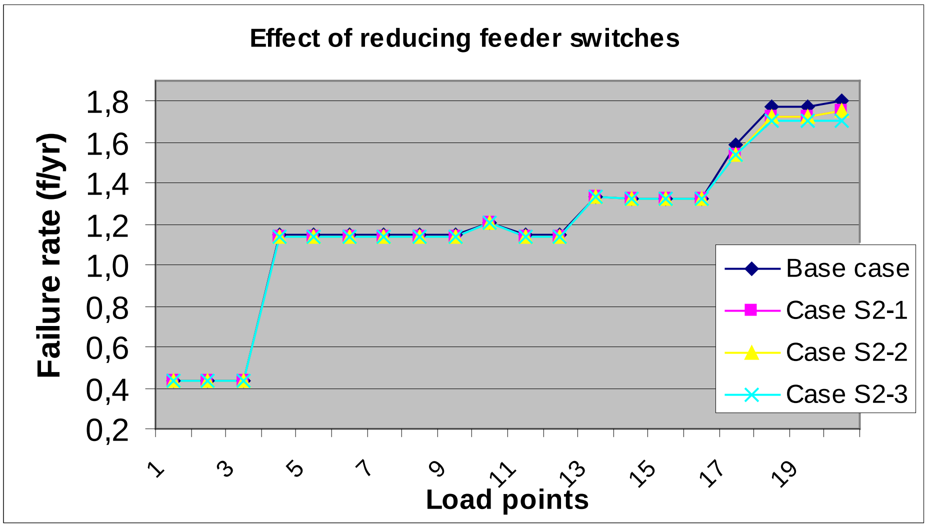


Figure 6-5: The results of Case study S2.

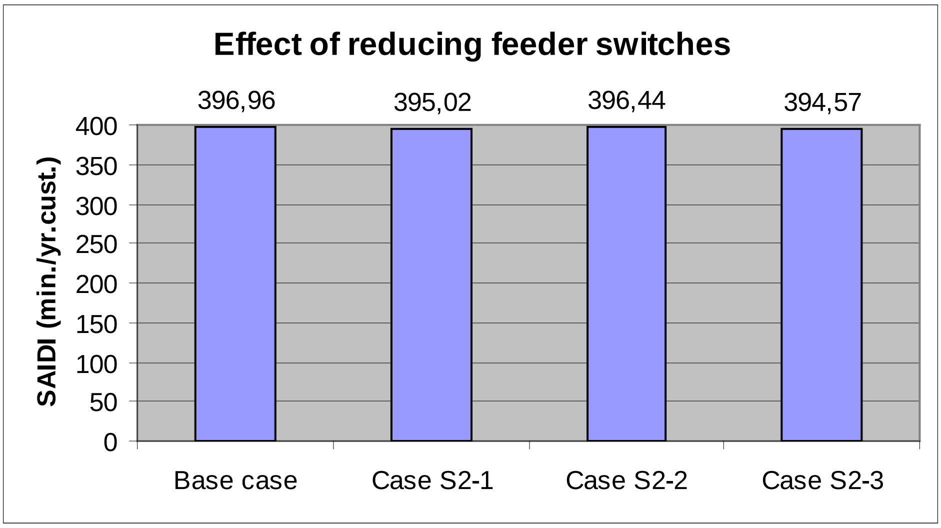


Figure 6-6: The results of Case study S2.

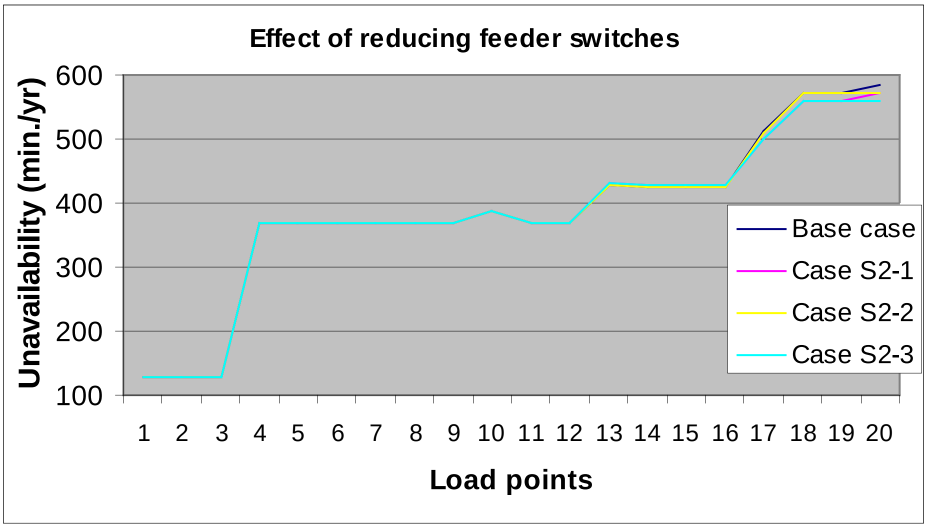


Figure 6-7: The results of Case study S2.

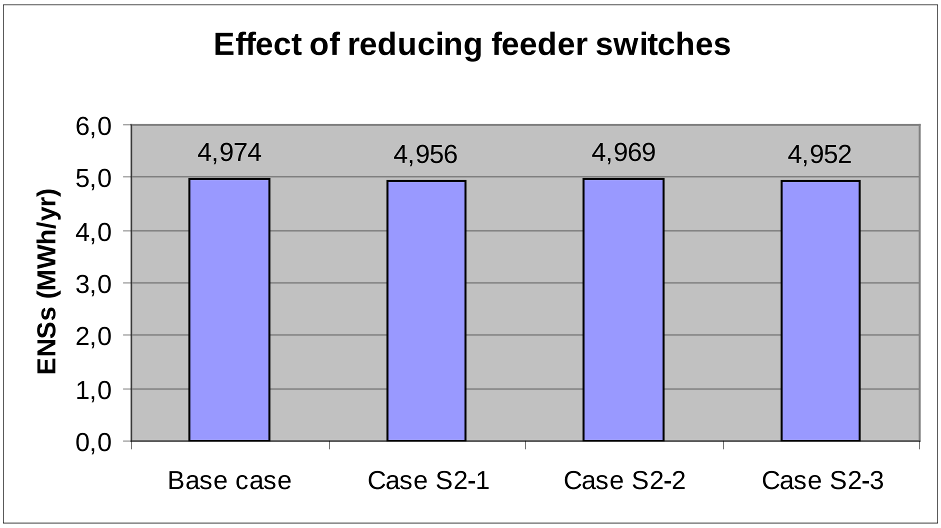


Figure 6-8: The results of Case study S2.

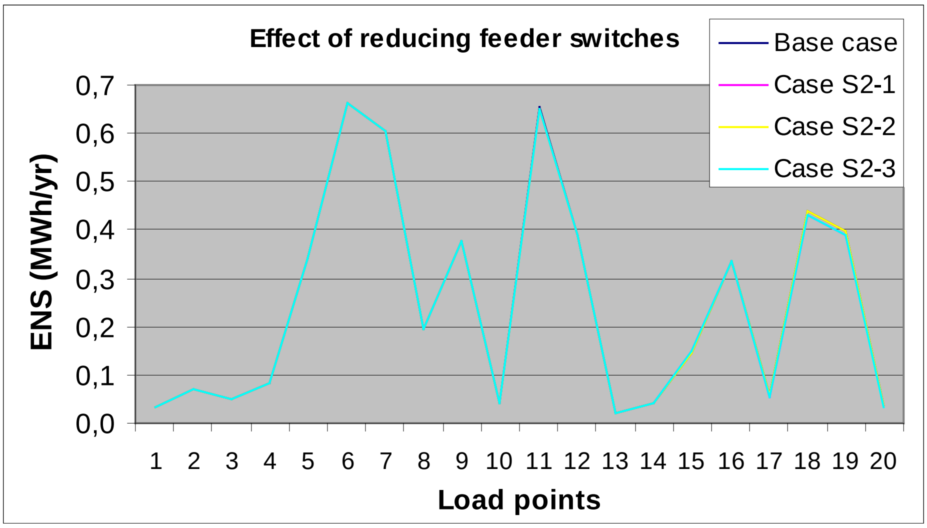


Figure 6-9: The results of Case study S2.

Table 6-1: The results of Case S2-1.

Case: S2-1 Remove BS5_m				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,435	126,8	4,87	0,0351
2	0,435	127,0	4,87	0,0688
3	0,435	126,8	4,87	0,0505
4	1,141	368,9	5,39	0,0836
5	1,141	368,9	5,39	0,3381
6	1,141	369,0	5,39	0,6630
7	1,141	368,9	5,39	0,6056
8	1,141	368,9	5,39	0,1943
9	1,141	368,9	5,39	0,3769
10	1,208	386,9	5,34	0,0400
11	1,141	368,9	5,39	0,6523
12	1,141	368,9	5,39	0,3910
13	1,333	431,3	5,39	0,0194
14	1,322	427,2	5,39	0,0421
15	1,322	427,1	5,38	0,1473
16	1,322	427,1	5,38	0,3360
17	1,541	500,2	5,41	0,0559
18	1,726	560,6	5,41	0,4308
19	1,726	560,6	5,41	0,3896
20	1,756	571,4	5,42	0,0352
SAIFI (int./yr.cust.)	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,224	395,02	4,956		

Table 6-2: The results of Case S2-2.

Case: S2-2 Remove BS7_r				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,435	126,8	4,87	0,0351
2	0,435	127,0	4,87	0,0688
3	0,435	126,8	4,87	0,0505
4	1,141	368,9	5,39	0,0836
5	1,141	368,9	5,39	0,3381
6	1,141	369,0	5,39	0,6630
7	1,141	368,9	5,39	0,6056
8	1,141	368,9	5,39	0,1943
9	1,141	368,9	5,39	0,3769
10	1,208	386,9	5,34	0,0400
11	1,141	368,9	5,39	0,6523
12	1,141	368,9	5,39	0,3910
13	1,334	429,1	5,36	0,0193
14	1,322	425,0	5,36	0,0419
15	1,322	424,9	5,36	0,1466
16	1,322	424,9	5,36	0,3342
17	1,541	509,2	5,51	0,0569
18	1,726	571,4	5,52	0,4390
19	1,726	571,4	5,52	0,3971
20	1,756	571,4	5,42	0,0352
SAIFI (int./yr.cust.	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,224	396,44	4,969		

Table 6-3: The results of Case S2-3.

Case: S2-3 Remove BS5_m and BS7_r				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,432	126,8	4,89	0,0351
2	0,432	126,9	4,90	0,0688
3	0,432	126,8	4,89	0,0505
4	1,138	368,7	5,40	0,0836
5	1,138	368,7	5,40	0,3380
6	1,138	368,9	5,40	0,6627
7	1,138	368,7	5,40	0,6053
8	1,138	368,7	5,40	0,1942
9	1,138	368,7	5,40	0,3767
10	1,205	386,7	5,35	0,0400
11	1,138	368,7	5,40	0,6520
12	1,138	368,7	5,40	0,3909
13	1,333	431,3	5,39	0,0194
14	1,322	427,2	5,39	0,0421
15	1,322	427,1	5,38	0,1473
16	1,322	427,1	5,38	0,3360
17	1,541	500,2	5,41	0,0559
18	1,706	559,4	5,46	0,4298
19	1,706	559,4	5,46	0,3888
20	1,706	559,4	5,46	0,0345
SAIFI (int./yr.cust.	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,218	394,57	4,952		

7 Case Study S3: Effect of Reducing Load-Disconnectors

Load-disconnectors are load break switches and widely used at distribution networks. They can open and close with normal load current flowing through them, and are used to visibly isolate parts of a distribution network during maintenance or repair periods. They can also be utilized to reconfigure connections distribution lines/cables and other equipment.

However load break switches occasionally fail in the same way like no-load break switches. A short circuit on load break switch can trip relevant feeder circuit breaker and interrupts the customers at the feeder load points.

On the Vattenfall rural system studied, load-disconnectors are installed at different locations on feeders or at tee-junctions. In the network portion shown in Figure 5-4, two load-disconnectors, BL1_r and BL2_r, are equipped at the feeding ends of lateral branches of load point 2 and 6. Figure 7-1 and 7-2 show the details of these switches.

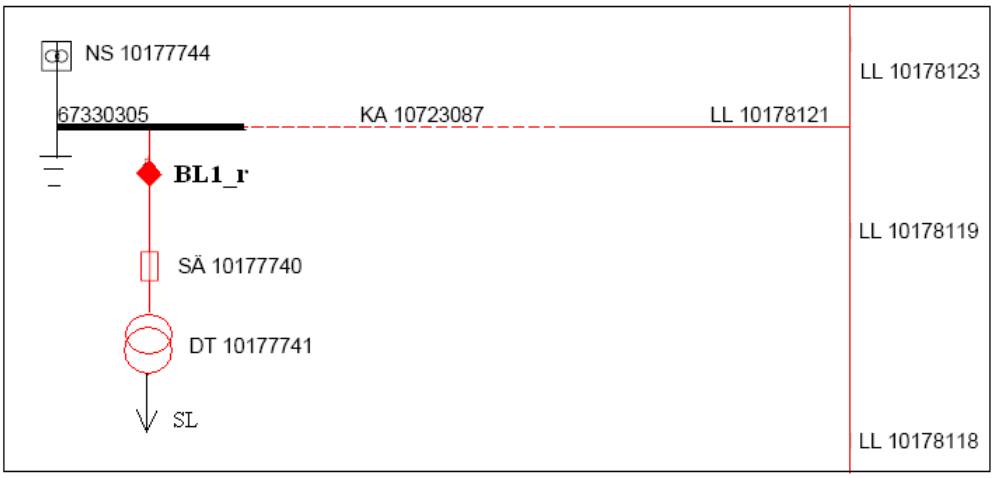


Figure 7-1: Load-disconnector BL1_r.

In order to study the impact of reducing load-disconnectors, the following three cases are evaluated:

- Case S3-1: same as Base case, but remove the load-disconnector BL1_r (BL10299463).
- Case S3-2: same as Base case, but remove the load-disconnector BL2_r (BL10299460).
- Case S3-3: same as Base case, but remove the two load-disconnectors BL1_r and BL2_r.

The reliability indices calculated for these cases are compared with the Base case and are presented in Figures from 7-3 to 7-8. Tables 7-1, 7-2, and 7-3 give the detail reliability indices for each of these cases.

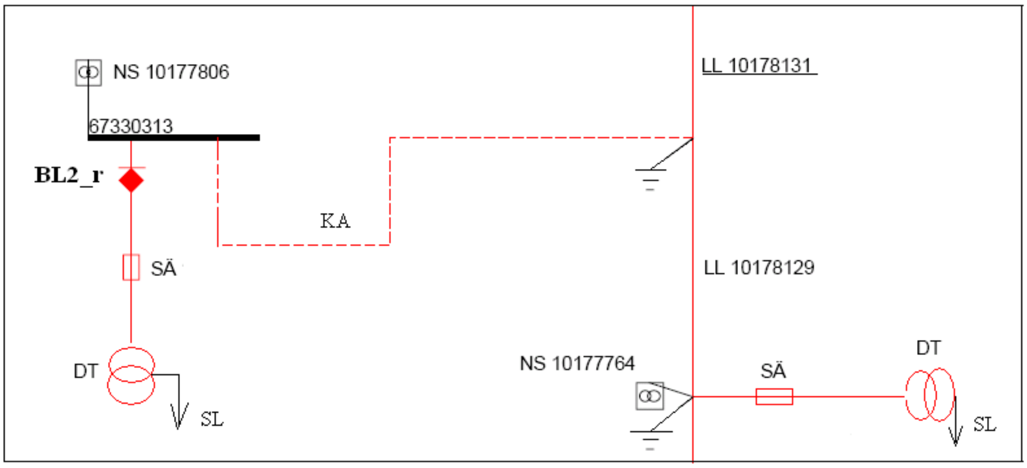


Figure 7-2: Load-disconnector BL2_r.

Since the load-switches BL1_r and BL2_r are installed at the start ends of the lateral branches, a fault on any of them causes the circuit breaker of the main feeder to open and disconnects all the load points on the main feeder. Removing theses load-switches eliminates the active failures on them and hence reduces the failure rates. This impact is clearly observed in Figure 7-3 and 7-4.

The comparison of the outage durations and energy not supplied with the Base case indicates that the removal of these load-switches does not affect these indices negatively. The reason is that in the failure event of the switch BL2, for example, the sectionalizing switches BS1 and BS3 should be opened to isolate the fault. This causes disconnection of the downstream of the sectionalizer BS1. The restoration of the downstream load points 4-20 becomes impossible until the repair of the load switch BL2 has completed. Removing the load-switch BL2 avoids the customer outages caused by its failure events.

It should be pointed out that the major benefit of load-break switches is the reduction or elimination of customer interruptions due to planned outages. The effect of load-break switches on outage durations should consider their impact of planned outages and maintenance. The reasonable extent to which load-break switches are used should therefore be evaluated on the basis of both forced equipment failures and the anticipated frequency of planned outages.

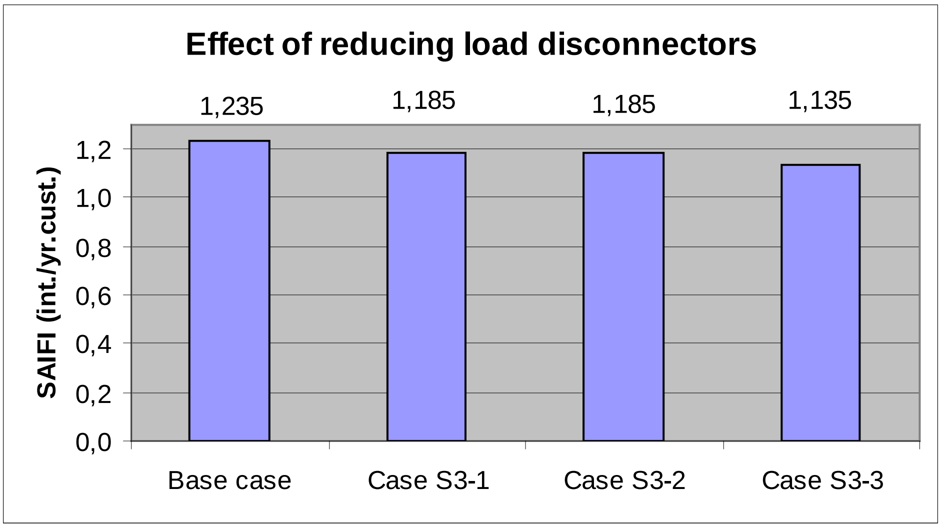


Figure 7-3: Results of Case study S3.

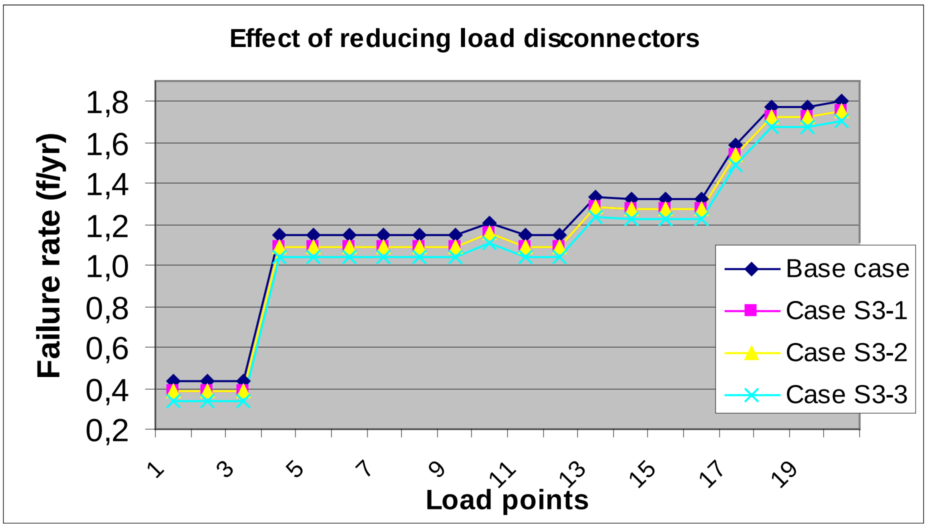


Figure 7-4: Results of Case study S3.

