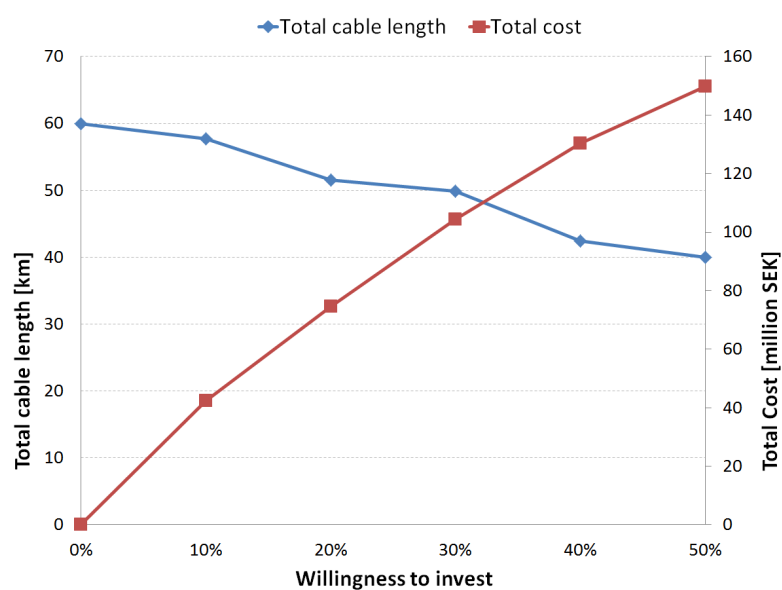


RELIABILITY EVALUATION OF DISTRIBUTION SYSTEMS

REPORT 2017:462



RISK- OCH
TILLFÖRLITLIGHETSANALYS



Reliability Evaluation of Distribution Systems

Considering Failure Modes and Network Configuration

SAJEESH BABU

ISBN 978-91-7673-462-9 | © ENERGIFORSK December 2017

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Förord

Detta projekt är en fortsättning på ett doktorandprojekt från programperioden Riskanalysprogrammet II och etappen Riskanalys III hanterade projektet från licentiat till doktorsavhandling.

Projektresultatet är framtagandet av en mer enhetlig risk- och tillförlitlighetsanalys för elkraftsystem. Metoden är en optimeringsalgoritm som beräknar optimal konfiguration av stationer (främst fördelningsstationer). Analysen bygger på flertalet discipliner (främst tillgänglighets- och kontrollsystemsanalys) som kombinerats. En viktig del av analysen är hur stor del av otillgängligheten som kan tillskrivas primära komponenter och kontrollutrustning.

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Sammanfattning

Eldistributionsnätet är den del av elnäten som leder till flest kundavbrott trots att felhändelserna oftast är mycket lokala jämfört med händelser inom transmission och generering. Av detta framgår vikten av de olika aspekterna av tillförlitlighet och prestanda för distributionssystem. Integrationen av ny teknik, automatisering och ökad penetration av distribuerad produktion, förväntas göra förbättringar och rent av upprätthållande av höga tillförlitlighetskrav till en komplex uppgift.

Denna projektrapport presenterar metoder för att kvantifiera och analysera de komplexa och korrelerade sannolikheterna för olika fellägen i distributionsnätet. En teoretisk simuleringsmodell baserad på verkliga data för sannolikheter och felaktiga brytarkommandon har utvecklats och testas. Förenklade tillvägagångssätt som elnätsföretag direkt kan använda, baserat på lättillgängliga data i felregister, presenteras också.

Metoden bygger på identifiering av optimala konfigurationer med hänsyn till systemprestanda och investeringskostnader, effekter på systemets tillförlitlighet och kostnader för nätinvesteringar modelleras. Optimeringen bidrar till att prioritera kritiska investeringar genom att knyta systemets prestanda till omkonfigurationer. Optimeringen tar hänsyn till kundernas krav och att bevara överföringskapaciteten i svaga länkar. Värdet av befintliga nät och villigheten hos nätägaren att investera kan undersökas som förslag, till ändringar, som stöd för beslut om planering och underhåll.

Projektrapporten gör både systemspecifika och generaliserbara observationer från en detaljerad datainsamling från elnätägare. Observationerna och resultaten kan dels användas i analyser av elnät och dels ge förbättrad förståelse i framtida forskning genom att viktig förståelse för tillförlitlighetseffekter av nätverksstrukturen i kombination med kontroll och skyddsutrustnings påverkan.

Summary

Power distribution networks are recognized as the constituent part of power systems with the highest concentration of failure events. Even though the faults in distribution networks have a local effect when compared to the generation and transmission sides, major contingency escalation events are being more frequently reported from this section. The various aspects regarding the reliability and performance of distribution networks are identified as an important topic. Integration of new technologies, automation and increased penetration of distributed generation is expected to make improving and even sustaining high reliability standards a complex task.

This project report presents developed approaches to quantify and analyze the complex correlated failure probabilities of different failure modes in distribution networks. A theoretical simulation model that relates to real world data to measure false tripping probabilities is developed and tested. More simplified approaches that utilities can exercise with readily available data in fault registers are also established. Optimal configurations that could improve system performance and respective investment costs are analyzed and savings in system reliability at the cost of grid investments are modelled. The optimization helps in prioritizing the most critical investments by considering the system impact of reconfigurations focusing on meeting customer demands and respecting transfer capacities of weak links. The value of existing networks and willingness of the grid owner in investing can be integrated into suggestive alterations to assist decision making in planning and maintenance allocation.

The project report makes both system specific and generalizable observations from detailed data collection from power utilities. The observations and results have potential in aiding future research by giving important understanding of the reliability impacts of network structures and of control and protection equipment.

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1 Introduction

This project report is on the comprehensive reliability evaluation of power distribution networks along with the doctoral thesis with the same title (TRITA-EE 2017:138, ISSN 1653-5146, ISBN 978-91-7729-552-5) successfully presented on 24th October 2017 at KTH Royal Institute of Technology by the author [39]. The research is conducted in two divisions with the first part focusing on the presence and impact of correlated events due to failures and mal-operations of control and protection systems, and the later part focusing on network structure optimization considering cost implications of expected unavailability of different grid designs.

Chapter 1 is the introductory section regarding the various topics discussed in this project report and mainly discusses the respective literature backgrounds, studied in [34- 36, 38]. Chapter 2 discusses the failure mode classifications discussed in [35, 36], and covers the observations and results from the analysis conducted in [35]. Chapter 3 is an in-depth discussion of the modelling approach and results covered in [36]. The extension of the work in [37] is also briefly reflected. Chapter 4 is on the second objective of the project report discussion, which is mainly covered in [38]. Chapter 5 concludes the report.

1.1 RELIABILITY OF POWER DISTRIBUTION SYSTEMS

Power systems are one of the most complex infrastructures found worldwide and they are expected to operate with high quality and reliability. The fundamental purpose of power systems is to provide an economic and reliable channel for electrical energy to transfer from points of generation to customer locations. The economic and reliability constraints can be mutually competitive, making planning and operation of power systems a complex problem [1].

The distribution system reliability evaluation considers the ability of the distribution system to transfer energy from bulk supply points such as typical transmission system end-stations, and from local generation points, to customer loads. In the early stages of extensive power system construction, relatively less attention was given to distribution networks because of their lower capital intensiveness when compared to generation and long distance transmission systems. Also, the outages in distribution networks are expected to have a localized effect [1]. However, analysis of practical utility failure registers and fault statistics reveals that distribution networks as a sub-section of the power systems contribute the most to customer interruptions and failure events [2–4]. With advancements in technologies both integrated in power systems and employed in relation to it, a risk of increase in failure frequencies in power distribution components is expected [34]. Introduction and additions in system automation, wide expansion in power demand complications due to distributed generation etc., are contributing factors to this risk [5]. These advancements are expected to improve the performance of power system. However, bearing in mind that the

added components are never perfect, the addition of a component which can undergo failure thus introduces an additional risk of failure in the system.

Hence, ways of sustaining an adequate level of system reliability and methods for improving it are topics of extreme significance and have key societal impacts. More aspects from this topic specific to the discussion here, such as subdivisions in distribution grid reliability, failure modes and respective probabilities, load point failure rate, system indices for reliability evaluation, configuration variations in power distribution, load demand and transfer capacities etc. are discussed and evaluated through the body of the project report.

As mentioned before, reliability and economic constraints might interfere with each other, and hence require an agreed balance. This balance should be achieved not only by the interest in making savings from the network and cost-effectiveness, but also by considering the societal requirements of high quality of uninterrupted energy requirements. The ethical aspects of research should cater to the social and environmental impact of optimal operation conditions in power systems, making the balance economically worth for both customers and grid owners [6].

1.2 RELIABILITY OF PRIMARY AND SECONDARY EQUIPMENT

The first focus of the project report is in making an improved understanding of the impact of the constituent subdivisions of power system, addressed here as the primary and secondary systems, on system reliability. The primary system grid components are those through which actual transfer of power happen between generation and consumption points in the network. Cables, overhead lines, station transformers, busbars, breaker switches etc. belong to this category by the given definition. The secondary system consists of equipment employed to monitor, manage, communicate information with, and control the primary system. Information and Communication Technologies, control equipment, protection system etc. are different operational units in the secondary system. Due to the complexities in operational design, the functional behavior of certain power system equipment units can also overlap on both primary and secondary system reliability all together. For example, consider the operation of a breaker switch by the control of protection system relaying.

Practical correlations between primary and secondary systems are complex in nature and cannot be effectively assessed from overall system level observations. Simple average calculations of reliability indices might not contain the required level of detail for understanding these correlations. Also, since the improvements in power systems usually occur by updating the existing network architectures, there will be wide variations in the degree of component interaction in the same system. Hence, system specific approaches might be required to address these issues. Such procedures are exemplified in [35, 36].

Paper [34] conducts a detailed review of the reliability studies involving primary and secondary equipment in power systems. A symbolic Venn representation of the distribution of reliability influences of various power system components on primary and secondary equipment is modelled through a comprehensive literature review, and shown in Figure 1.1.

During the investigation of state of the art on reliability studies in [34], it was perceived that a majority of studies that were reviewed confine their evaluations within either primary or secondary system sides without regarding the other. Nordel's guidelines for the classifications of grid disturbances 2009, recognizes the constituent components of control equipment and states that control equipment faults can impact the performance of other components and that such impacts are not identified individually [7]. Analyses which ignore these factors can have sub-optimal results by blaming one component for the faults or problems in different equipment. Analysis in [36] addresses this issue by identifying the range and impact of culprit components on customer interruptions during various modes of failure. Also, in [35] various reports on the standards in classifying faults and outage events were reviewed along with actual fault statistics over several years [7–10]. The percentage division of faults according to component and equipment sections in these reported are studied. Figure 1.2 is a chart showing the distribution of component faults observed in the Nordic region during the years 2004 to 2013 consolidated from the reviewed reports.