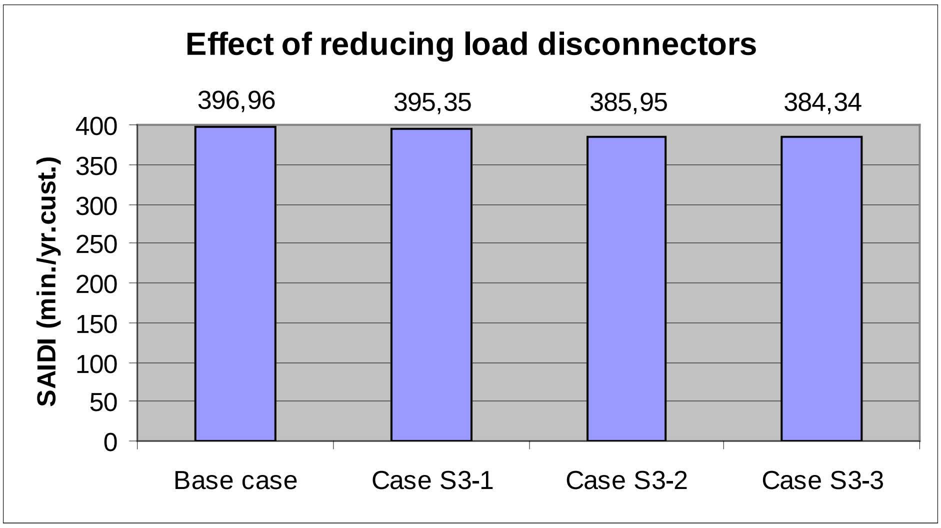


Figure 7-5: Results of Case study S3.

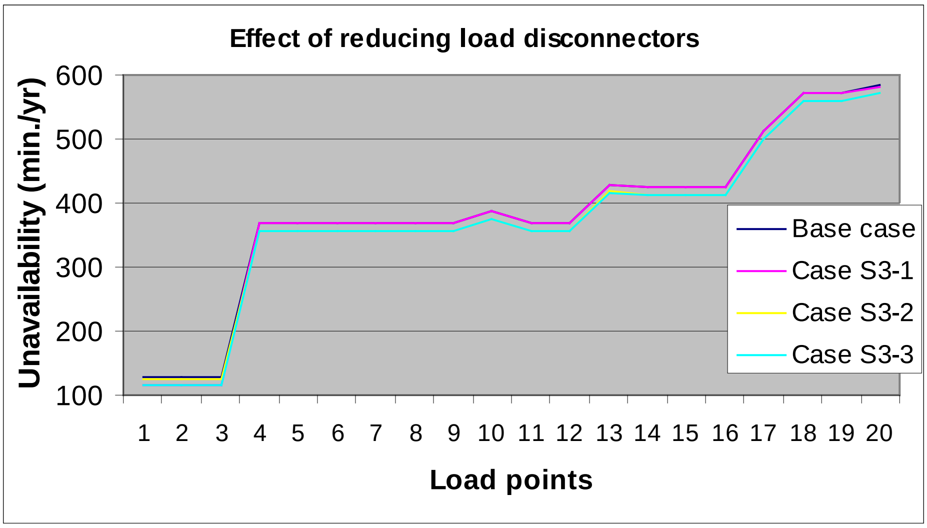


Figure 7-6: Results of Case study S3.

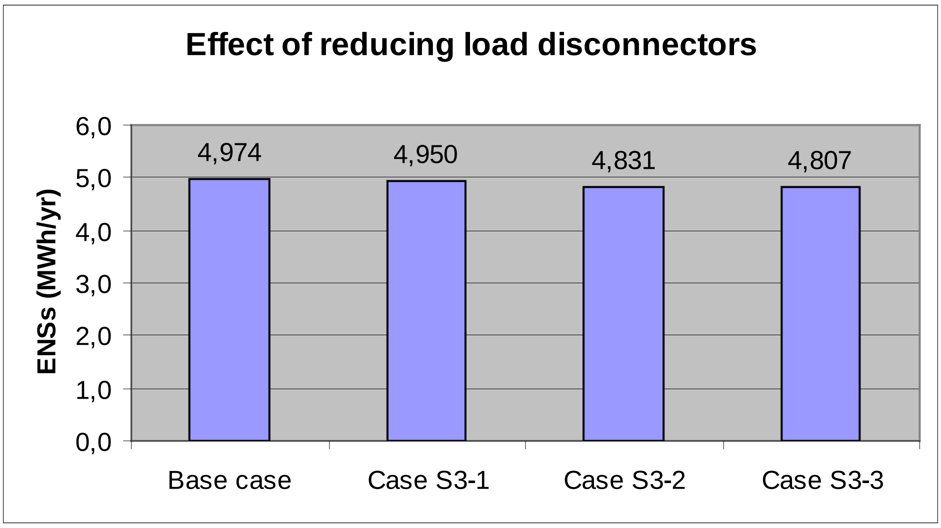


Figure 7-7: Results of Case study S3.

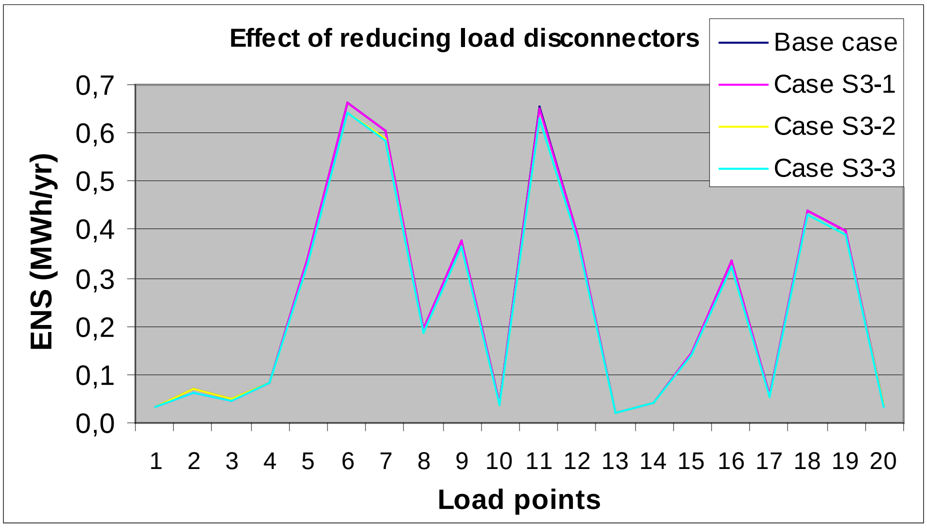


Figure 7-8: Results of Case study S3.

Table 7-1: The reliability indices of Case S3-1.

Case: S3-1 Remove BL1_r at load pint 2				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,387	115,0	4,95	0,0318
2	0,387	115,0	4,95	0,0623
3	0,387	115,0	4,95	0,0458
4	1,093	368,3	5,62	0,0835
5	1,093	368,3	5,62	0,3376
6	1,093	368,4	5,62	0,6619
7	1,093	368,3	5,62	0,6046
8	1,093	368,3	5,62	0,1940
9	1,093	368,3	5,62	0,3763
10	1,160	386,3	5,55	0,0399
11	1,093	368,3	5,62	0,6512
12	1,093	368,3	5,62	0,3904
13	1,286	428,5	5,55	0,0193
14	1,274	424,4	5,55	0,0419
15	1,274	424,3	5,55	0,1464
16	1,274	424,3	5,55	0,3338
17	1,541	511,4	5,53	0,0571
18	1,726	571,9	5,52	0,4394
19	1,726	571,9	5,52	0,3974
20	1,756	582,6	5,53	0,0359
SAIFI (int./yr.cust.	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,185	395,35	4,950		

Table 7-2: The reliability indices of Case S3-2.

Case: S3-2 Remove BL2_r at load pint 6				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,387	126,1	5,43	0,0349
2	0,387	126,3	5,44	0,0684
3	0,387	126,1	5,43	0,0502
4	1,093	357,2	5,45	0,0810
5	1,093	357,2	5,45	0,3274
6	1,093	357,2	5,45	0,6417
7	1,093	357,2	5,45	0,5864
8	1,093	357,2	5,45	0,1881
9	1,093	357,2	5,45	0,3649
10	1,160	375,1	5,39	0,0388
11	1,093	357,2	5,45	0,6316
12	1,093	357,2	5,45	0,3786
13	1,286	417,3	5,41	0,0188
14	1,274	413,2	5,41	0,0408
15	1,274	413,2	5,40	0,1425
16	1,274	413,2	5,40	0,3250
17	1,541	500,3	5,41	0,0559
18	1,726	560,8	5,41	0,4308
19	1,726	560,8	5,41	0,3897
20	1,756	571,5	5,42	0,0352
SAIFI (int./yr.cust.	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,185	385,95	4,831		

Table 7-3: The reliability indices of Case S3-3.

Case: S3-3 Remove BL1_r and BL2_r				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,337	114,3	5,65	0,0316
2	0,337	114,3	5,65	0,0619
3	0,337	114,3	5,65	0,0455
4	1,043	356,4	5,70	0,0808
5	1,043	356,4	5,70	0,3267
6	1,043	356,4	5,70	0,6404
7	1,043	356,4	5,70	0,5851
8	1,043	356,4	5,70	0,1877
9	1,043	356,4	5,70	0,3642
10	1,110	374,4	5,62	0,0387
11	1,043	356,4	5,70	0,6303
12	1,043	356,4	5,70	0,3778
13	1,236	416,6	5,62	0,0187
14	1,224	412,5	5,62	0,0407
15	1,224	412,4	5,62	0,1423
16	1,224	412,4	5,62	0,3244
17	1,491	499,6	5,58	0,0558
18	1,676	560,0	5,57	0,4303
19	1,676	560,0	5,57	0,3892
20	1,706	570,7	5,58	0,0352
SAIFI (int./yr.cust.	SAIDI (min./yr.cu	ENSs (MWh/yr)		
1,135	384,34	4,807		

8 Case Study S4: Effect of Reducing Number of Switch Devices

Switch devices, including load break switches, no-load break switches, sectionalizing switches, and lateral switches, play an important role for network reliability. How to place switch devices on a distribution network is an important consideration in network planning. Generally switch devices have potential to reduce outage durations and improve duration-oriented reliability indices by allowing faults to be isolated and customers to be restored before the fault is repaired.

However switch devices should be optimally allocated on the network. In order to achieve maximum benefits, right number of devices need to be installed at right locations. Place more switches than needed may eventually result in degradation of system reliability due to the failure probability of each switch.

To analyse possibility of simplifying network by reducing number of switch devices, an interesting investigation that can be made is to study how the system reliability varies when the locations and number of switch devices change.

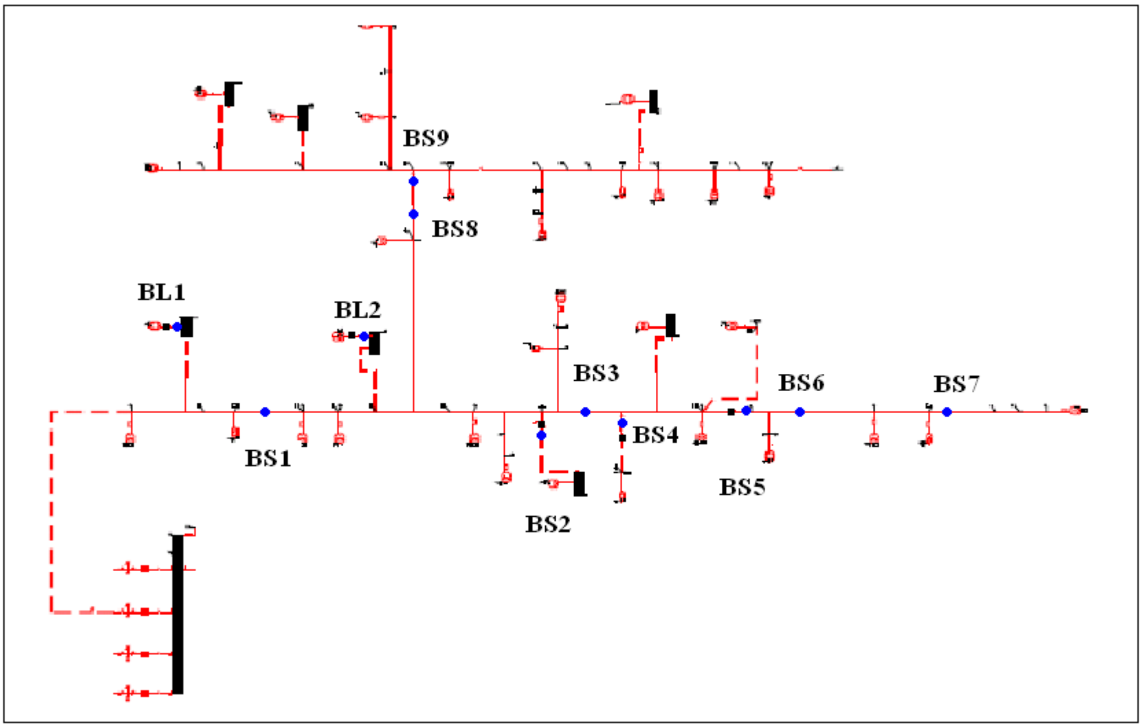


Figure 8-1: The network portion used in Case study S4.

A series of cases are specified. The cases are designed so that the switch devices are reduced gradually and each reduction is made at alternative locations. Reconsider the network portion shown in Figure 8-1. There are totally 11 switch devices, of which two are load-switches, two lateral switches, and seven sectionalizing switches. Table 8-1 lists all the cases specified, where the calculated indices for each case are also presented.

Table 8-1: Cases studied.

Case: S4 Impact of number of switches					
Case	Number of switches	Switches	SAIFI (int./yr.cust.	SAIDI (min./yr.cust.	ENSs (MWh/yr)
Base	11	BL1,BL2,BS1,**BS2-BS5**, BS6,BS7,BS8_as,BS9	1,235	396,960	4,974
S4-1	10	All, except **BS4**	1,185	393,247	4,931
S4-2	10	All, except **BS2**	1,231	397,014	4,978
S4-3	10	All, except **BS5**	1,224	395,024	4,956
S4-4	10	All, except BS7	1,224	396,440	4,969
S4-5	10	All, except BL1	1,185	395,350	4,950
S4-6	10	All, except BL2	1,185	385,946	4,831
S4-7	9	All, except **BS2,BS4**	1,181	395,011	4,962
S4-8	9	All, except **BS5,**BS7	1,218	394,573	4,952
S4-9	9	All, except BL1,BL2	1,135	384,335	4,807
S4-10	8	All, except **BS2,BS4,**BL1	1,131	393,461	4,940
S4-11	8	All, except **BS5,**BS7,BL1	1,168	392,968	4,928
S4-12	7	All, except **BS5,** BS7,**BS2,BS4**	1,164	389,785	4,908
S4-13	6	All, except **BS5,** BS7,**BS2,BS4**,BL1	1,114	388,175	4,885
S4-14	5	All, except **BS5,** BS7,**BS2,BS4**,BL1, BS6	1,105	394,793	4,932

The effect of number of switch devices can be visualized in Figures 8-2, 8-3, and 8-4. As expected the curve of SAIFI moves gradually downward when the devices are reduced. Figure 8-3 and 8-4 clearly show that the SAIDI and ENSs are sensitive to the locations of the switches.

It is observed that both SAIDI and ENSs vary as the number of devices change. But this reduction of the devices does not degrade the system reliability. As the devices are reduced from 11 to 5, the values of SAIDI and ENSs keep at the same level as that of Base case. This implies that there is a potential to simplify the existing network by reducing switch devices without affecting the reliability negatively.

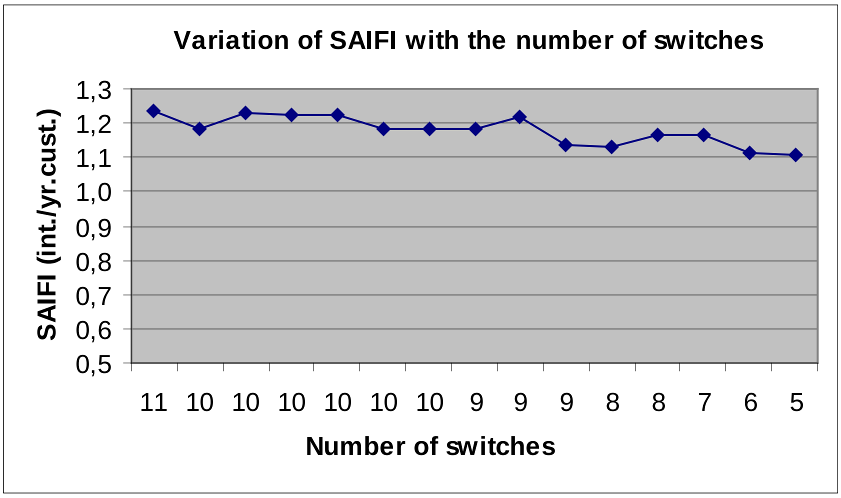


Figure 8-2: The results of Case study S4.

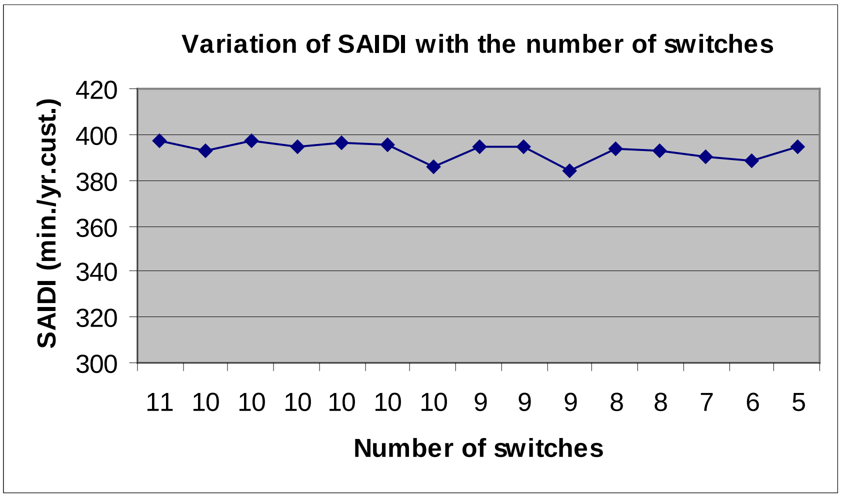


Figure 8-3: The results of Case study S4.

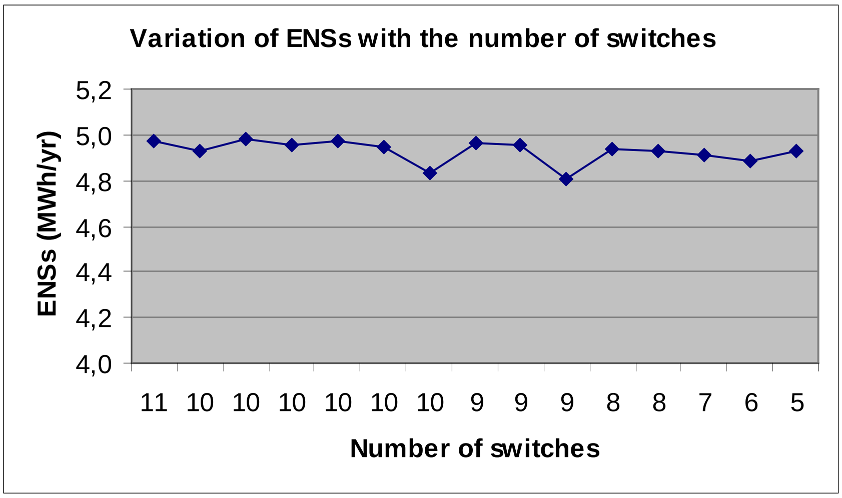


Figure 8-4: The results of Case study S4.