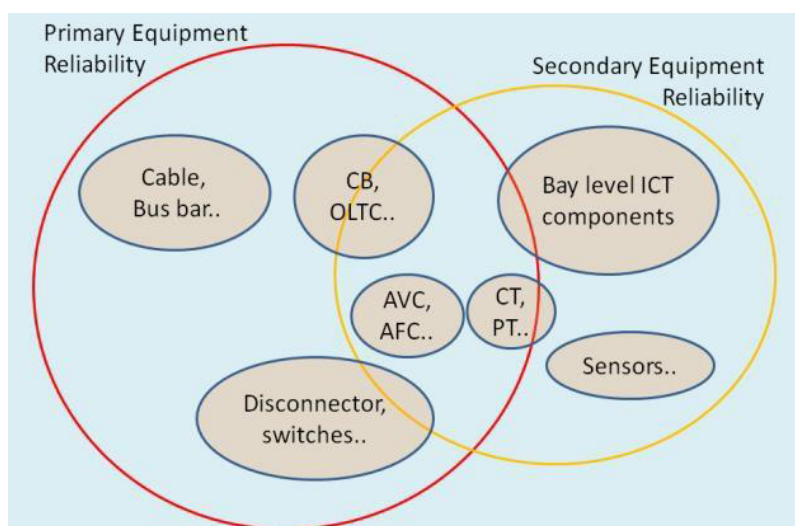


Figure 1.1: Distribution of component reliability over primary and secondary sides.; Circuit Breaker (CB), On-Load Tap Changers (OLTC), Automatic Voltage Control (AVC), Automatic Frequency Control (AFC), Current Transformer (CT), and Potential Transformer (PT).

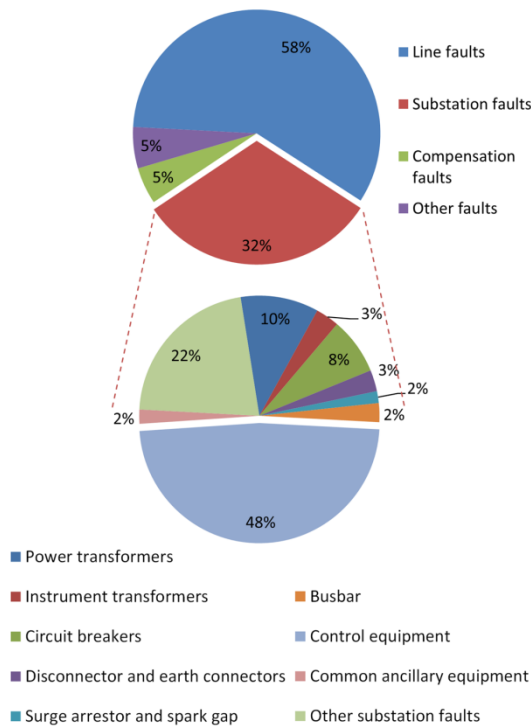


Figure 1.2: System and component fault classification

The literature review in [34], along with identifying key research works from the topic background, also looks into challenges associated with the combined analysis of primary

and secondary systems. This exercise was to frame a basis for the next step in research where protection system reliability was quantified from load end failure rate calculations in distribution system architectures [36]. Works related to this topic were also reviewed prior to the modelling practice and they are presented in [36]. Some related works are shortly discussed here.

One important work uses ‘control functions’ as a linking key between primary and secondary equipment within the bounded considerations [11]. In automated systems, control functions are the signals generated by secondary equipment to make a pre-defined action in a respective primary component. The work identifies the secondary system components required to properly generate a set of different control functions with an understanding of criticality. A mapping of the control functions to the respective functionality of the primary equipment is also made. Thus, a two-step relation of the primary and secondary system is established and reliability indices relating the unavailability of components and functions are derived.

Among the background literature, [12] identifies the criticality of simultaneous availability of protection system and communication technologies to achieve reliable operation and recommends the use of communication protocols to minimize signal errors and effective faults in the primary system. Modes of protection system failures and cascading failure events are investigated in [13, 14]. Paper [36] and Chapter 3 in this project report approach this problem with real

world data and make quantitative observations of failure probabilities compared to the test system approaches in these references.

The next section discusses the background of the second objective of the project report, which is network structure optimization considering cost implications of expected unavailability of different grid designs.

1.3 NETWORK RECONFIGURATION CONSIDERING INVESTMENT COSTS AND RELIABILITY IMPACTED OUTAGE COSTS

Power distribution networks developed and expanded over the years driven by overall power demand and network capacity requirements due to an increasing number of customers. Expansions and reconfigurations are introduced to existing systems and the design of the network thus has an organic growth into demand intensive geographic hotspots [6]. Such network expansions and alterations should be planned and designed such that the load requirements are satisfied in quantity and quality, power loss during the delivery is minimal and reliability of the system is high [15].

While reviewing the background of network reconfiguration from literature, it is observed that the focus in this area has been mostly in power transmission, power losses and voltage stabilization [16–19]. The challenges and margins put forward by the existing design of power networks and investment limitations have restricted the role of system reliability in making optimal network configuration plans and related decisions [20, 21]. Normally in power systems, investments for increasing reliability are compared with the additional expected costs during operations in the absence of these investments in the form of power outages and maintenance requirements [22]. Hence, it is critical to have system specific analysis where different potential network configurations are introduced with a reliability improvement objective and the operational and investment costs of the potential options are considered.

Since the majority of customer outages occur due to faults in distribution systems, improvements in the configuration of the network can have important advantages [2, 4, 22]. Reconfiguration of distribution systems has been approached in literature through various methodologies and algorithms as reviewed in [16, 23]. Different objectives that can be addressed by reconfiguration such as loss reduction, load balancing, voltage stabilization, service restoration etc. for normal operation and faulty conditions are reviewed in [24]. Advantages and shortcomings of different methods to address these objectives are examined in [23]. Technology specific analysis, such as, investigation of switching options to bring forth alternate configurations is considered in [25].

Here in this project report, the objective is to compare different possible configurations of distribution networks with a combined optimization of both the cost of investment required to introduce new links in an existing system and the effective operational cost in the suggested networks due to outages and system reliability. Contribution to system reliability from component unavailability is considered while calculating the costs. Chapter 4 further discusses the model and optimization.

2 Correlated Failures: Observing Presence and Impact

Prior to stepping into modelling using the different modes of failures, it is important to understand the different possible circumstances of grid failure. The literature review on this topic has highlighted the classification of failure modes and various scenarios of correlated failure events. This chapter examines such cases and classification. The discussion is followed by formulating a direct method to observe and to make estimations on frequencies of different failure events from utility registers. The observations hence made on medium voltage (MV) grid in specific cases are also discussed.

The discussion here focuses on the station and feeder architecture at the utilization end of power grid. The logical operations and failure impacts of circuit breakers and respective protection systems are considered. Here, the term ‘failure’ can indicate either an unavailable status of a component while operation is required or an unwanted mal-operation when no such action is required [26]. The different possible modes of failure in such a scenario are active failure events, passive failure events, stuck-condition of breakers and overlapping failure events [27].

2.1 FAILURE MODES IN STATION AND FEEDER ARCHITECTURE

2.1.1 Active failure events

Active failure events are the most common mode among power system failures [27]. Consider a short circuit fault in a conductor component for example. In such a case, the faulty conductor is isolated from the rest of the system by the opening action of a circuit breaker responsible for the particular protection zone. In this example, the only faulty component is the conductor which experienced a short circuit and the protection system and the breaker relay operated consequently as designed for.

The customer impact of failures fundamentally depends on the design of the grid. In a simple radial system with no redundancy, the opening of a feeder section due to conductor short circuit disconnects all customers feeding through that line and the duration of disconnection depends on the time to repair the short circuit condition of the conductor and restore power supply. Later in this chapter, in Section 2.3, possible variations in the impact of active failure events depending on grid designs are discussed further. Also, in Chapter 3, the modelling of active failures in cables and breaker components are discussed.

2.1.2 Passive failure events

While defining the term failure, one of the possible conditions in consideration is an unwanted mal-operation in a system where no active failure is present to initiate it [26]. Passive failure events are such cases where an undesired open

circuit occurs with no other fault in the system to trigger it. Hence, passive failures are not characterized by fault currents that are sensed by protection systems. The reasons for passive failure events can be physical or material failure, false relay triggering from protection systems, lack of situation awareness from human operator etc. Hence, the culprit component in the case of a passive failure event should be understood from the cause of the event, to avoid wrong estimations in component failure statistics. Even though there is possibility of passive operations such as disconnecter failures escalating to short circuit events due to contact with surrounding components or ground [28], a typical passive failure event only disconnects the customers directly supplied through the line that got opened.

In the operation of practical power systems, passive failure events are very rare in occurrence [22]. Hence this mode of failure is not in the key focus of the discussion here. However, the developed modelling discussed in the next Chapter has provisions to consider passive failure events.

2.1.3 Stuck condition of breakers

Stuck condition probability of a breaker is defined as the ratio of number of failures to operate due to the stuck condition to the total number of commands for the breaker to operate [26]. The implications of a stuck condition of breakers from a reliability calculation perspective should be modelled according to specific cases. Hence, in this project report, the stuck breaker condition is not addressed directly, but through case specific reliability approaches. For example, a failure of a breaker to operate due to physical stuck condition can be modelled as an overlapping failure. The additional customer disconnection required in order to repair the stuck breaker switch and restore functionality by opening another breaker upstream, can be blamed on the stuck breaker. The case can be considered among the active component failures of the breaker (Further discussed in Section 3.1 and 3.2). However, failure of the control or protection equipment to correctly deliver the relay trip signal can also cause the breaker fail to operate and in such cases, the culprit component belongs to the control equipment side. It is vital to understand the correct failure probabilities of breaker and protection system in order to formulate optimal maintenance strategies. Preventive maintenance is a key process in avoiding stuck condition in breakers.

2.1.4 Overlapping failure events

This failure mode is in the key focus of the discussion here. Overlapping failures are the events where a system is experiencing a partial or complete failure or undergoing a respective repair process and an additional failure occurs overlapping with this condition. Such overlapping failures occur in power system operation either due to random reasons or due to the increased failure risk imposed by the first failure or repair situation. Introduction of more automation in power system operation and control increases the expected frequency of these types of failures. Very short disconnections and failures overlapping in orders higher than two component faults are neglected, as generally suggested for these calculations [13]. The following section further expands the specific cases considered and the respective causes and features of overlapping failure events.