9 Case Study S5: Effect of Upgrading Manual Switches to Remote-controlled

Reliability and quality of supply have always primary importance for power utilities, and this importance will continue to grow in future. In reliability improvement of future distribution systems, using new technologies is an important aspect. Control and automation is an enabling technology. It facilitates the transference of physical requirement into an automated process. It is now recognized as a way that helps to increase the reliability of distribution systems.

Distribution automation and remote control extend to three levels: automated devices, substation automation, and distribution system automation. Automated and remote-controlled devices mean automation and control applications at component (device) level.

Installing remote controlled/automated switch devices will allow a system operator, or automatic restoration program, to quickly identify a faulted section and remotely/automatically operate certain switches to restore service to customers, to reduce significantly the average annual customer minutes of outages, and hence improve supply reliability.

Power distribution utilities are increasingly adopting automation and remote control to provide reliable services to electric consumers. Automation is the heart of a smart grid of the future. In developing future smart grid automation and remote control will play a key role to achieve high level of power supply reliability.

As analysed in previous chapters, there is possibility to simplify the existing networks by reducing devices. What is the impact of this simplification when the network is automated? This case study analyzes this effect.

Define three cases:

- Case S5-0: same as Base case but the switch time was set to two hours for manual switches and three minutes for remote controlled switches.
- Case S5-1: same as Case S5-0 but upgrade four manual switches BS2, BS3, BS4, and BS5 (BS2_m, BS3_m, BS4_m, BS5_m) shown in Figure 8-1 to remote-controlled.
- Case S5-2: same as Case S5-0 but upgrade only one manual switch BS3 to remote-controlled and remove the other three manual switches (BS2, BS4, BS5).

The calculated reliability indices of these cases are compared and are presented in Figures from 9-1 to 9-5. The detail indices of the three cases are given in Table 9-1, 9-2, and 9-3.

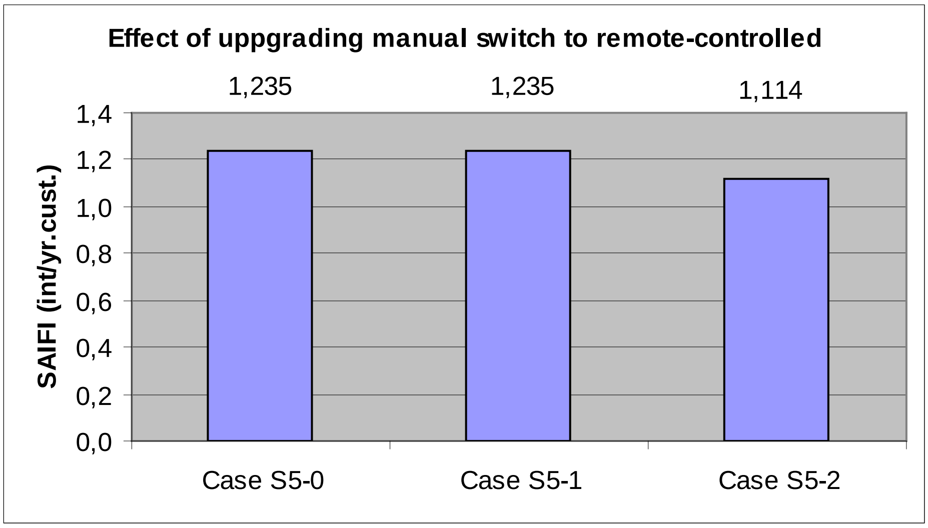


Figure 9-1: The results of Case study S5.

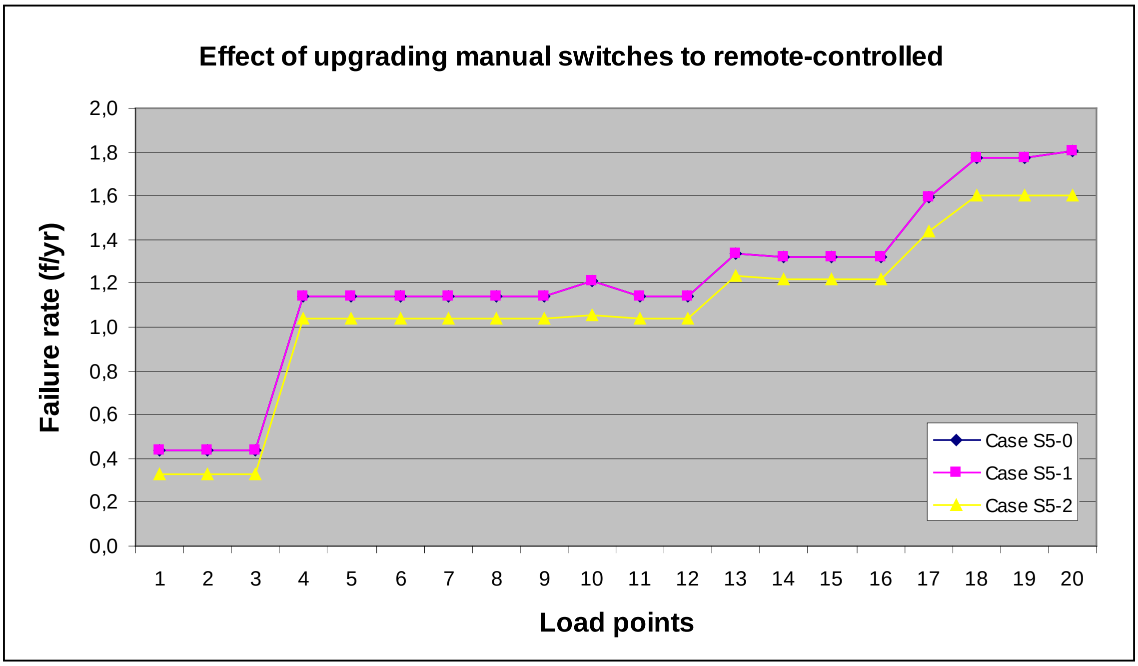


Figure 9-2: The results of Case study S5.

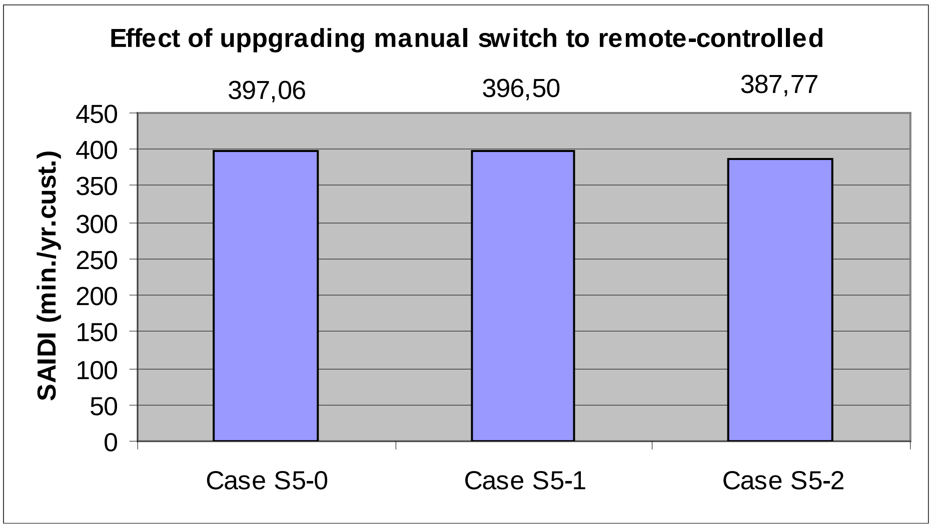


Figure 9-3: The results of Case study S5.

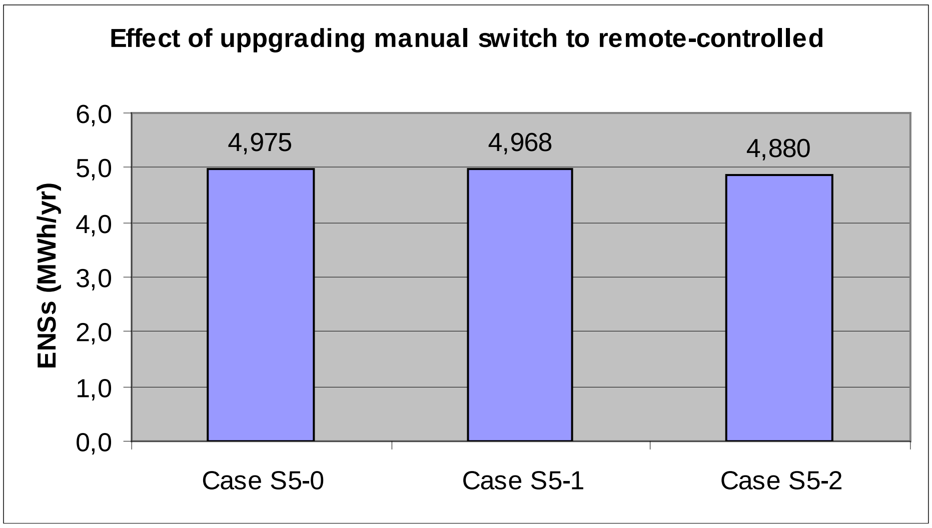
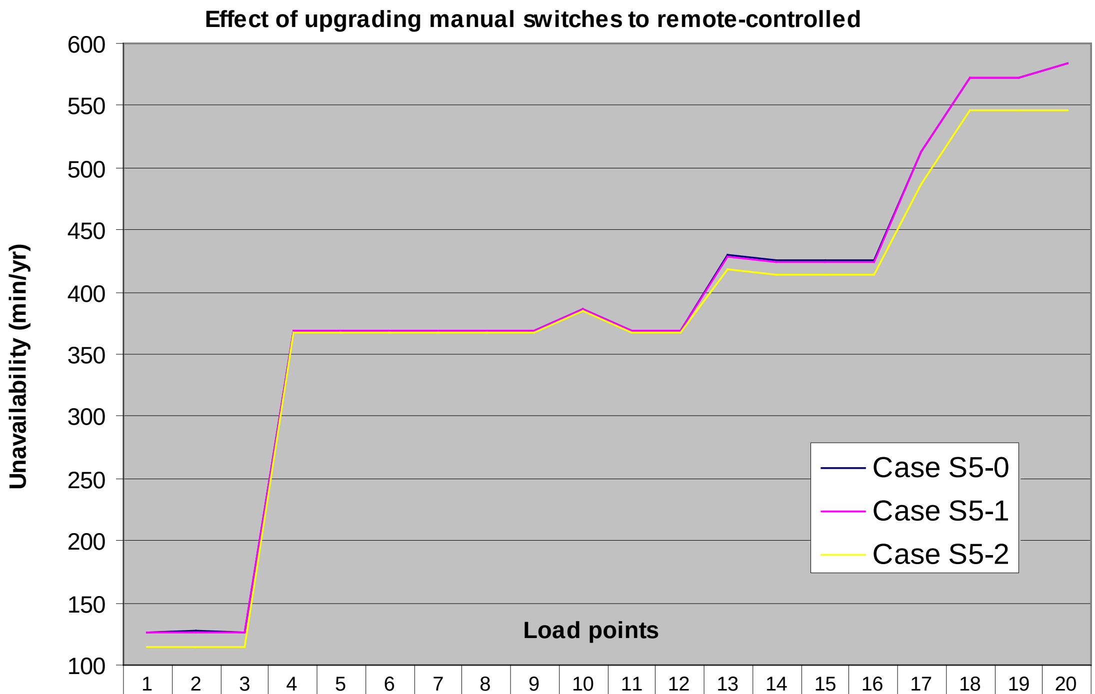


Figure 9-4: The results of Case study S5.

The reliability can be generally improved as manual switches are upgraded to remote controlled. However, it is evident that the remote control does not change the failure rate as shown in Figure 9-1. This is because the number of failures seen by the circuit breaker of the main feeder remains the same. The degree of the improvement in reliability is sensitive to locations of switches. It is seen that upgrading one switch after removing the other three manual switches in Case S5-2 gives more improvement in reliability index ENSs than

that in Case S5-1. Since the number of faults on the switches seen by the circuit breaker of main feeder decreases as the switch devices are reduced in Case S5-2, the individual contributions of equipment failures to outage durations and the annual unavailability decrease. This effect is reflected therefore not only in the failure rate measured by SAIFI, but also in the outage duration related indices measured by SAIDI and ENSs. It is noted that not all customers gain the same degree of benefit in reliability improvement by upgrading the switches. As shown in Figure 9-5 the load points 13-20 connected on downstream of the switch BS3 benefit more than other load points because they could now rapidly restored by remote control after fault occurrences.
The case study illustrates that it is beneficial to consider possibility of simplifying networks when automating the networks in order to ensure cost-effective investment.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Case S5-0	126,	127,	126,	369,	369,	369,	369,	369,	369,	387,	369,	369,	429,	425,	425,	425,	512,	572,	572,	583,
Case S5-1	126,	126,	126,	368,	368,	368,	368,	368,	368,	386,	369,	369,	428,	424,	424,	424,	512,	572,	572,	583,
Case S5-2	114,	114,	114,	366,	366,	366,	366,	366,	366,	384,	366,	366,	417,	413,	413,	413,	486,	545,	545,	545,

Figure 9-5: The results of Case study S5.

Table 9-1: The results of Case S5-0.

Case: S5-0				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,437	126,87	4,84	0,0350
2	0,437	127,02	4,85	0,0690
3	0,437	126,87	4,84	0,0510
4	1,143	369,02	5,38	0,0840
5	1,143	369,02	5,38	0,3380
6	1,143	369,17	5,38	0,6630
7	1,143	369,02	5,38	0,6060
8	1,143	369,02	5,38	0,1940
9	1,143	369,02	5,38	0,3770
10	1,210	387,05	5,33	0,0400
11	1,143	369,02	5,38	0,6530
12	1,143	369,02	5,38	0,3910
13	1,336	429,76	5,36	0,0190
14	1,324	425,67	5,36	0,0420
15	1,324	425,58	5,36	0,1470
16	1,324	425,58	5,36	0,3350
17	1,591	512,20	5,37	0,0570
18	1,776	572,65	5,38	0,4400
19	1,776	572,65	5,38	0,3980
20	1,806	583,39	5,39	0,0360
SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)		
1,235	397,06	4,975		

Table 9-2: The results of Case S5-1.

Case: S5-1: Upgrade four manual switches to remote-controlled				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,437	126,62	4,83	0,0350
2	0,437	126,77	4,83	0,0687
3	0,437	126,62	4,83	0,0504
4	1,143	368,29	5,37	0,0835
5	1,143	368,29	5,37	0,3376
6	1,143	368,43	5,37	0,6620
7	1,143	368,29	5,37	0,6046
8	1,143	368,29	5,37	0,1940
9	1,143	368,29	5,37	0,3763
10	1,210	386,21	5,32	0,0399
11	1,143	369,02	5,38	0,6526
12	1,143	369,02	5,38	0,3912
13	1,336	428,67	5,35	0,0193
14	1,324	424,57	5,34	0,0419
15	1,324	424,49	5,34	0,1464
16	1,324	424,49	5,34	0,3339
17	1,591	512,14	5,37	0,0572
18	1,776	572,59	5,37	0,4399
19	1,776	572,59	5,37	0,3979
20	1,806	583,33	5,38	0,0360
SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)		
1,235	396,50	4,968		

Table 9-3: The results of Case S5-2.

Case: S5-2: Upgrade one manual switch to remote-controlled				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,330	114,0	5,77	0,032
2	0,330	114,2	5,78	0,062
3	0,330	114,0	5,77	0,045
4	1,036	366,8	5,90	0,083
5	1,036	366,8	5,90	0,336
6	1,036	367,0	5,91	0,659
7	1,036	366,8	5,90	0,602
8	1,036	366,8	5,90	0,193
9	1,036	366,8	5,90	0,375
10	1,055	384,8	6,08	0,040
11	1,036	366,8	5,90	0,649
12	1,036	366,8	5,90	0,389
13	1,231	417,9	5,66	0,019
14	1,220	413,8	5,66	0,041
15	1,220	413,7	5,65	0,143
16	1,220	413,7	5,65	0,325
17	1,439	486,8	5,64	0,054
18	1,604	545,9	5,67	0,419
19	1,604	545,9	5,67	0,379
20	1,604	545,9	5,67	0,034
SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)		
1,114	387,775	4,880		

10 Case Study S6: Effect of Adding Reserve Power Feeding

The distribution system of the past is characterized by radial configuration. The distribution system of the future is interconnected and intelligent. There are many technologies and methods that will have a role, more or less, to move distribution systems forward towards future smart grids. This includes advanced digital meters, distribution automation, communication systems, and distributed energy resources.

Distributed generation dominant contribution from renewable local power production will continue to increase its penetration into distribution networks of the future. The integration of local generation will affect the network technically in a number of ways and bring significant effect on network infrastructure in the future.

The local generation can have impact on systems, such as voltage support, reserve power feeding, and reliability improvement. In order to understand effect of local reserve power on the reliability and how the benefit gained in reliability could be influenced by the possible network simplification, two cases are designed and studied in this Chapter.

Considering that the feeder downstream of BS3 on the network studied would be left disconnected in a failure event on the feeder, a local reserve power G is added at the end of the feeder near load point 20 as shown in Figure 10-1.

Assume that when the system main supply is interrupted due to the outage at the upstream of the main feeder, the un-faulted downstream is supplied from the local reserve feeding G. The following two cases are evaluated:

- Case S6-1: same as Base case but enhancing the network by adding a local reserve power G at load point 20.
- Case S6-2: same as S6-1 but removing five switches: BL1, BS2, BS4, BS5, and BS7.

The calculated indices are compared with the Base case. The results are presented in Figures from 10-2 to 10-7. Table 10-1 and 10-2 summarize the calculated indices.

It is evident that adding the local reserve power as in Case S6-1 does not improve the rate of failure. However the annual unavailability measured by SAIDI and energy not supplied decrease significantly. Since the downstream of the feeder can now be quickly restored by the reserve power from the local generation G in the case of a failure event on the feeder upstream. The results of Case S6-1 confirm that providing reserve power is an efficient way to increase system reliability. The curves in Figures 10-5 and 10-7 show that the customers connected on the downstream at load points 13-20 receive most benefit from adding the local generation because they are directly connected to the backfeed.

The results of Case S6-2 indicate that the simplification of the network could further improve reliability by reducing equipment failures. The rate of failure measured by SAIFI is decreased in Case S6-2 compared with Base case as indicated in Figure 10-2. This implies that it is beneficial to consider possibility of simplifying networks when introducing distributed generation and local reserve feedings into the networks to ensure cost-effective investment in future systems.

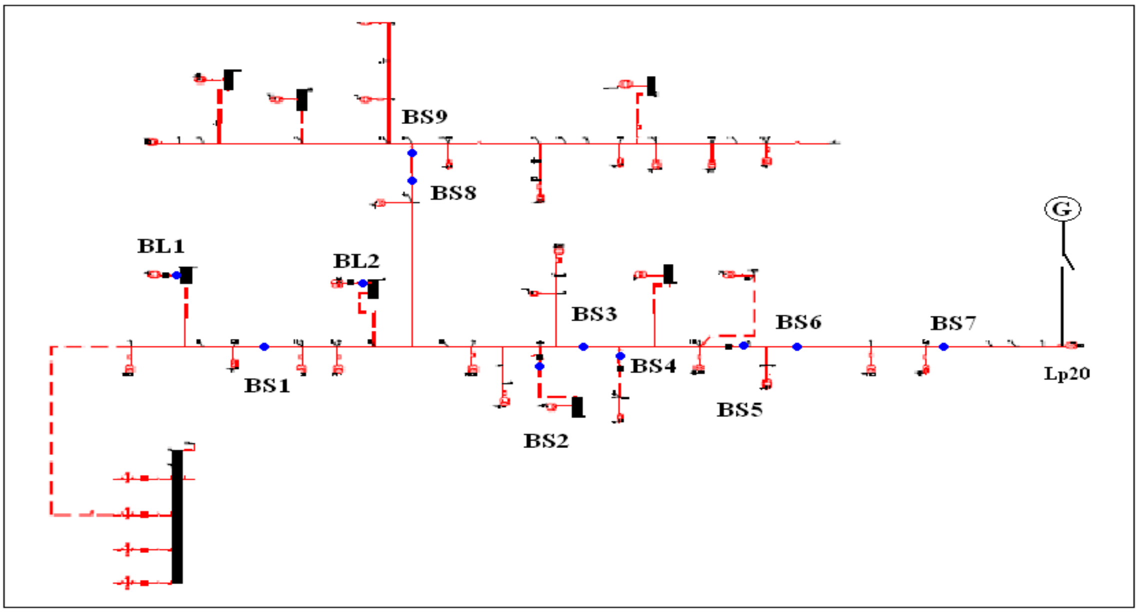


Figure 10-1: A local reserve power at load point 20.

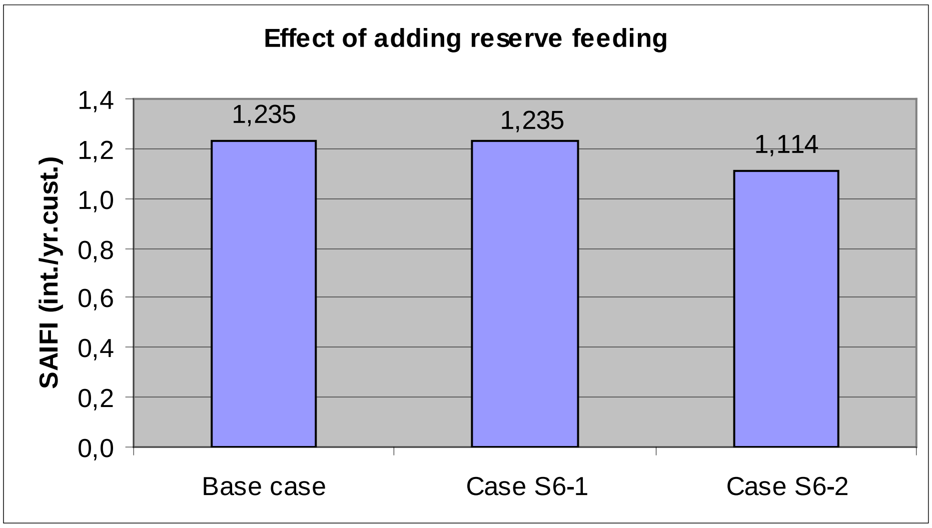


Figure 10-2: The results of Case study S6.

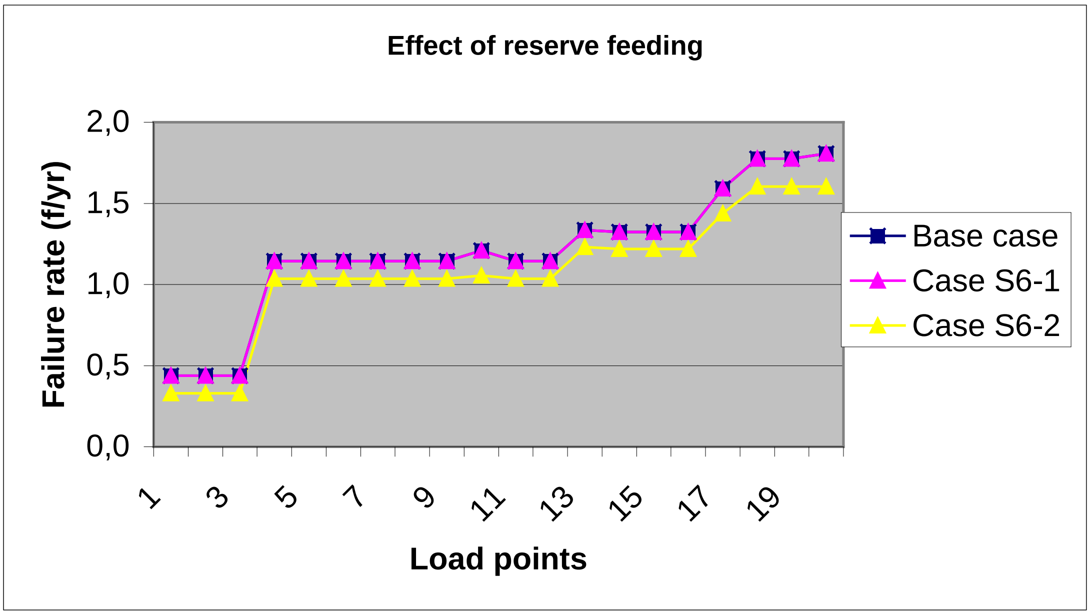


Figure 10-3: The results of Case study S6.

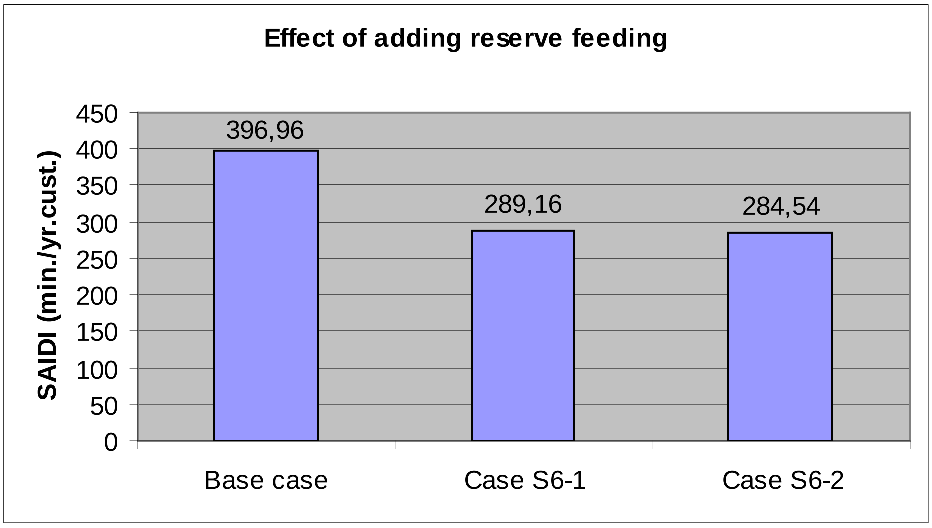


Figure 10-4: The results of Case study S6.

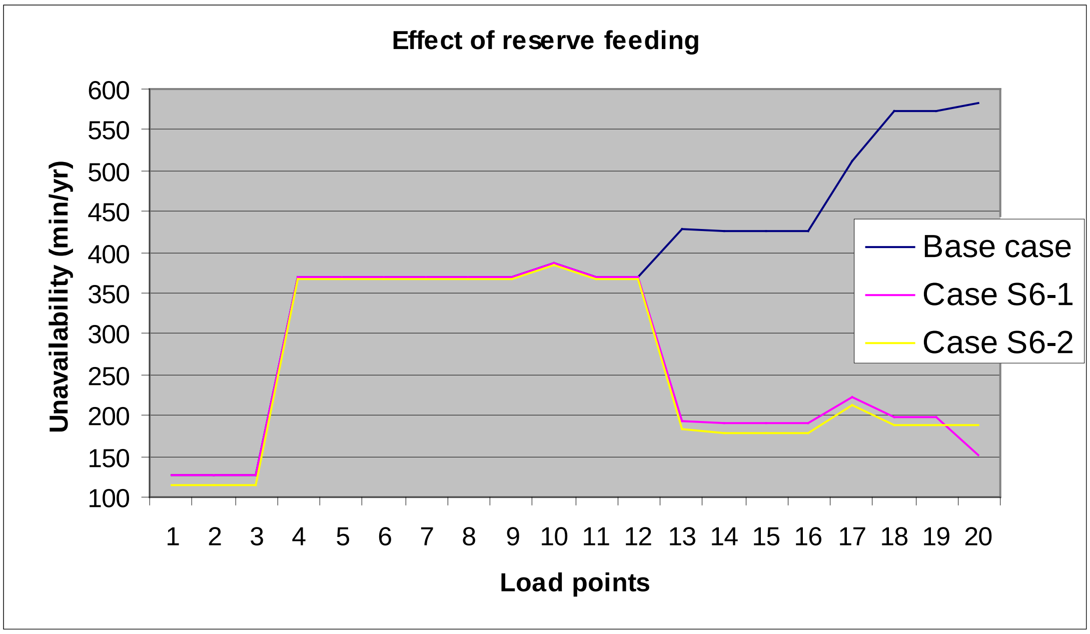


Figure 10-5: The results of Case study S6.

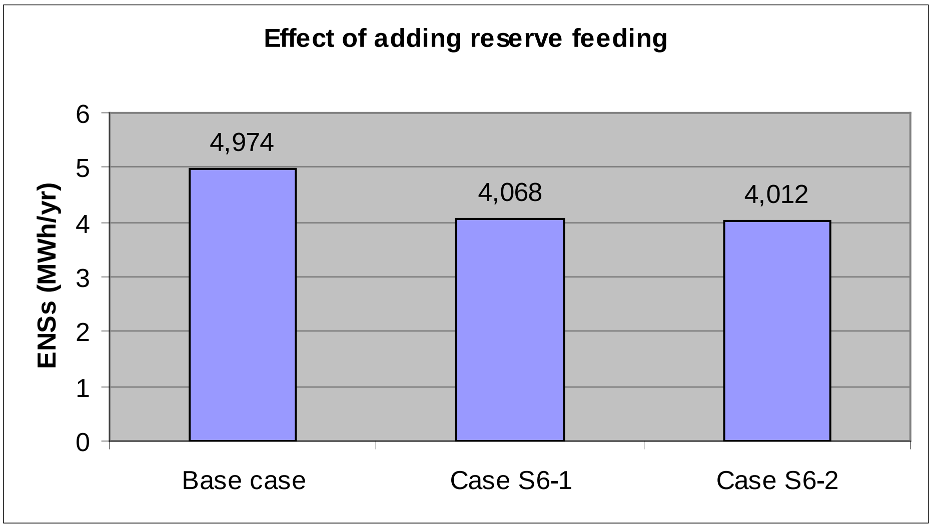


Figure 10-6: The results of Case study S6.

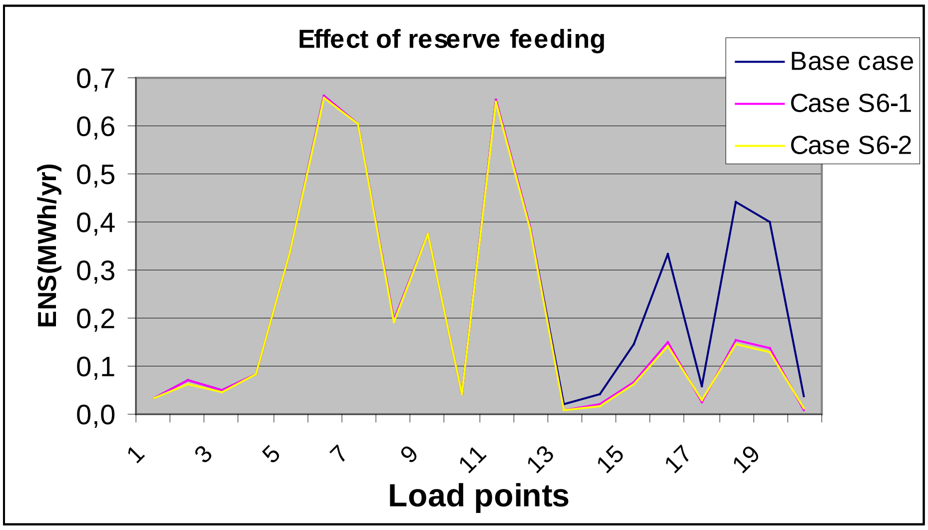


Figure 10-7: The results of Case study S6.

Table 10-1: The reliability indices of Case S6-1.

Case: S6-1: Same as Base case, but with reserve feeding at load point 20				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,437	126,9	4,84	0,035
2	0,437	127,0	4,84	0,069
3	0,437	126,9	4,84	0,051
4	1,143	369,0	5,38	0,084
5	1,143	369,0	5,38	0,338
6	1,143	369,2	5,38	0,663
7	1,143	369,0	5,38	0,606
8	1,143	369,0	5,38	0,194
9	1,143	369,0	5,38	0,377
10	1,210	387,0	5,33	0,040
11	1,143	369,0	5,38	0,653
12	1,143	369,0	5,38	0,391
13	1,336	194,1	2,42	0,009
14	1,324	190,0	2,39	0,019
15	1,324	190,0	2,39	0,066
16	1,324	190,0	2,39	0,149
17	1,591	222,9	2,34	0,025
18	1,776	198,8	1,87	0,153
19	1,776	198,8	1,87	0,138
20	1,806	150,9	1,39	0,009
SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)		
1,235	289,156	4,068		

Table 10-2: The reliability indices of Case S6-2.

Case: S6-2: Same as Case S6-1, but removing five switches.				
Load point	λ (f/yr)	U (min/yr)	r (h/f)	ENS (MWh/yr)
1	0,330	114,2	5,77	0,032
2	0,330	114,3	5,78	0,062
3	0,330	114,2	5,77	0,045
4	1,036	367,2	5,91	0,083
5	1,036	367,2	5,91	0,337
6	1,036	367,3	5,91	0,660
7	1,036	367,2	5,91	0,603
8	1,036	367,2	5,91	0,193
9	1,036	367,2	5,91	0,375
10	1,055	385,2	6,09	0,040
11	1,036	367,2	5,91	0,649
12	1,036	367,2	5,91	0,389
13	1,231	182,8	2,48	0,008
14	1,220	178,8	2,44	0,018
15	1,220	178,7	2,44	0,062
16	1,220	178,7	2,44	0,141
17	1,439	251,8	2,92	0,028
18	1,604	188,4	1,96	0,145
19	1,604	188,4	1,96	0,131
20	1,604	188,4	1,96	0,012
SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)		
1,114	284,538	4,012		

11 Urban System Analysis

An urban distribution network supplies power to a city. Its topological structure is usually characterized by looped and meshed underground cable network. Today, underground distribution networks have become a well-established and crucial part of the utility power systems and are required to deliver high levels of reliability and power service to city industrial, commercial, and residential customers.

Utility urban distribution systems are, as rural networks, challenged by an aging infrastructure, conventional designs, and increasing customer and society demands for higher reliability and power quality. The pressures of economics and reliability have caused electric utilities to seek efficient ways to manage their urban distribution systems. In addition to increases in system enforcement investment, the utilities give further emphasis to system optimal planning, design and engineering, and reliable system construction of the future urban underground systems.

This Chapter and subsequent Chapters 12-17 analyze the inherent reliability of an urban distribution system. The analysis focuses on the possibilities to simplify the network structure and system design with an emphasis on reliability performance and quantification. The reliability quantification is associated with different alternatives of system designs and network structure changes including the connection of back up feedings and the use of network devices. The analysis is intended to provide more bases and promote engineering practices that will contribute to the development of economical, and reliable rural distribution systems of the future.

11.1 Urban Network Studied

The system studied is a typical urban network from Vattenfall Distribution Nordic over Uppsala west. It has typical structure characteristics of power network for large cities. The network consists of underground feeders that deliver power from distribution primary substations to secondary substations. A main feeder begins with a feeder breaker with an associated disconnector switch at the primary substations and then is routed around the feeder service area. A main feeder is usually connected to other feeders through normally open tie switches.

From a main feeder, a number of underground laterals may be taped off to cover power demand of a feeder’s service territory. The laterals are normally protected by fuses and connected to main feeder through fuse-load switches. A number of load-switches are installed along the main feeder at tap points to allow feeder reconfiguration.

To accomplish feeder routes passing near every customer, each primary substation uses multiple main feeders to cover the service area. In most cases, these feeder routings are interconnected and linked by normally open tie switches to permit back up feedings.

Figure 11-1 shows the meshed underground system studied. The network connects two primary substations and distributes power to 31 secondary substations spread in the service territories. The total length of the underground cables in the network is approximately 30 km. No overhead lines are used. Table 11-1 summarizes the items of the system.

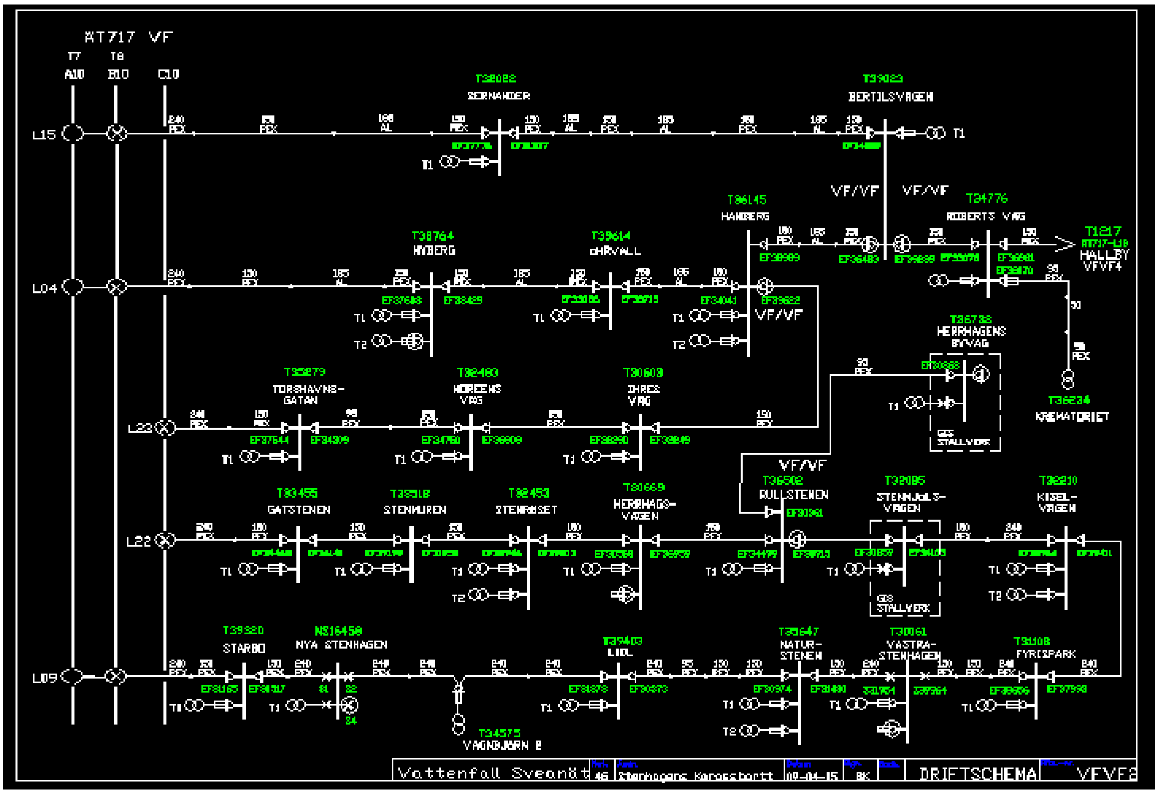


Figure 11-1: Urban network studied.

Table 11-1: Summary of the network objects

Items	Number
Primary substation	2
Secondary substation	31
Underground cable	29,51 km
Circuit breaker	7
Fuse-load-switch	87
Disconnect-switch	14
Distribution transformer	36
Customer	3813
Customer load	8906 kW

In the secondary substations, distribution transformers step down the voltage from 11 kV to 0.4 kV to serve the customers connected to it. A total of 3813 customers are served by the system. The total average load demand of the network is approx. 8906 kW.

11.2 Structure Characteristics

Although the network studied is a typical utility system, it is recognized that the system was built and constructed by basic configurations and common feeder routings for urban systems. In order to understand the structure features of the system, these basic feeder configurations are described below.