2.2 FALSE TRIPS CAUSING OVERLAPPING FAILURE EVENTS

False tripping of a breaker during a component failure can be in two ways: fail to operate and unwanted tripping [13]. If an unwanted tripping of a breaker occurs in the absence of any faults in the system, then it should be counted as a passive failure and not an overlapping failure. However, when a false trip happens in the presence of an actual component failure in the system it is effectively an overlapping failure event. False trips and such overlapping events are experienced more frequently in modern power system architectures with different levels of automation. Sensitivity setting and tuning of protection zones in distribution system protection is a complex task. Because of the limitations imposed by system design, lack of operator's situation awareness and complexities in control and protection schemes, probability of false trips vary [36]. Quantification of false tripping probabilities causing overlapping failures in power systems is a critical task which could assist in maintenance allocation, investment planning, identification of optimal configuration for operation etc. Hence, utility fault registers are studied thoroughly and the major players among these failure events are identified. After introducing these cases, the discussion proceeds to identifying and assessing their impact from faults registered by utilities.

2.2.1 Overlapping events with sympathetic tripping

Sympathetic tripping is a mode of failure that overlaps with grid faults, escalating customer interruptions. The escalation is due to the disconnection of healthy feeders from the supply because of the unwanted sympathetic response of a breaker corresponding to the healthy section, to an actual fault in a neighboring line [29]. While the customer interruptions due to the actual fault can be blamed on the grid fault, the range of escalation of interruptions is because of the protection system which makes an undesired sympathetic trip. Typically the customers interrupted through the fault escalation can be reconnected to the supply faster than the section with the actual grid fault. Even though the occurrence of sympathetic tripping is rare compared to active failure events, the impact on customer interruptions due to fault escalation can be serious. When automation is introduced on existing grid infrastructures, overlapping events such as sympathetic tripping are expected to be relatively more frequent [30]. There can also be other contributing factors like wrong setting and tuning of protection system sensitivity, high capacitance currents in systems with more cable feeders etc.

In Section 2.3, the distribution of customers disconnected during each grid failure is observed and sympathetic trips are identified from faults reported by utilities. Accurate quantification of sympathetic tripping probabilities is conducted later in the next chapter.

2.2.2 Overlapping events with breaker operation failure

While discussing the stuck condition of breakers, the reliability impact of it as an overlapping event was mentioned. There also exist other practical cases such as wrong sensitivity of breaker protection to respective protection zones, failure of protection system to effectively respond to faults, setting errors due to lack of

situation awareness etc. that result in contingency escalation. Overlapping events with breaker operation failure indicate the cases of false tripping where the breaker which should act as a backup protection becomes the one actually isolating a grid fault, typically at the cost of increases customer outages [35]. Such events, though rare, are hence of high impact in range of customer interruption. In the next section, these fault escalations are identified as the cases where grid failures that should actually be confined to affect only the customers feeding from one feeder, getting escalated to impact an entire distribution of customers feeding from the same busbar or even the whole station. To aid this approach, the cases in which a station or busbar breaker operated unrelated to faults in the MV grid are excluded from the list of failures analyzed. That is, in case a failure at the substation in a main line component such as a transformer occurred, such cases are not considered as they are not overlapping events with breaker operation failure.

2.3 DIRECT ESTIMATION APPROACH

A classification approach observing the grid design and affected customers corresponding to each grid fault event is formulated in [35]. The classification is a grading approach based on the number of customers each fault should have affected in contrast with those it actually affected, keeping in consideration how those customers are distributed in the grid. The intention of the direct classification approach is to assist utilities in recognizing the distribution of different modes of failures in their grid and to find out the hot spots where fault escalations are present, with the help of readily available data in fault registers. Thus, this method was applied on the faults registered under the MV grid of ten substations in the Stockholm municipality region in Sweden. These ten substations vary in size, design, geographic locality and customer distribution.

Different types of active grid failures and overlapping events classified by the approach are already discussed here and in [35]. Before discussing these observations, a sub category of active grid failures need to be introduced. This additional categorization is the result of the commonly present link-line structure in the case study. The link-line structure as shown in the Figure 2.1 consists of two neighboring feeders running along a geographic area. This physical vicinity is represented by the mutually approaching tapering of the feeder lines. The purpose of the structure is to achieve better reliability than simple radial systems by the capability of secondary stations to feed from either one of the feeders among the link-lines. If such secondary stations are equipped with an automatic switching apparatus that shifts the feeding to the alternate line in case of zero-voltage detection in the default line, (because of a fault in the default feeder line) there is enhanced redundancy in effect, and thus, the supply reliability is improved.

However, this redundancy functionality is determined by the capacity of the feeder lines and whether or not switching equipment is present at the secondary station feed in points.