A. Open-loop configuration

It is a simple and commonly used basic configuration of MV primary main feeder as shown in Figure 11-2. It has two radial feeders separately routed from a power source through load areas and tying together by means of normally open switching devices. In the normal operation, the system effectively operates as two radial feeders. In this configuration, feeders and loop components have sufficient reserve capacity to serve the load that may be transferred through the loop switching. The failure and isolation of the source of one line section will not result in an extended outage. At the load tap points which are supplying individual distribution load have some form of disconnecting devices on the incoming and outgoing feeder and on the transformer. Manual, automatic or supervisory controlled switching is usually provided to isolate faulted line sections and close-in alternate feeders so that service to the un-faulted sections can be restored quickly.

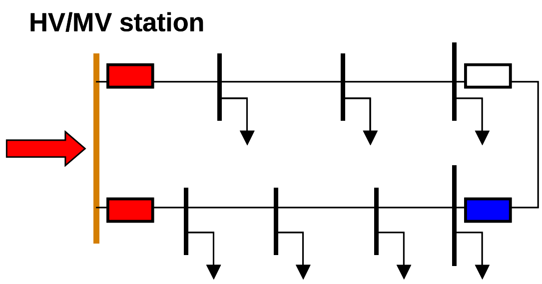


Figure 11-2: Open-loop feeder configuration.

B. Double open-loop configuration

A system similar in design and configuration to open-loop configuration but is with one more feeder constituting two loops, as shown in Figure 11-3. This system consists of three radial main feeders which may originate from the same or different bus-bars at a primary substations. Each of feeders normally has reserve loading capacity to supply the entire load in the event of outage of the other feeder. Loss of any feeder will result in interruption of service until the load interrupted is transferred to the other feeder by automatic, supervisory, or manually controlled tie switches. This feeder configuration costs more than parallel radial feeders but can substantially reduce the frequency and duration of customer interruptions.

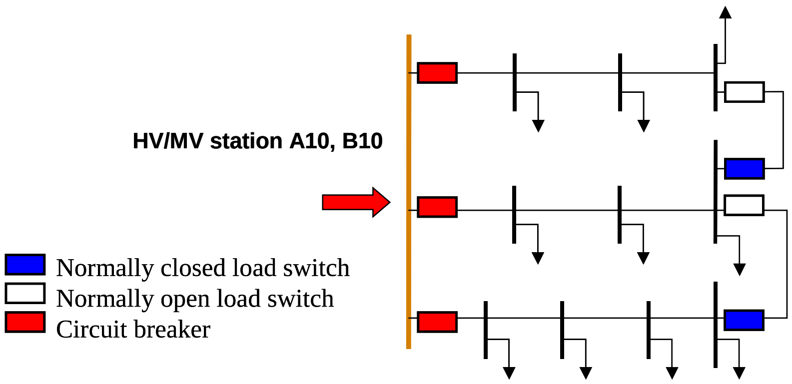


Figure 11-3: Double open-loop feeder configuration.

C. Multiple open-loop configurations

A main feed system consisting of duplicate open-loop feeder configurations is shown in Figure 11-4.

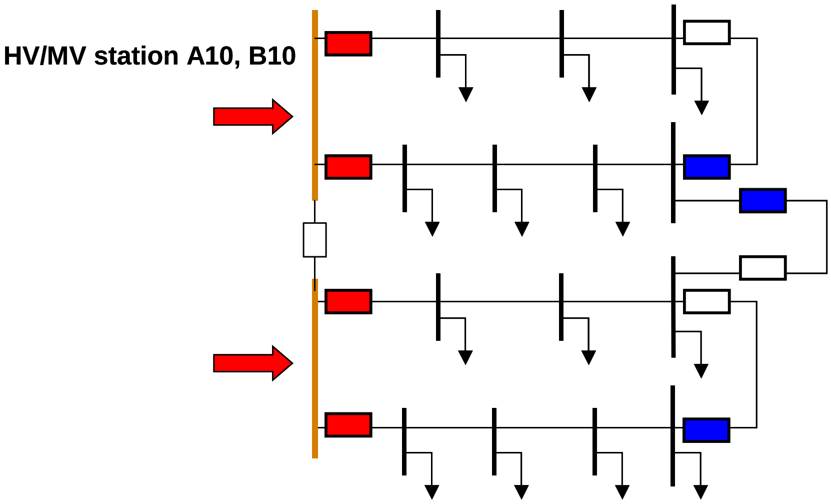


Figure 11-4: Multiple open-loop feeder configurations.

The system is similar in design to open loop configuration but with an additional normally open tie switch between two loops. Power feedings may originate from the same or different bus-bars at a source station. Load flow may be bi-directional, and an open or faulted feeder section may be back-fed.

A parallel loop feed system could provide quick restoration of power service through installed tie switch. The system would normally be capable of sustaining the customer service when a feeder failure occurs in a loop. Manual or remote controlled transfer equipment is commonly used in conjunction with two loops.

D. Open-ring inter-station connection

A common MV feeder arrangement is shown in Figure 11-5. This configuration connects two feeders together at their endpoints with a normally open tie switch. The two primary feeders connect the sources of power from two different primary substations. This primary open-ring configuration increases reliability by allowing customers on a feeder of a fault to receive power from the other source station by closing the tie switch. With additional power sources available this configuration supplies power even in the case of a failure on a primary substation.

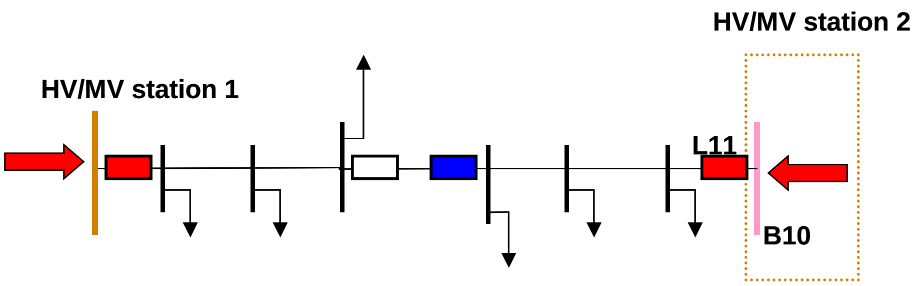


Figure 11-5: Open-loop inter-station connection.

11.3 Reliability Data

Component reliability data is an important aspect of reliability analysis. Considering that the good component parameters for the system reliability calculations are the data related to the system studied, the data from Vattenfall Distribution Nordic were used [10, 11]. Table 11-2 summarized the component reliability data used in the reliability analyses. The manual switch time was set to 1 hour for manual switches in the calculations.

Using these data, the subsequent Chapters 12-17 examines the possibilities to simplify the distribution system. A series of case studies were performed to analyze the inherent reliability on both system and load points levels associated with different modifications of feeder looped configurations and changes of component types.

Table 11-2: Component reliability data used for urban system analyses.

Equipment	Based on data from	Failure rate (f/100unit.yr), (f/100km.yr)	Outage duration (h/f) (incl. Sectionalizing)	Unavailability (%)
MV underground cable (Jordkabel PEX 10 -20 kV)	Vattenfall	0,5	10,5	0,001
Distribution transformer 10-20/0.4 kV		1,0	5,0	0,001
Fuse-load-switch 10 - 20 kV		1,3	4,0	0,001
Disconnect-switch 10-20 kV		1,3	4,0	0,001
Circuit breaker		1,0	4,0	0,0005
Primary substation		0,1	4,0	0,00005
Fuse		Stuck probability: 5%		

12 Case Study U1: Effect of Removing Extra Tie Connection TC3

Tie connections via open switches are frequently used in urban networks as inter-feeder connections to provide reserve power feedings. Many urban distribution systems are interconnected by several tie lines, and each of which has capacity to give emergency assistance of power feeding through the interconnection in the case of failure.

Consider the system configuration shown in Figure 12-1. There are three tie connections: TC1, TC2, and TC3. At the station ÄT717 the busbar B10 is connected to the busbar C10 via an open switch. Each of these two busbars is connected separately to a feeding power transformer. Tie line TC1 connects two feeders L04 and L23 together at their endpoints. Tie connection TC2 links feeder L15 to L11, through which links two stations ÄT717 and ÄT12 together. In this configuration, an extra tie line TC3 was built to link feeders L15 and L04 at their endpoints.

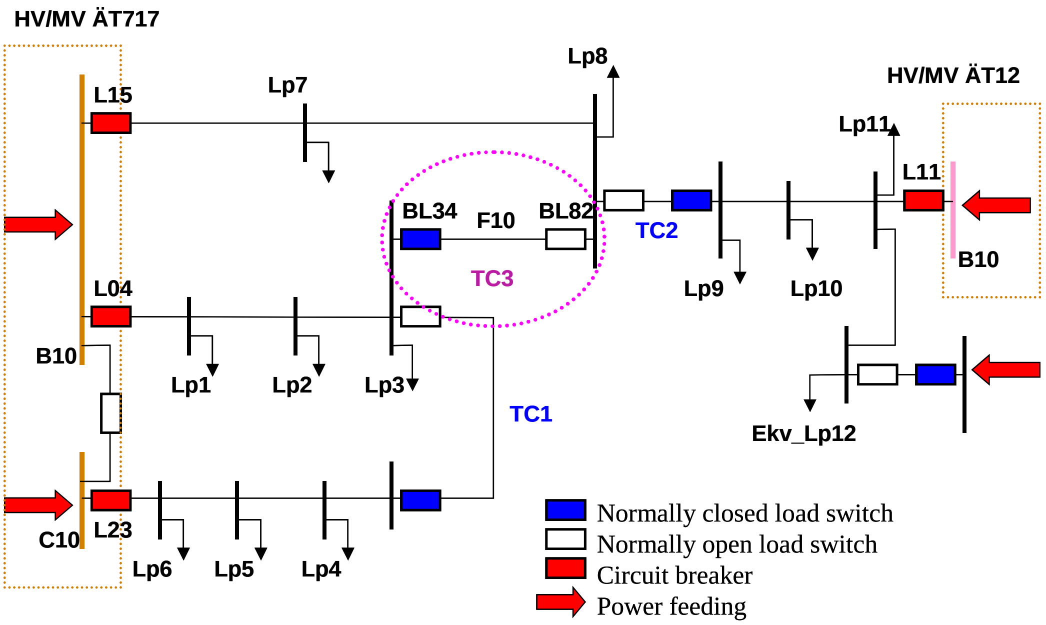


Figure 12-1: Network configuration studied in Case U1.

How does this extra tie connection TC3 affect reliability? Can we get more reliability benefit by building this tie line? We study the following two cases:

- Base case: the existing network with all the three tie lines, TC1, TC2, and TC3.

- Case U1: Same as Base case but remove the tie connection TC3.

Table 12-1 and Figures 12-2, 12-3, and 12-4 summarizes the results of the study. As shown by Table 12-1, removing the tie connection TC3 results lower values of SAIFI, SAIDI, and ENSs. This means that building the extra tie connection TC3 does not give reliability benefit and removing this tie line would not affect network reliability negatively.

By examining the load point (Lp) indices in Figures 12-2, 12-3, and 12-4. It is seen that removing the tie connection TC3 leads to reduced failure rate and outage durations at load points 1-3. This reduction of the failure rates results decreased energy not supplied at these load points.

Table 12-1: Results of Case study U1.

Case	SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)
Base case	0,138	18,36	1,639
Case U1	0,132	17,19	1,602

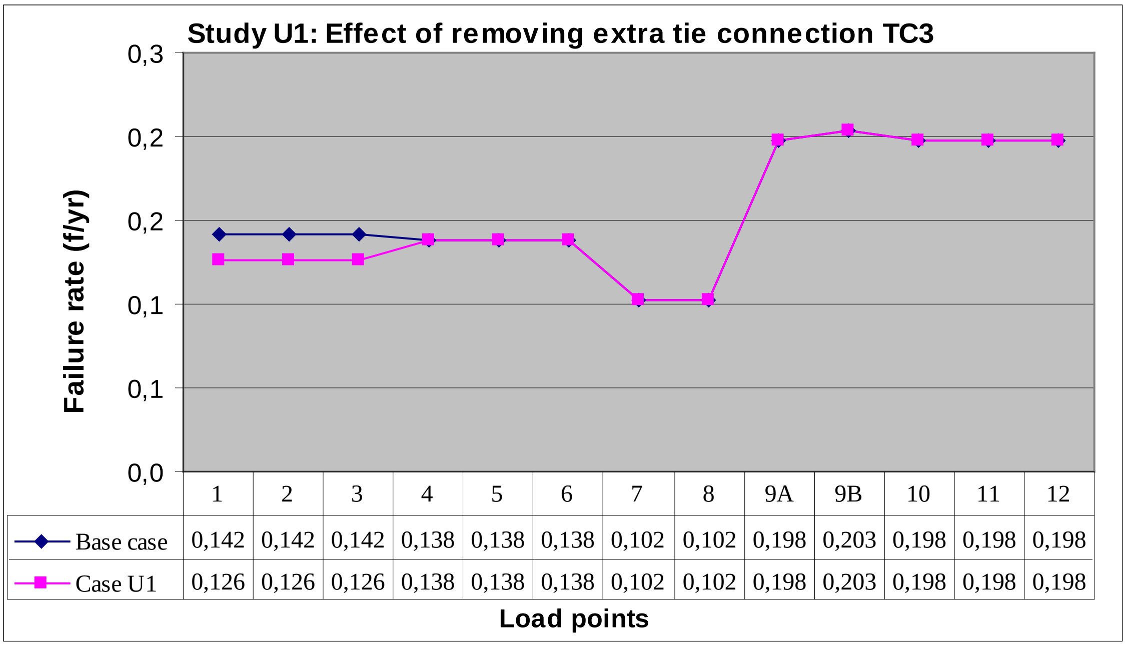
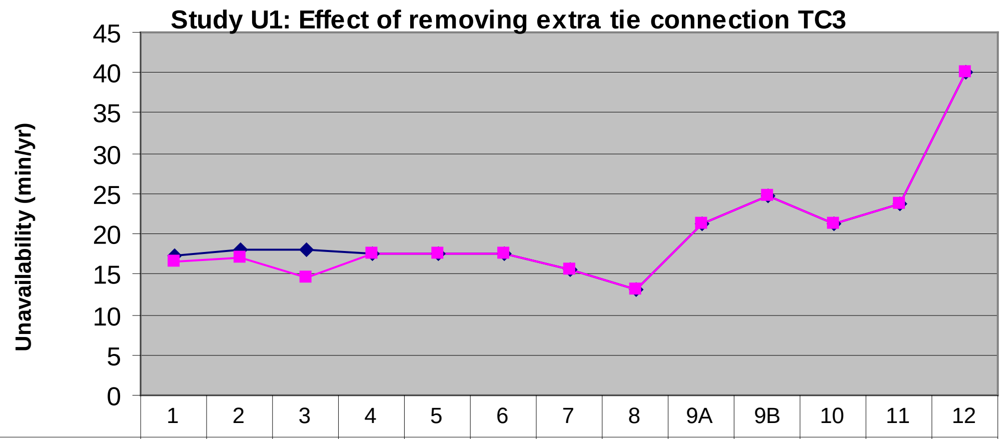


Figure 12-2: Results of Case study U1.

The network, by tie switches between busbars at the station ÄT7171, and by tie lines TC1 and TC2, was well inter-connected between feeders and stations. Adding more tie line TC3 does not contribute extra to system reliability. This extra connection, however, introduce more components to the system. When these components fail, for example, a short circuit on switch BL34, the circuit breaker of feeder L04 will be tripped and the customers at load points 1-3 are interrupted. The reliability of these load points is, therefore, improved when removing this extra tie line.

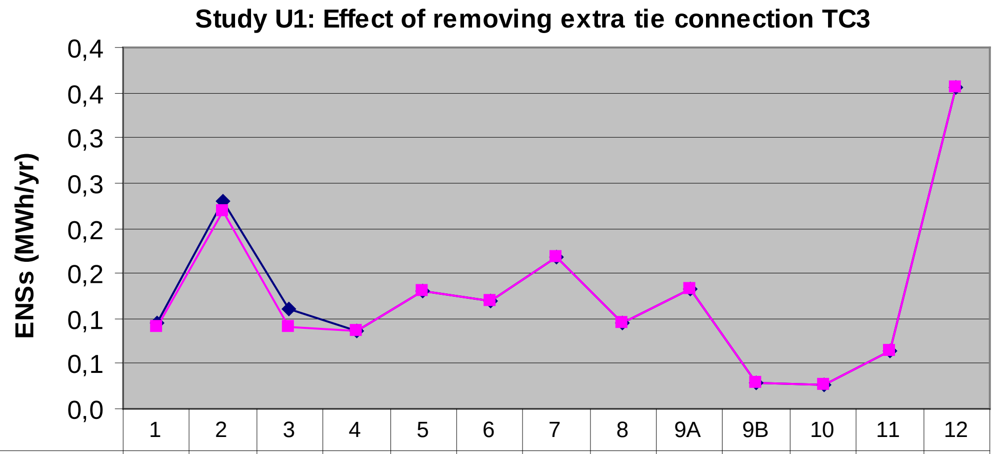
Interconnected and meshed network increase reliability. Reasonable interconnections of feeders, loops, and stations give reliability benefit. However extra highly interconnected network configuration will not necessarily give extra benefits to system reliability. Do not, therefore, try to build tie lines everywhere on the networks.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Base case	17,40	17,94	17,94	17,68	17,68	17,68	15,53	13,19	21,29	24,62	21,29	23,63	40,08
Case U1	16,47	17,01	14,67	17,68	17,68	17,68	15,53	13,19	21,29	24,62	21,29	23,63	40,08

Load points

Figure 12-3: Results of Case study U1.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Base case	0,095	0,229	0,110	0,086	0,131	0,119	0,167	0,095	0,133	0,029	0,026	0,063	0,355
Case U1	0,090	0,218	0,090	0,086	0,131	0,119	0,167	0,095	0,133	0,029	0,026	0,063	0,355

Load points

Figure 12-4: Results of Case study U1.

13 Case Study U2: Effect of Removing Tie Connection of Two Connected Loops

A common configuration in urban power systems is a loop structure. A number of load points are connected by a ring-formed feeder, which in turn is interconnected to other loop or feeders.

Study the configuration shown in Figure 13-1. Four lines go out from the primary station. Two lines from same busbar forms a loop through a normally open tie line. The two busbars are connected together by a normally open switch, and this interconnects two loops at their feeding points. The two loops are also linked at their endpoints through the tie line TC4.

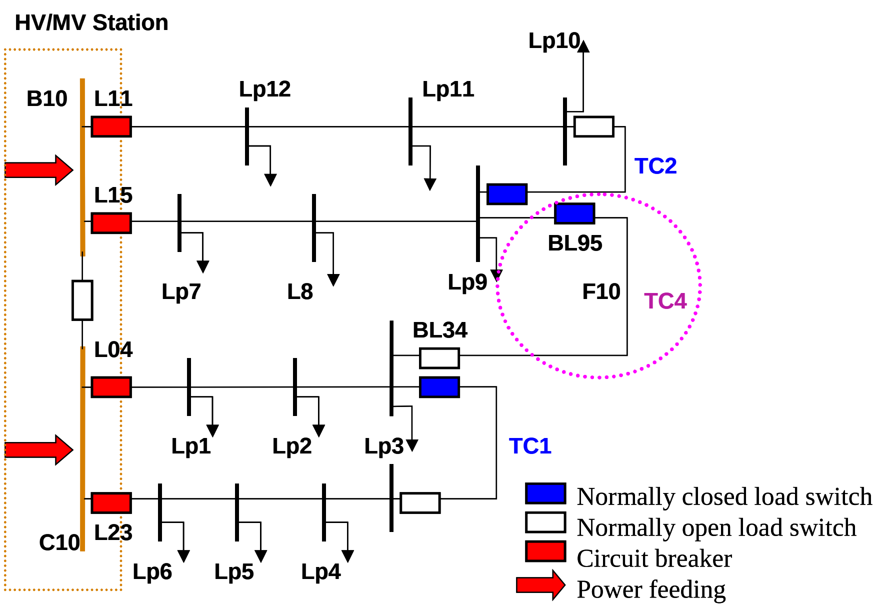


Figure 13-1: Network configuration studied in Case U2.