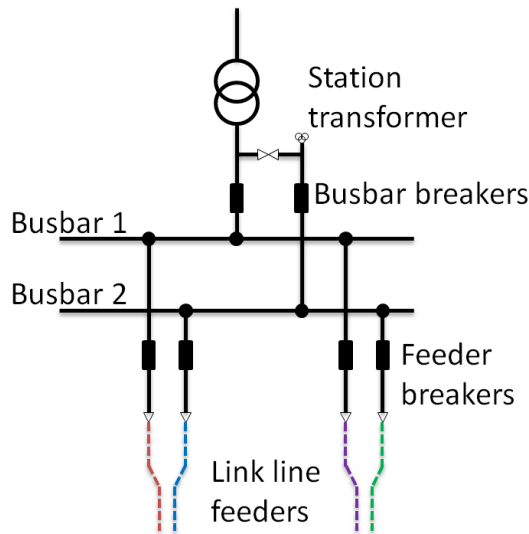


Figure 2.1: Parallel feeders in link-line structure

Note from the structure that at every point of operation, the grid is effectively in a radial fashion and not a mesh design, as in usual distribution networks [31]. However, this arrangement makes the identification of active faults more complex, depending on the number of customers connected to each feeder in the link line pair before and after the fault. Effectively, the number of customers affected by an active fault in a feeder line thus can vary between zero and the total number of customers feeding from the two feeders in the link-lines. Hence, there are cases when an active failure occurred in a feeder and the number of customers thus affected is less than those connected to the faulty feeder prior to the fault. In this situation, we restrain the definition of active grid failures to the cases where at most, all the customers connected to the faulty feeder (and as discussed, in practical cases, fewer customers) got disconnected from supply. The additional classification category, where active failures can have a larger number of customer disconnections than those feeding from one of the link-line feeders is addressed here as 'active grid failures with minor escalation', and is introduced next.

For the minor escalation cases, the mode of failure is essentially an active failure. However, there is a minor escalation in customer disconnections due to practical disadvantages of the link-line structure. More customers from the parallel link-lines can set to feed from the non-default feeder due to practical reasons during operation or maintenance. When such additional customers connected through secondary stations lack the ability to automatically switch back to default feeder during faults, an escalation of customer interruption occurs. In most of the cases this situation arises because of the design of the secondary station connection with no automatic switching option and in rare cases the unavailability or failure of automatic switching systems might contribute to the problem. Hence, the majority of such cases can be directly treated as simple active failures from a system reliability perspective.

2.4 OBSERVATIONS FROM CASE STUDY

The failure modes discussed in the previous section are restricted within four categories here. Four indication terms are used in [35] to represent these classes:

- Active grid failures: A,
- Active grid failures with minor escalation: A+,
- Overlapping events with sympathetic trip: B and
- Overlapping events with breaker operation failure: C.

Descriptions and direct comments from the fault registers can be referred from [35]. The key observations from the analysis are described next.

The case study data consists of fault registers for the selected MV grid with its stations. The data is recorded in two registers for two consecutive sections of time. The first register for January 2009 to December 2012 has 160 reported failure events and the second register for January 2013 to September 2015 has 101 failure events. Note again that the cases in which a station or busbar breaker operated unrelated to faults in the MV grid are excluded from the list of failures. Contrasting observations and charts in the classification are presented in [35] on various indices such as total number of registered faults, total number of customers affected, Energy Not Delivered etc. The classification was followed by an analysis of the observations.

The data sets were normalized considering yearly distribution of various faults belonging to different modes. It is clear that the total number of failures per year has declined with time. This can be the result of new investments and maintenance practices in the system. However, while individually comparing the faults reported under different failure modes, it is seen that an approximate 18% reduction in active failures, which are the most frequent ones, is the main reason for the decline in total number of failures per year. The faults with major contingency escalations are seen to have increased over the years. The correlation of reliability of control and protection equipment in overlapping events with major contingency escalation is already established in [34]. This strongly recommends focusing investments and maintenance on secondary equipment further, so that more reduction in failures and customer interruptions are possible.

The classification approach was also extended to make localized observations on the stations included in the case study data, to see secondary equipment fault hotspots in the network. Paper [35] presents a detailed description of this. Some key points are highlighted here.

Figure 2.2 shows the distribution of faults both with and without contingency escalation among the substations in the case study. Among the stations, substation 5 has the highest number of overlapping events with breaker operation failure recorded over the years. It is observed that these events have caused more than 23000 customer interruptions. The performance of the control and protection equipment responsible for these events hence needs to be thoroughly reviewed. There are other substations such as 3, 8 and 9 where the distribution of overlapping events with sympathetic trip is higher. On the other hand, substation 1 has have only one case of minor contingency escalation and hence all the faults

that occurred there are active failures. The secondary equipment responsible for this station has shown relatively good results and hence there can be value in comparing this with the weak points and identifying the good practices that provide improvement in system performance.