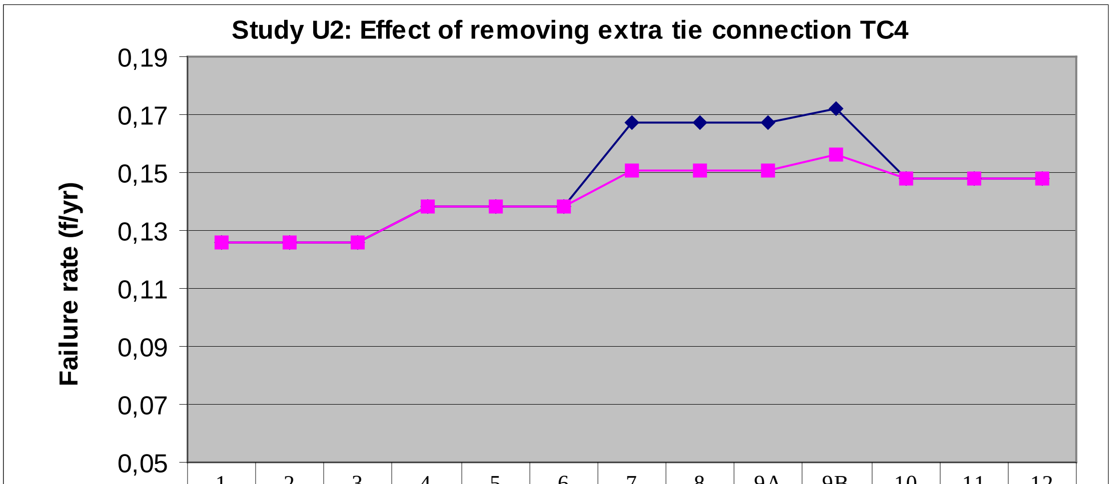
In order to understand how much this tie connection TC4 contributes to system reliability, study the two cases:

- Case U2_1: Network of two rings with tie connection TC4.
- Case U2_2: Same as Case U2-1, but remove the tie connection TC4.

The results of the calculations are given in Table 13-1 and Figures 13-2, 13-3, and 13-4. As indicated by the Table 13-1, removing tie line TC4 decreases SAIFI, SAIDI, and energy not supplied. This implies that building the extra tie line TC4 at this case does not contribute improvement of system reliability.

Table 13-1: Results of Case study U2.

Case	SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)
Case U2_1	0,143	18,04	1,652
Case U2_2	0,138	17,67	1,611

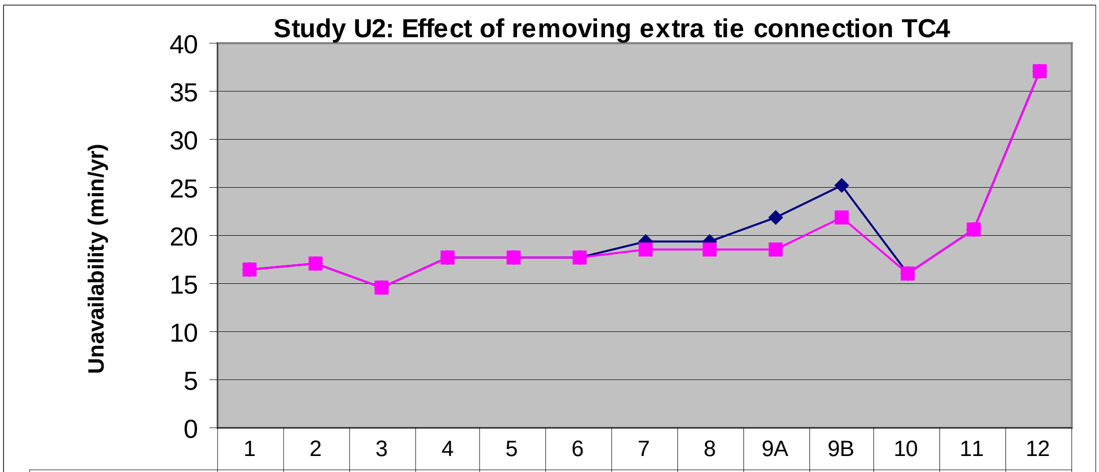


	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U2_1	0,126	0,126	0,126	0,138	0,138	0,138	0,167	0,167	0,167	0,172	0,148	0,148	0,148
Case U2_2	0,126	0,126	0,126	0,138	0,138	0,138	0,151	0,151	0,151	0,156	0,148	0,148	0,148

Figure 13-2: Results of Case study U2.

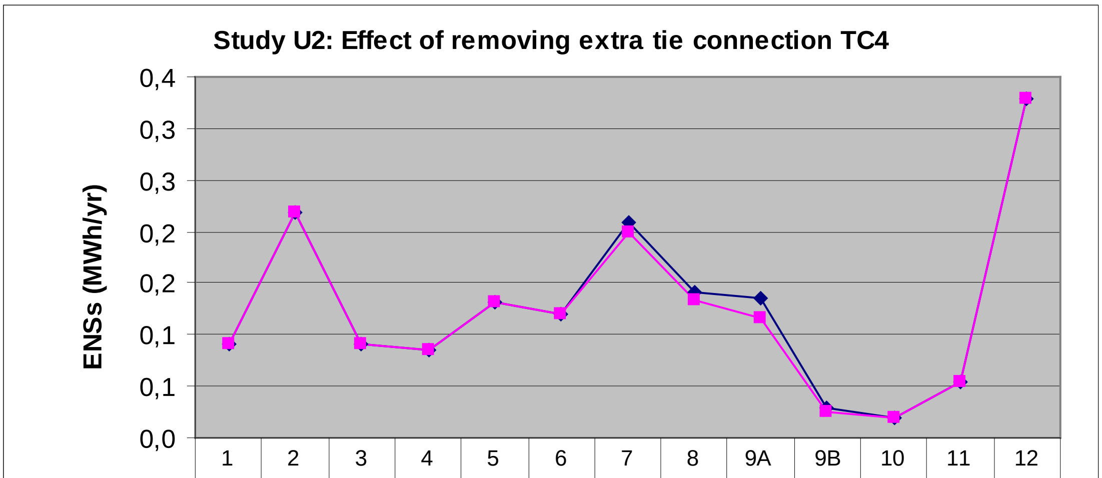
Study the load point indices shown in Figures 13-2, 13-3, and 13-4. It is observed that removing the tie line TC4 decreases failure frequency and unavailability at load points 7-9, and this reduction leads to reducing not supplied energy at these load points. This is due to that the removal of the line TC4 eliminates the customer interruptions on the feeder L15 that may be caused by the component failures associated with the line TC4.

The results of the study illustrate that when two loops are interconnected at their feeding points, building an additional tie connection between them does not necessarily increase further the system reliability. Removal of this line may not, therefore, affect the reliability negatively.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U2_1	16,47	17,01	14,67	17,68	17,68	17,68	19,44	19,44	21,78	25,11	15,98	20,66	37,10
Case U2_2	16,47	17,01	14,67	17,68	17,68	17,68	18,51	18,51	18,51	21,84	15,98	20,66	37,10

Figure 13-3: Results of Case study U2.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U2_1	0,090	0,218	0,090	0,086	0,131	0,119	0,209	0,141	0,136	0,029	0,019	0,055	0,329
Case U2_2	0,090	0,218	0,090	0,086	0,131	0,119	0,199	0,134	0,116	0,025	0,019	0,055	0,329

Figure 13-4: Results of Case study U2.

14 Case Study U3: Effect of Removing Tie Connection of Two Separate Loops

For looped urban distribution system, a basic requirement is providing alternative feeding point for load points to increase availability on demand. In the previous case study U2, it is seen that when two loops are already interconnected, building an additional tie line between the loops does not give further reliability improvement. It is interesting to see how interconnection between separate loops influences system reliability. This case examines this effect.

Reconsider the looped network shown in Figure 14-1. Feeder L11 and L15 form a loop connecting to feeding busbar B10, and the ring consisting of feeder L04 and L23 connects to feeding busbar C10. Two busbars connect to respective feeding transformers, and there is no link between these two busbars.

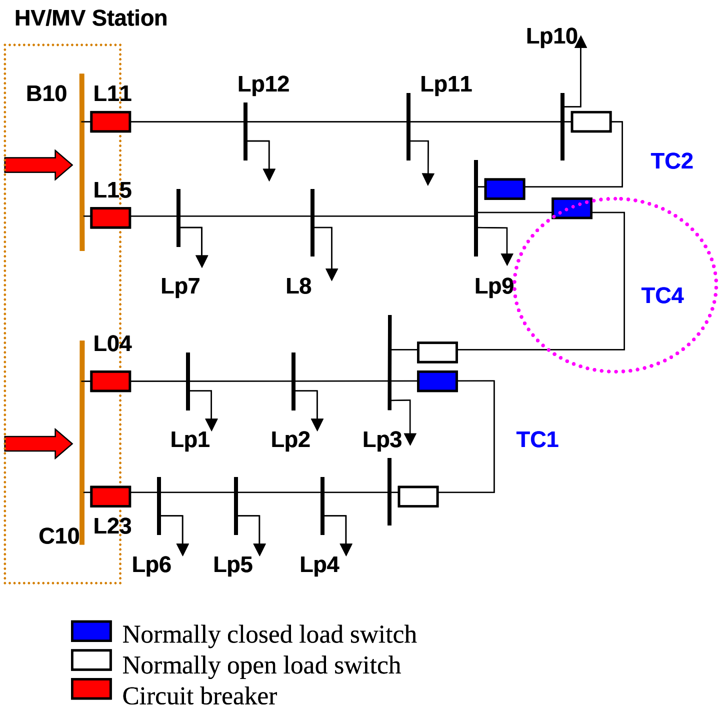


Figure 14-1: Network configuration studied in Case U3.

Study the following two cases:

- Case U3_1: network of two rings is interconnected by tie line TC4.
- Case U3_2: same as Case U3-1 but remove the tie line TC4.

Using the same reliability data as that in Case study U2, the system reliability indices and load point indices are calculated. The results are presented in Table 14-1 and Figures 14-2, 14-3, and 14-4. As expected the failure rates at load points 7-9 decrease when removing the tie line TC4, which results in decreased SAIFI in Case U3_2. This is due to that removing the tie line TC4 eliminates the component failures associated with this line.

However, it is clearly observed the negative impact of the removal of this tie line on SAIDI and not supplied energy. The results shown in Table 14-1 and Figures 14-3 and 14-4 indicate the degradation of the reliability caused by removal of this line TC4 for transferable load. Both SAIDI and ENS increase when removing the interconnection of the loops.

Table 14-1: Results of Case study U3.

Case	SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)
Case U3_1	0,147	18,28	1,675
Case U3_2	0,142	19,46	1,785

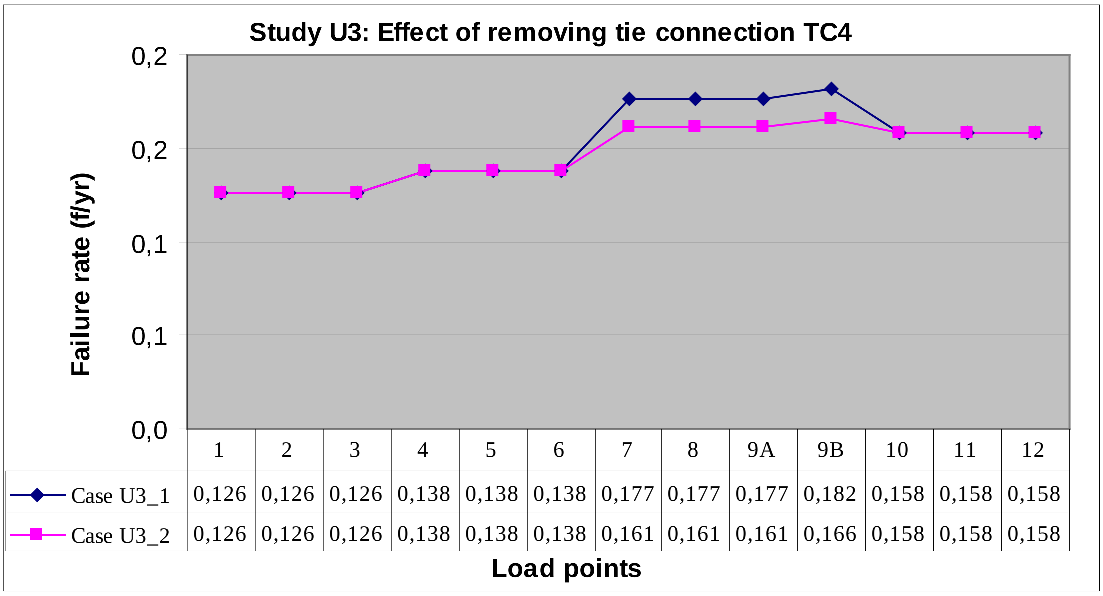
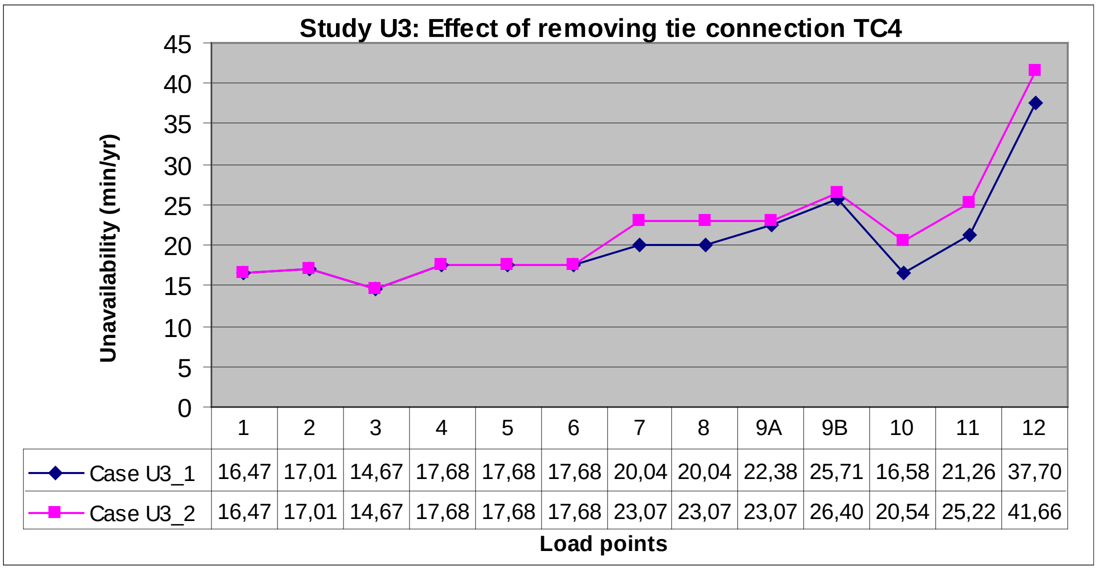


Figure 14-2: Results of Case study U3.

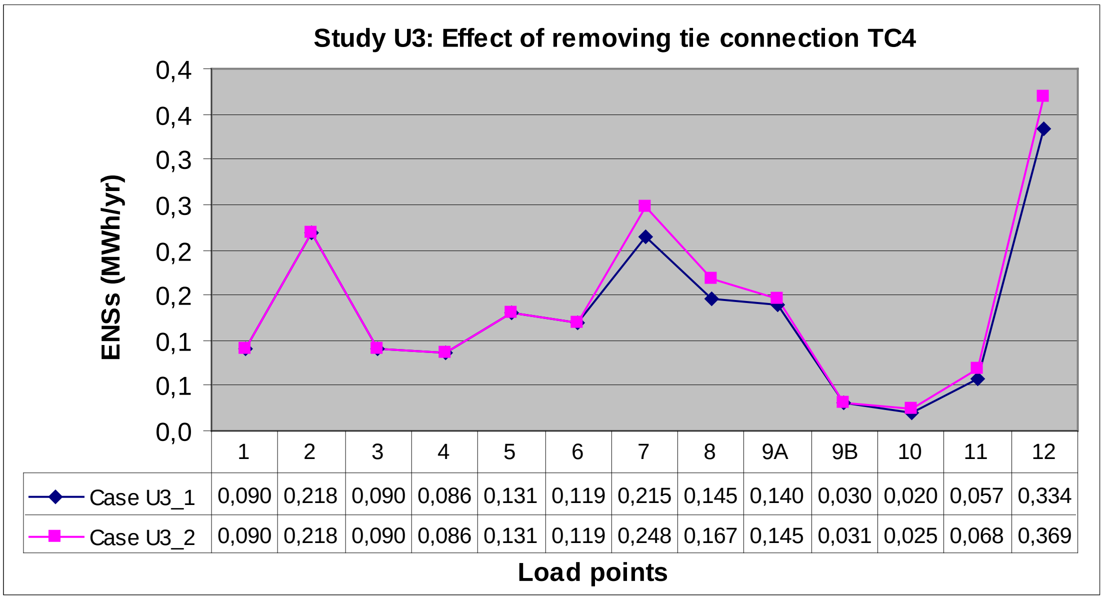
The analysis shows that it is important to interconnect separate loops. In an outage condition, say, a failure on feeding busbar B10, all the load points on the feeder L11 and L15 are disconnected and could not be restored until the repair of the busbar is completed, if there is no the loop interconnection TC4.

In the case of interconnected network as in Case U3_1, the load points can be quickly restored before the repair process has been completed by available assistance from other feeding point C10 through the tie line TC4, and this results in reduced SAIDI and not supplied energy.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U3_1	16,47	17,01	14,67	17,68	17,68	17,68	20,04	20,04	22,38	25,71	16,58	21,26	37,70
Case U3_2	16,47	17,01	14,67	17,68	17,68	17,68	23,07	23,07	23,07	26,40	20,54	25,22	41,66

Figure 14-3: Results of Case study U3.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U3_1	0,090	0,218	0,090	0,086	0,131	0,119	0,215	0,145	0,140	0,030	0,020	0,057	0,334
Case U3_2	0,090	0,218	0,090	0,086	0,131	0,119	0,248	0,167	0,145	0,031	0,025	0,068	0,369

Figure 14-4: Results of Case study U3.

15 Case Study U4: Effect of Moving Tie Connection TC3

How to enhance power reliability in cost effective way has become a more and more important concern for power utilities in planning distribution networks. There may be several alternatives in planning for network reinforcement. A question we may meet is: with the same capital investment, which reinforcement alternative will give higher overall system reliability. This Chapter studies a scenario of this case.

The network studied is show in Figure 15-1. Assume that a tie line TC3 will be built to enhance load transfer and there are two alternatives: (1) using TC3 to link feeder L15 and L04, (2) using TC3 to connect feeder L15 and L11.

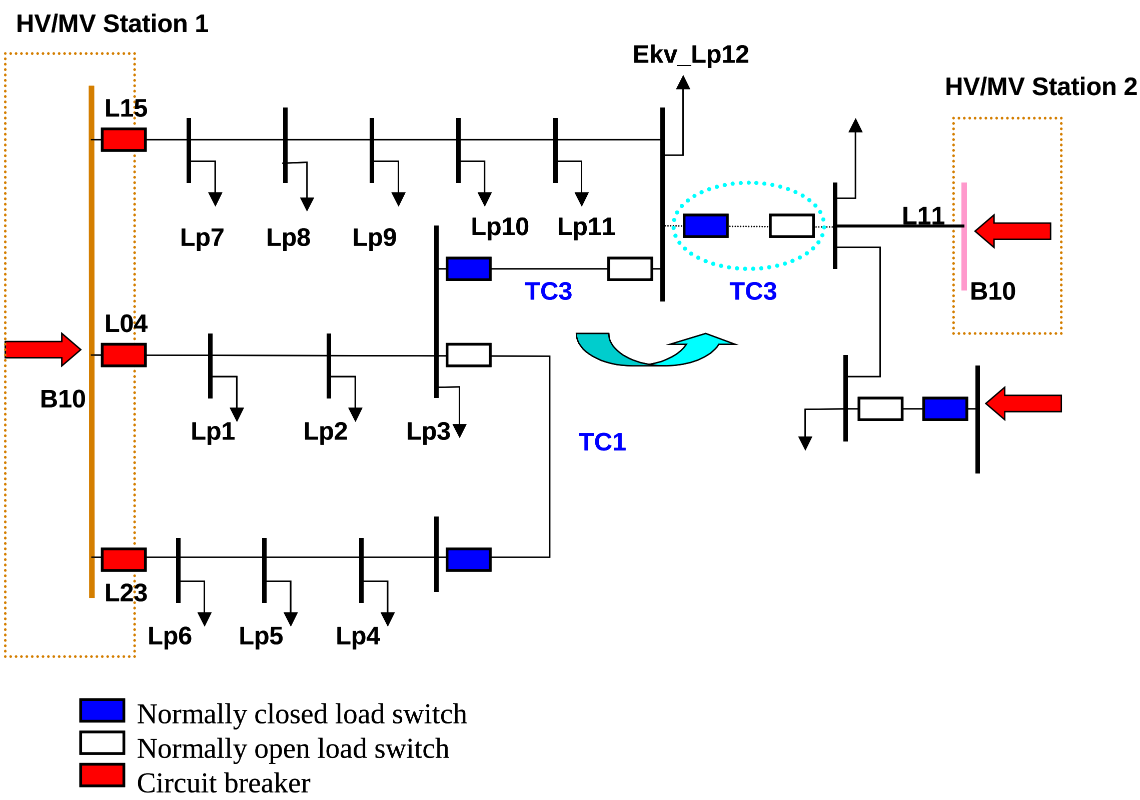


Figure 15-1: Network configuration studied in Case U4.

Specify and evaluate the following two cases:

- Case U4_1: the network is looped with the tie line TC3 to connect feeder L15 to the adjacent ring consisting of feeder L04-L23.

- Case U4_2: same as Case U4_1, but move the tie connection TC3 to link feeder L15 to the line L11 outgoing from Station 2.

The results of the calculations are summarized in Table 15-1 and Figures 15-2, 15-3, and 15-4. As expected the SAIFI remains the same in both cases because moving the tie line TC3 does not introduce nor eliminate the component failures associated with the line TC3. It is interesting noticed that SAIDI and ENS are significantly improved in Case U4_2. The SAIDI and ENS are reduced approximately 10% in Case U4_2 compared with Case U4_1. This means that building the tie line TC3 to connect feeder L15 and L11 can give more benefit in reliability than using the line TC3 to link feeder L15 and L04.

Table 15-1: Results of Case study U4.

Case	SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)
Case U4_1	0,205	28,559	2,471
Case U4_2	0,205	25,491	2,256

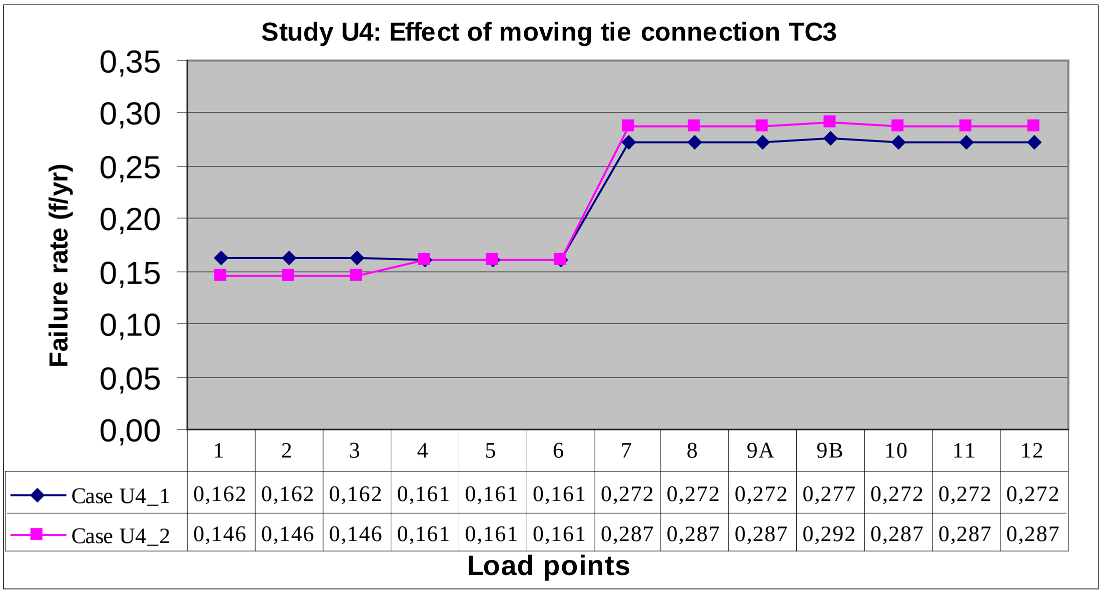
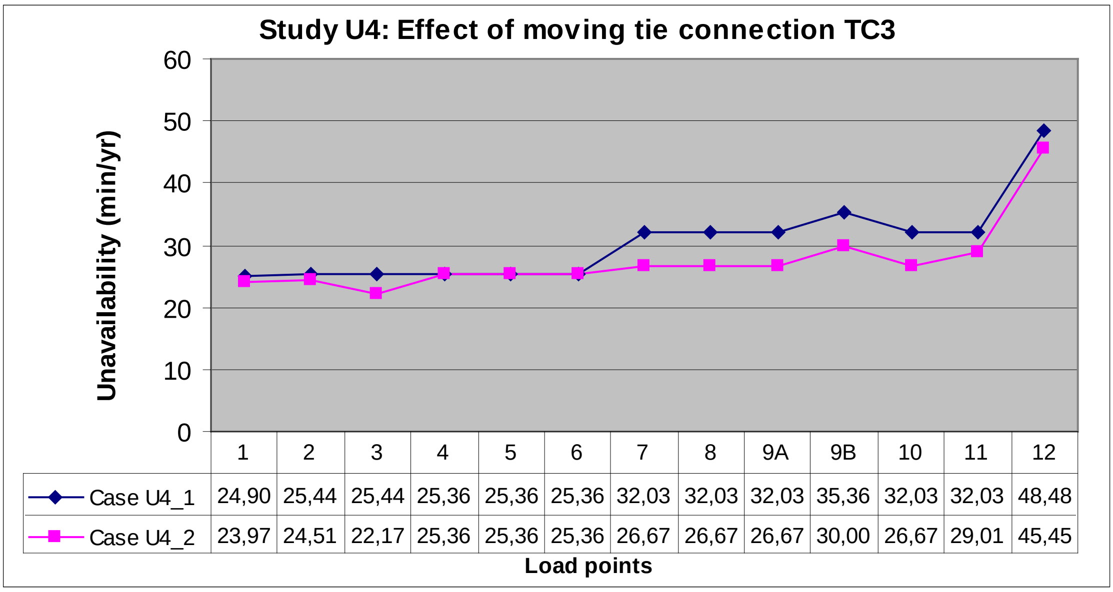


Figure 15-2: Results of Case study U4.

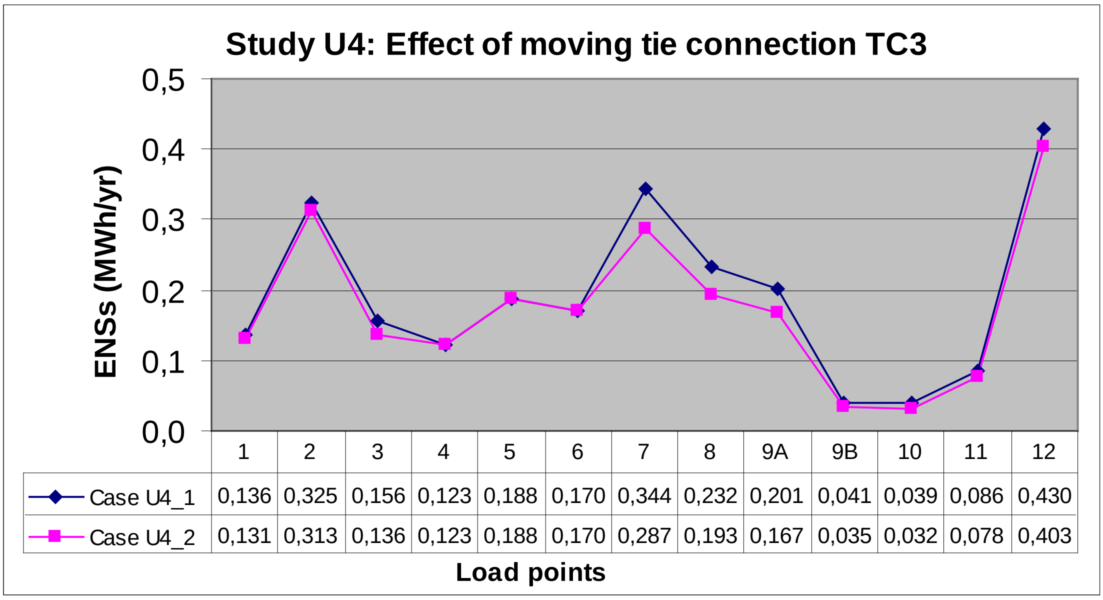
The Figures 15-3 and 15-4 confirm that to link the feeder L15 and Station 2 in case U4_2 can effectively enhance the reliability of load points 7-12. In the failure event of feeding busbar B10, the load points on feeder L15 could be quickly recovered by power feeding from Station 2 through the tie line TC3 in Case U4_2, and hence reduce the outage time, while in Case U4_1, all these load points would be left disconnected until the repair has been completed.

The results of this case study illustrate again that reliability benefits can be received by building tie lines in urban networks through providing emergent power assistance. However the benefits gained from tie line interconnections can be influenced by the way to build them. It is of great value to take into account this factor into the planning process to obtain the most beneficial solutions.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U4_1	24,90	25,44	25,44	25,36	25,36	25,36	32,03	32,03	32,03	35,36	32,03	32,03	48,48
Case U4_2	23,97	24,51	22,17	25,36	25,36	25,36	26,67	26,67	26,67	30,00	26,67	29,01	45,45

Figure 15-3: Results of Case study U4.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U4_1	0,136	0,325	0,156	0,123	0,188	0,170	0,344	0,232	0,201	0,041	0,039	0,086	0,430
Case U4_2	0,131	0,313	0,136	0,123	0,188	0,170	0,287	0,193	0,167	0,035	0,032	0,078	0,403

Figure 15-4: Results of Case study U4.

16 Case Study U5: Effect of Adding Inter-station Tie Connection

In the previous case study U4 it is shown that a tie line connecting to adjacent station increases effectively reliability by allowing customers disconnected to receive emergent power from the adjacent station by closing the tie switch. This Chapter examines further a network structure with inter-station tie line.

Consider the network configuration shown in Figure 16-1. The feeder L15 and ring from feeder L04 to L23 are well interconnected by tie lines TC1 and TC3. Is it beneficial to reliability to build an additional tie line TC2? If yes, how much will this line improve the reliability? In order to answer the questions, specify a new case as follows:

- Case U5: same as Case U4_1 defined in previous Chapter, but add inter-station tie line TC2.

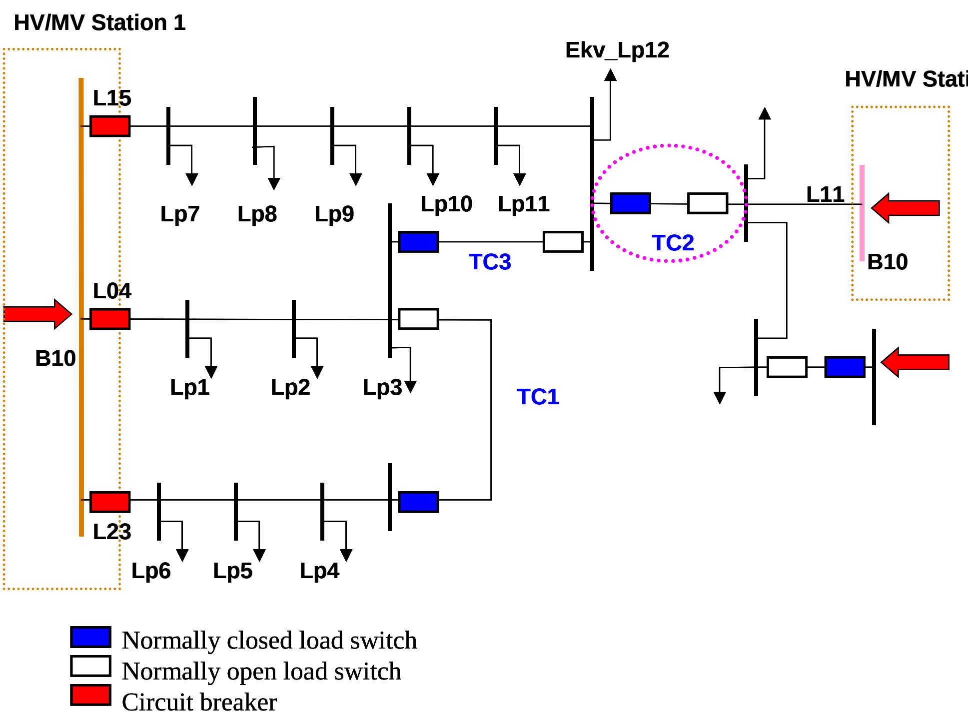


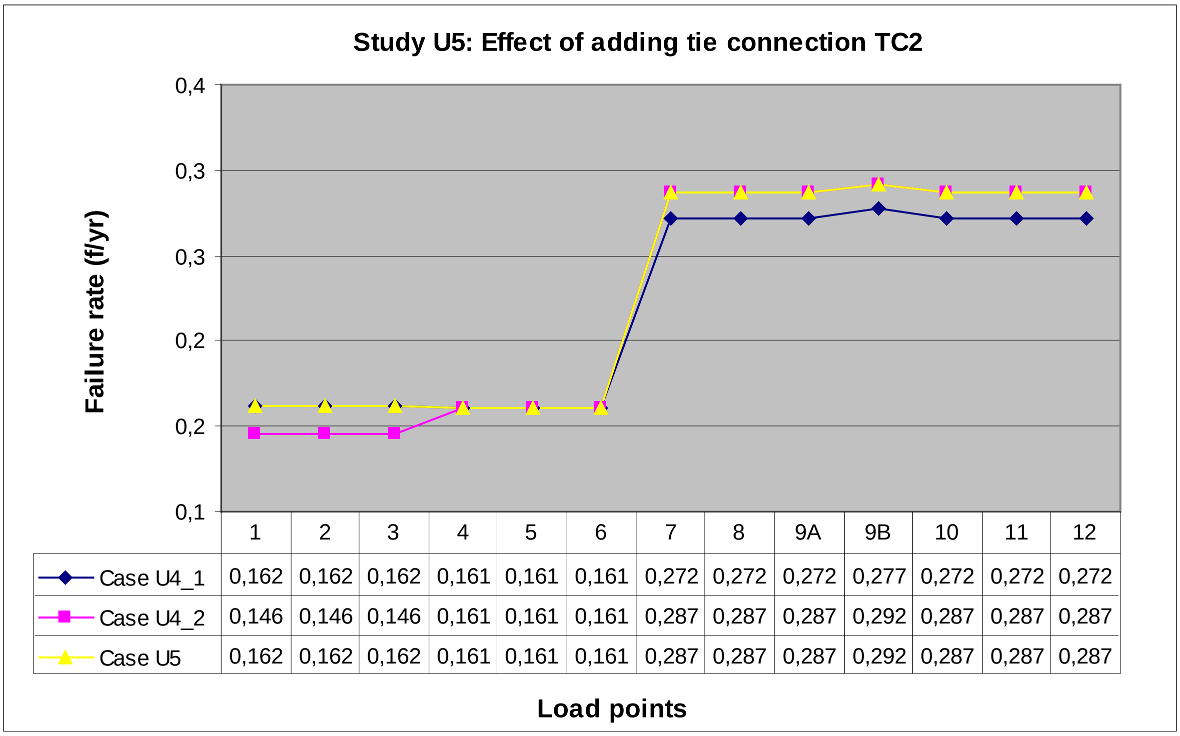
Figure 16-1: Network configuration studied in Case U5.

The new results of the calculations are given in Table 16-1 and Figures 16-2, 16-3, and 16-4 together with the results from Case study U4 for comparison. Adding a new line introduces additional component failures related to this line.

The SAIFI increases therefore in Case U5. All the load points 7-12 on feeder L15 see higher failure rate due to these introduced component failures. However it is observed a further significant improvement in SAIDI and ENS in Case U5 as the inter-station tie line is added. The SAIDI and ENS decrease approximately 20% in Case U5 compared with Case U4_1.

Table 16-1: Results of Case study U5.

Case	SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)
Case U4_1	0,205	28,559	2,471
Case U4_2	0,205	25,491	2,256
Case U5	0,211	22,830	2,020



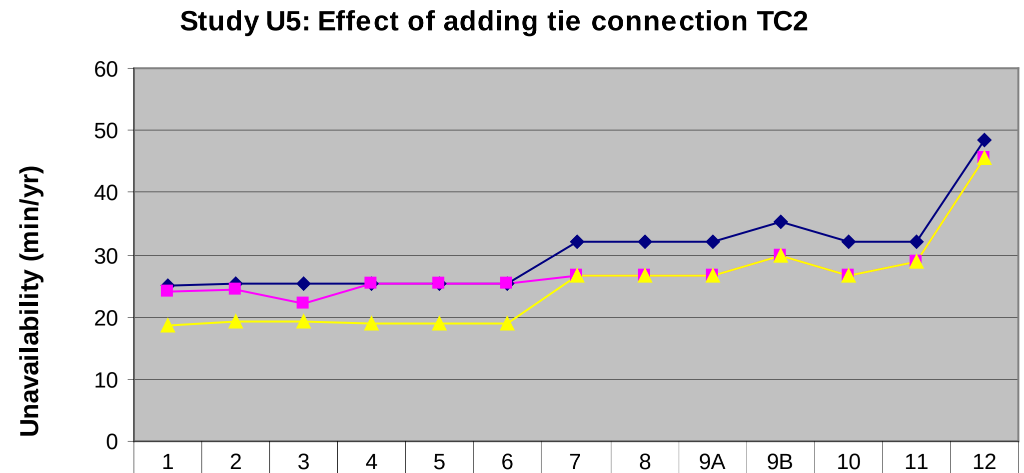
	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U4_1	0,162	0,162	0,162	0,161	0,161	0,161	0,272	0,272	0,272	0,277	0,272	0,272	0,272
Case U4_2	0,146	0,146	0,146	0,161	0,161	0,161	0,287	0,287	0,287	0,292	0,287	0,287	0,287
Case U5	0,162	0,162	0,162	0,161	0,161	0,161	0,287	0,287	0,287	0,292	0,287	0,287	0,287

Figure 16-2: Results of Case study U5.