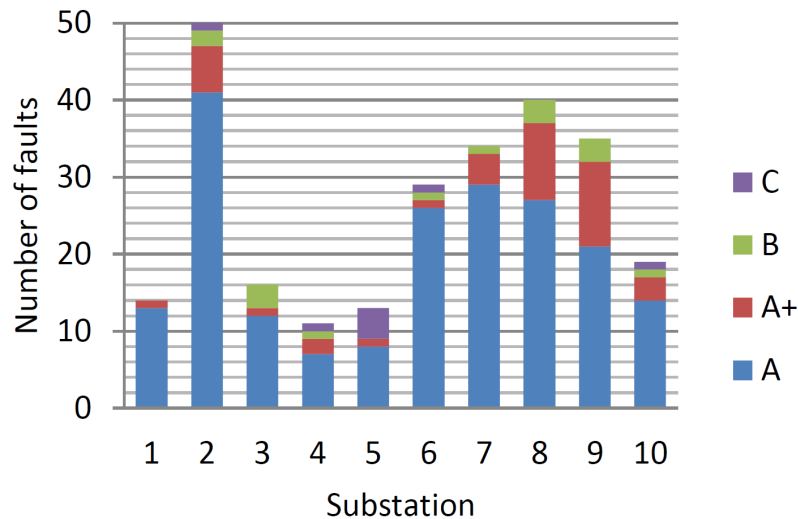


Figure 2.2: Fault type distribution among recorded faults for the substations

To have an understanding of the degrees of fault escalations caused by the different modes of failures, the whole set of faults were graded in the order of contingency escalation caused, divided in to ten equal packets, as shown in Figure 2.3. On the axis with degree of fault escalation (affected customers/ connected customers), the ranges that different failure modes occupy are visible as the respective section width. Note that this is a case study system specific view. The range in which the link-line feeder structure aids and opposes fault isolation can also be seen. For example, the first packet on the left consists of active failure cases where the customer disconnections were substantially less than the customers connected to the faulty feeder. Multiple thin lines in the vicinity of 100% on the horizontal axis show that the majority of faults affected all the customers that are connected to the faulty feeder in those cases. The approximate range of initiation of the fault types with major escalation impacts can also be seen. The low number of packets and high width of the section denotes the less frequent yet high impact nature of these faults.

This concludes the introduction of failure modes and discussion on their observations from case study data with direct methods. In the next chapter, the discussion progresses to the development of a model to capture the different failure modes and determine the hidden overlapping failure probabilities as a generalizable method.

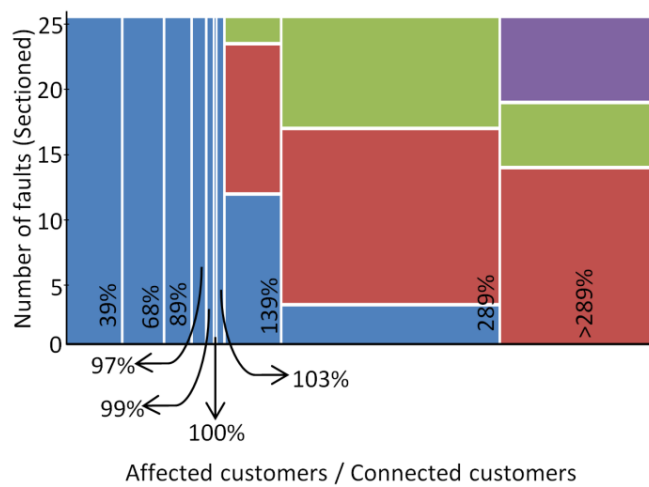


Figure 2.3: Fault case packets sorted according to degree of fault escalation

3 Reliability Evaluation of Distribution Architectures Considering Failure Modes and Correlated Events

This chapter discusses the theoretical background, model development using Reliability Block Diagram (RBD) method and results obtained through trend fitting analysis. The sensitivity trends of the hidden failure probabilities thus obtained within practical ranges are also observed.

3.1 ARCHITECTURE FOR BUSBAR AND FEEDER PROTECTION

A basic representation layout of a busbar with several lines feeding from it, as shown in Figure 3.1, is considered as the basis of the RBD model. Both the busbar and the individual feeder lines are assumed to have separate breakers for protection and fault isolation. B0 denotes the busbar protection breaker and B1, B2, ..., Bn represents the feeder protection breakers for lines 1, 2, ..., n. The conductor components in each line and the total feeder section as a whole are denoted by C and L respectively.

3.2 FAILURE MODE CLASSIFICATION IN RBD MODEL

It was pointed out in Section 2.1 that stuck condition of breakers depending on the cause can be modelled from a reliability perspective either as an active fault or as an overlapping failure event. Hence, the discussion here considers the rest of the failure modes. The RBD model of the busbar and feeder architecture introduced in Section 3.1 is shown in Figure 3.2. Note that while making calculations such as failure rate of constituent components, each respective block in the RBD can signify the respective component failure rate.

3.2.1 Active and passive failure events

The term α is used here to represent the proportion of active failures of feeder breakers, which are the cases where the station or busbar breaker needs to operate to isolate any of the feeder breakers. Subscript i represent the feeder section.

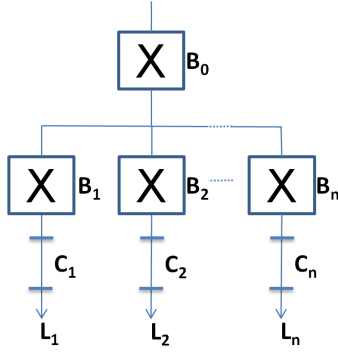


Figure 3.1: Branching feeder structure. Circuit Breaker (B), Conductor component (C), Feeder Section (L).

$$\alpha_i = \frac{\text{active failure frequency of } B_i}{\text{total failures frequency of } B_i} \quad (3.1)$$

Also, $(1-\alpha_i)$ denotes the ratio of passive failures of a breaker B_i among its total failures as per the model design in RBD. The net failure rate experienced at the end of each feeder section considering the individual failure rate of all affecting components by an approximation method [22] can hence be expressed as

$$\lambda_{L_i} \approx \lambda_{B_0} + (1 - \alpha_i)\lambda_{B_i} + \lambda_{C_i} + \sum_j \alpha_j \lambda_{B_j} \quad (3.2)$$

Excluding the failure frequencies of simultaneous events as per approximation method is accepted, as possible overlapping failure events are counted here separately. For a system with components which never or rarely undergo passive failures, $\alpha_i \approx 1$. In such a case, Equation (3.22) implies that the overall failure rate expected for a load point is the sum of the component failure rates of all the breakers and that of the conductor line connecting to the corresponding load point j [36].