Examining the load point indices given in Figures 16-3 and 16-4, building this tie line could effectively decrease outage durations at all the load points of the network and hence reduce energy not supplied at each load point compared with case U4_1. In the failure event of the feeding busbar B10, for example, not only the load on feeder L15 can be quickly recovered through closing this inter-station tie line but also the customers connected on the ring from feeder

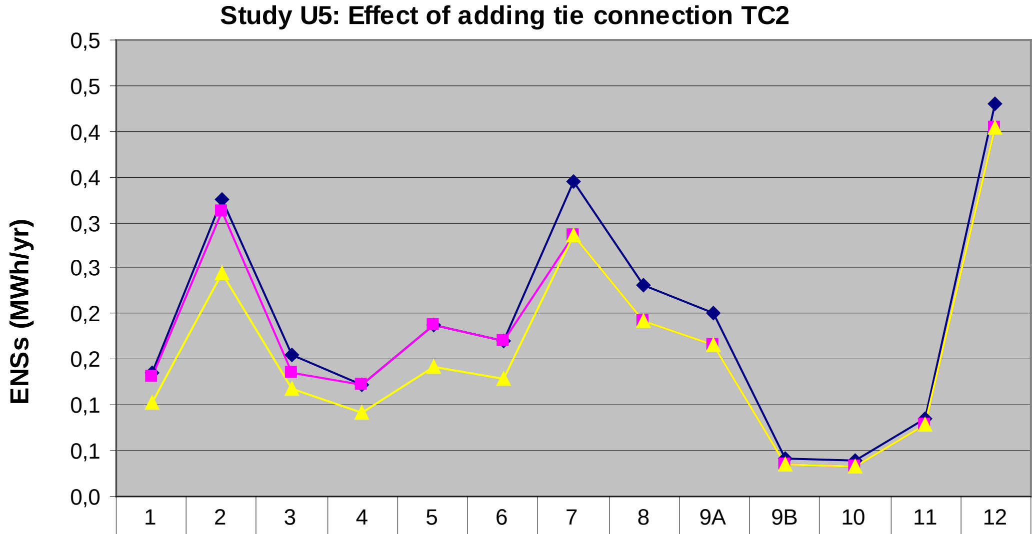
L04 to L23 could be restored by receiving power from Station2 by closing the tie switches of TC3 and TC1.

Many urban distribution systems are highly interconnected and have multiple tie lines between multiple feeders. These tie lines give greater switching flexibility. But it is important to recognize that building multiple tie lines does not necessarily always imply reliability improvement. The benefit in reliability received from the multiple tie connections may vary from case to case. An interesting comparison can be made for Case study U1 and U5. In both cases, the networks have similar looped configuration with same number of tie lines. However, building tie line TC3 does not give further reliability improvement in Case U1, while having both tie lines TC2 and TC3 in Case U5 could significantly enhance the system reliability. It is therefore valuable to do reliability assessment in the network planning process in order to obtain the cost effective solutions of reliable network configurations.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U4_1	24,90	25,44	25,44	25,36	25,36	25,36	32,03	32,03	32,03	35,36	32,03	32,03	48,48
Case U4_2	23,97	24,51	22,17	25,36	25,36	25,36	26,67	26,67	26,67	30,00	26,67	29,01	45,45
Case U5	18,60	19,14	19,14	19,06	19,06	19,06	26,67	26,67	26,67	30,00	26,67	29,01	45,45

Figure 16-3: Results of Case study U5.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Case U4_1	0,136	0,325	0,156	0,123	0,188	0,170	0,344	0,232	0,201	0,041	0,039	0,086	0,430
Case U4_2	0,131	0,313	0,136	0,123	0,188	0,170	0,287	0,193	0,167	0,035	0,032	0,078	0,403
Case U5	0,102	0,245	0,117	0,092	0,141	0,128	0,287	0,193	0,167	0,035	0,032	0,078	0,403

Load points

Figure 16-4: Results of Case study U5.

17 Case Study U6: Effect of Changing Fuse-Load Switch to Fuse at Switchable Lateral Taps

In the Cases studies U1-U5 the analysis is focused on system structures and interconnections of networks. This Chapter studies possibility to simplify the component type.

Placing a protection device, typically a fuse, on lateral branch of an urban system is a straightforward and effective method for improving system reliability. On the Vattenfall urban system studied, a fuse-load switch is installed at tee-point in each lateral branch as shown in Figure 17-1.

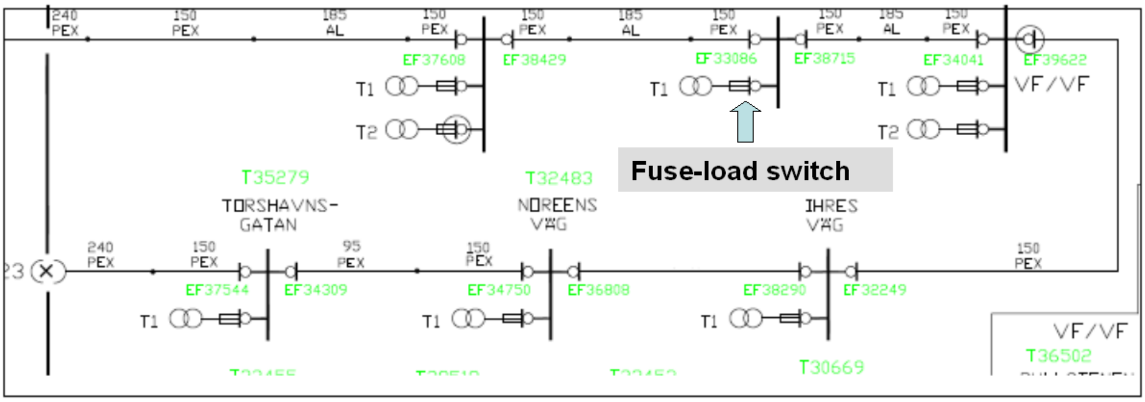


Figure 17-1: A fuse-load switch at lateral tap of Vattenfall urban system.

A fuse-load switch is basically a combination of two components, a fuse and a load switch. It is used to protect against over-current on a lateral distributor as well as to provide connecting and disconnecting operative mechanism at lateral tee-junction. On this cable network, all the feeders are equipped with load-switches at cable terminations to enable sectionalizing feeders and switching lateral branches.

At lateral tap both the fuse-load switch and the load-switches at the cable terminations of incoming and outgoing feeders have operative function for connecting or disconnecting lateral branch. Is there possibility to simplify this arrangement while not to affect the reliability negatively? In order to answer it, the following case is studied:

- Case U6: same as Base case specified in Case study U1, but change fuse-load switches to fuses at the lateral taps of six load points 1, 2, 5, 6, 7, and 10 as shown in Figure 17-2.

The lateral taps of all of these six load points have the same structure arrangement, one incoming feeder, one outgoing feeder, and one tap branch, as shown at LP7 in Figure 17-2. In the failure event on the lateral branch, the two load-switches at cable-terminations can be used to isolate the faulted branch without affecting power feeding to other load points.

The calculated reliability indices of Case U6 are presented in Table 17-1 and Figures 17-3, 17-4, and 17-5, together with the indices of Base case calculated in Case study U1 for comparison.

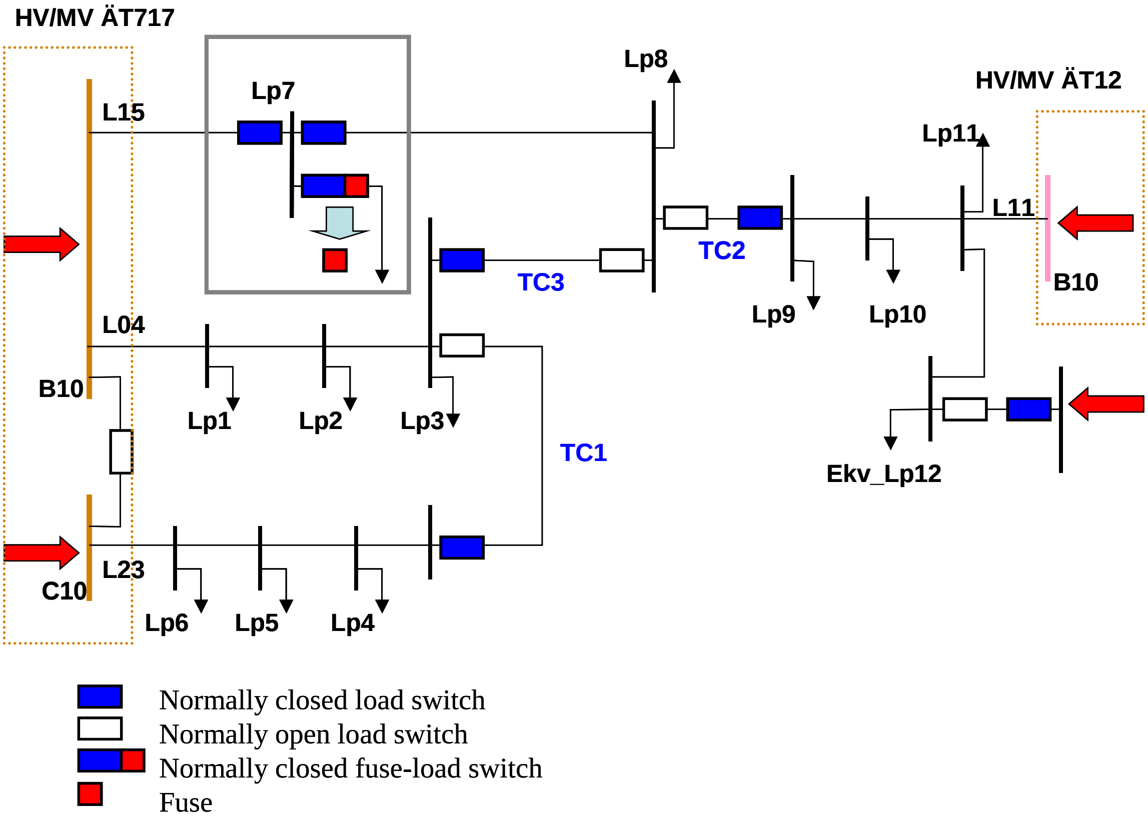
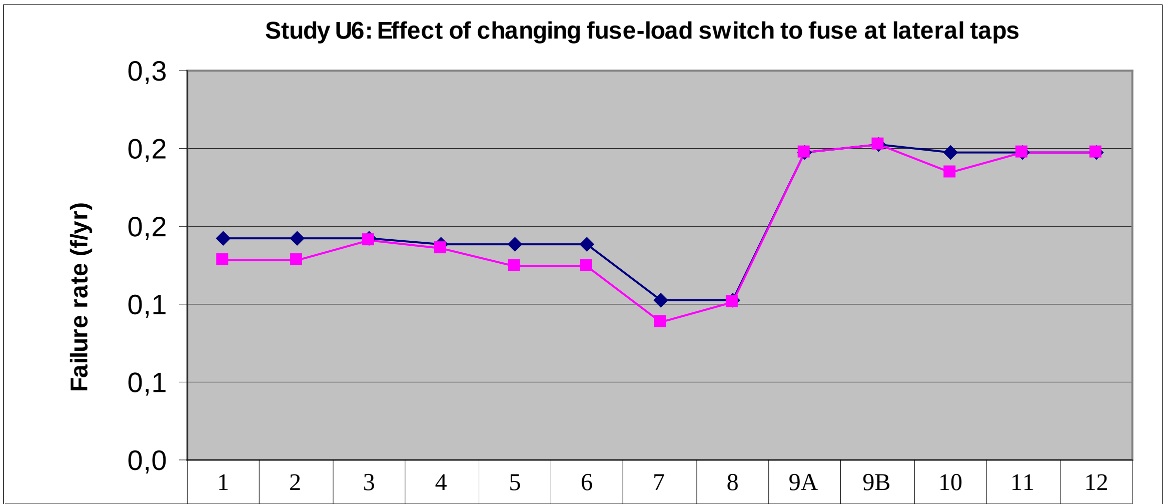


Figure 17-2: Network studied in Case U6.

Table 17-1: Results of Case study U6.

Case	SAIFI (int./yr.cust.)	SAIDI (min./yr.cust.)	ENSs (MWh/yr)
Base case	0,138	18,359	1,639
Case U6	0,131	16,899	1,497

It can be seen from Table 17-1 that the system failure rate SAIFI is lower in Case U6 than that in Base case due to the simplification of the components. In the failure event of a short circuit on the load-switch of a fuse-load switch at the lateral tap of load point 1, for example, the circuit breaker on feeder L04 will open and causes disconnection of all the customers of load points 1-3. Changing the fuse-load switches to fuses eliminates this kind of active component failures and therefore decreases system failure rate.



	1	2	3	4	5	6	7	8	9A	9B	10	11	12
Base case	0,142	0,142	0,142	0,138	0,138	0,138	0,102	0,102	0,198	0,203	0,198	0,198	0,198
Case U6	0,128	0,128	0,141	0,136	0,124	0,124	0,089	0,101	0,197	0,202	0,185	0,197	0,197

Figure 17-3: Results of Case study U6.

The results of the case study U6 show also the effect of the simplification of fuse-load switches on outage durations and energy not supplied. It can be noted that the system annual unavailability measured by SAIDI and ENS value decrease considerably. This effect is also reflected in the load point indices shown in Figures 17-4 and 17-5. It is observed that the average outage durations at the load points are generally improved, and those six load points benefit more than others because they are directly connected to the simplified components. In the Base case the network has fuse-load switches at the tee-point to each load, which would interrupt supply to the load point if an active failure would occur on the fuse-switch, and the load point should keep disconnected until the repair is completed. When these active failure events are removed, then the outage durations caused by such failures are eliminated, the annual unavailability and energy not supplied are consequently improved.

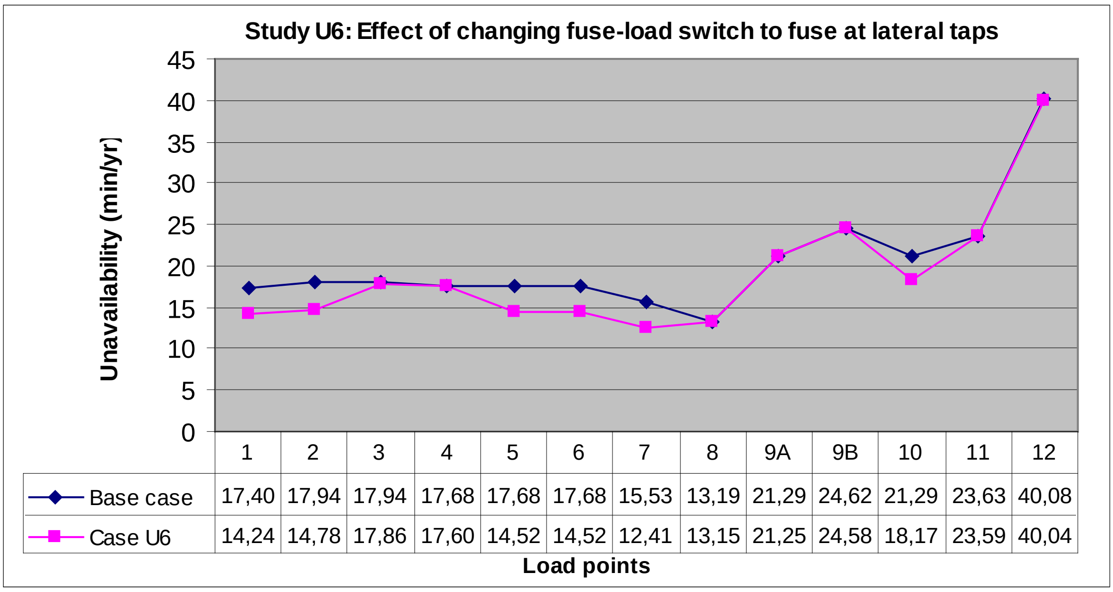


Figure 17-4: Results of Case study U6.

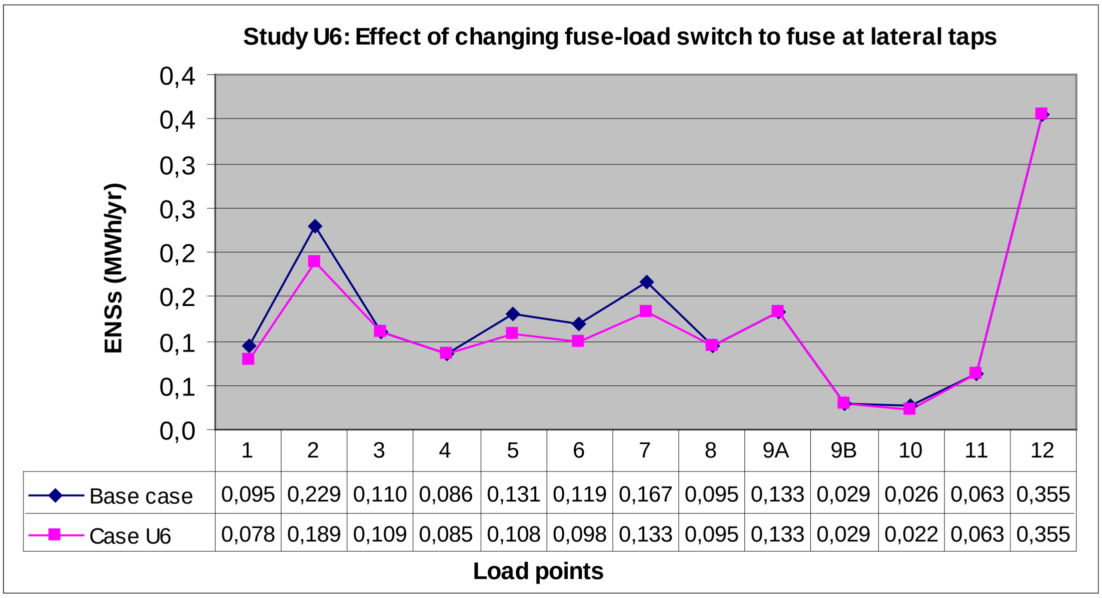


Figure 17-5: Results of Case study U6.

18 Conclusions

Overall conclusions

This project has performed a series of reliability evaluations to investigate possibilities to simplify networks and reduce the network components while maintaining network reliability. It addresses the important considerations of how to build a reliable distribution network in a cost effective way and how network configurations and network components and their placement affect customer reliability indices.

The project has focused on three studies:

- The world-around study to identify trends of future network structure development;
- Rural network study;
- Urban network study.

The details about these studies are presented in the report.

The results show that there is potential to reduce the number of network components and simplify the existing network structures without degrading network reliability. The inclusion of reliability evaluation is important in distribution system planning and design process to ensure cost effective investment. It is feasible to build future networks with less components, simpler structures, and reliable customer service.

The studies demonstrate that network components affect the reliability in different ways. It cannot be concluded that an increased number of components automatically increases the network reliability. Switch devices have potential to improve reliability by allowing faults to be isolated and customers to be restored before the fault is repaired. However, place more switch devices will introduce more active component failures and may eventually result in degradation of system reliability due to the failure probability of each device.

It is therefore of great value to consider these effects and perform reliability quantification in order to obtain the most beneficial solutions of network structures of future distribution networks.

Trends in network structure development

The future electric system will be built on the existing electric network infrastructure. The same types of power equipment used today for power delivery, e.g. power lines, cables, stations, and transformers, will continue to play important roles in the future. However, the emergence of new techniques including distributed intelligence and energy resources will increase the efficiency, quality, and reliability of the existing power systems and enable developing a new architecture for the future smart grid.

The grid of the future will be automated power supply network that monitors and controls consumers and network nodes, ensures a two-way power flow and information exchanges between all points of the network. From architecture perspective its characteristics are:

- Controllable with remote-controlled switch devices, faster detection of outages and rapid customer restoration;
- Flexible, and having compact stations, back up connections, and local power feeding.

Conclusions from rural system study

The main results from the rural system study are summarized as follows.

- On existing rural distribution networks some of lateral switches, feeder switches, and certain load-disconnectors can be removed without affecting the network reliability negatively.
- There is potential to reduce sectionalized switches on rural distribution networks through optimizing feeder sections.
- It is beneficial to consider possibility of simplifying networks when automating the networks to ensure cost-effective investment.
- Tie switches could have a direct effect on outage duration experienced by customers. It is beneficial to consider possibility of simplifying networks when introducing distributed generation and reserve power into the networks to ensure cost-effective investment.

Conclusions from urban system study

The following summarizes the main results from the urban system study.

- On existing urban distribution networks there is potential to improve reliability by modifying network structures.
- On urban distribution networks some of extra tie connections between meshed network parts can be removed without affecting the network reliability negatively.
- On urban distribution networks some of reserve feeding connections between ring-configured network parts can be, under certain conditions, removed without affecting the network reliability negatively.
- On urban distribution networks some of network equipment can be simplified without affecting the network reliability negatively.

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