3.2.2 Overlapping events with sympathetic trip

The failure rate contribution due to sympathetic tripping can be found as the product of the probability of sympathetic fault overlap and the failure rate of the component with which the overlapping occurs. Let δ_j denote the probability of sympathetic faults event that can overlap with a failure event in a conductor C_j .

$$\delta_j = \frac{\text{sympathetic trip frequency overlapping with failure of } C_j}{\text{total failures frequency of } C_j} \quad (3.3)$$

Then, the effective failure rate in a feeder line due to sympathetic tripping,

$$\lambda_{Lsy_i} = \sum_{j=1}^{n, j \neq i} \delta_j \lambda_{C_j} \quad (3.4)$$

3.2.3 Overlapping events with breaker operation failure

Let β_j represent the proportion of active failure of conductor components C_j which only impacts the feeder section in which C_j belongs.

$$\beta_j = \frac{\text{active failure frequency of } C_j}{\text{total failures frequency of } C_j} \quad (3.5)$$

Then by RBD design $(1-\beta_j)$ represents the probability of all the cases of overlapping events with breaker operation failure where a failure in a feeder section conductor λ_{C_j} , which should only affect the particular section alone escalates to operate the busbar breaker B_0 , thus impacting all the feeder sections; See Figure 3.2. Thus, the effective failure rate due to breaker operation failure is:

$$\lambda_{Lg_i} = \sum_j (1 - \beta_j) \lambda_{C_j} \quad (3.6)$$

Note that overlapping failure probabilities assumed here overlap with conductor component failures alone. This design is because, in the busbar and feeder architecture, the busbar breaker needs to operate to isolate the entire faults occurring in the feeder breakers. Hence irrespective of overlapping probabilities, the breaker B_0 should open to isolate for all the faults and repair of the feeder breakers. If knowledge of specific faults overlapping with failure events in components other than conductors is known, such probabilities can be separately added to the top section in the RBD model.

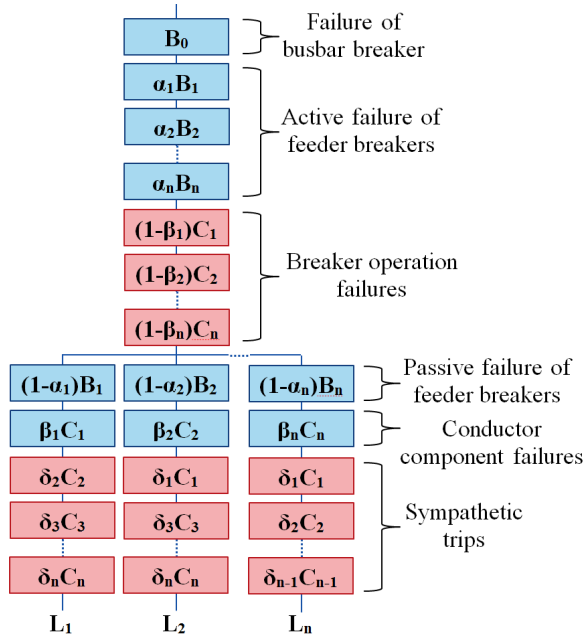


Figure 3.2: RBD model counting failure modes such as active, passive, overlapping events with sympathetic and breaker operation failures represented by component blocks and probability indices.

The net failure rate experienced at the load end of each feeder section can be expressed by combining Equations 3.2, 3.4 and 3.6. Thus,

$$\lambda_{Li} \approx \lambda_{B0} + (1 - \alpha_i)\lambda_{Bi} + \beta_i\lambda_{Ci} + \sum_j[(\alpha_j\lambda_{Bj}) + (1 - \beta_j)\lambda_{Cj}] + \sum_{j=1}^{n,j \neq i} \delta_j\lambda_{Cj} \quad (3.7)$$

For a fictitious system with only active component faults, the designed model will adopt the values $\alpha_i = 1$, $\beta_j = 1$ and $\delta_j = 0$. In practical systems, these probabilities vary depending on various factors such as network design, performance quality of secondary equipment, situation awareness of human operator, failure frequency of primary components etc. In the following sections, a method to derive these hidden probabilities in actual distribution systems is presented.

3.3 TREND FITTING MODEL RELATING THEORETICAL FRAMEWORK AND REAL WORLD DISTRIBUTION SYSTEM DATA

Combining the formula for calculating net failure rate experienced at the load ends of the feeder sections given in Equation 3.7, with various busbar architectures in real world distribution systems, the trends of system reliability in these designs can be derived. These trends are observed here over the number of feeders connected to each busbar. With increase in the number of feeders connected to each busbar in a station, and in different stations, more potential failure scenarios and higher risk and probability of failure escalation exist. [36] describes this in detail along with the relevant data regarding component reliability and various station designs.

The approach here is to use the RBD model to generate a framework in which different real world station architecture data can be processed. The theoretical model and the data model handshakes to fit trends and thus derive system accurate values of the hidden probabilities as α , β and δ indices by which false trips and overlapping failure events occur. Both the theoretical simulation model and the data model should consider the same template for including the trends and distributions.

3.3.1 Theoretical simulation model

The details on how the theoretical simulation model reads component connections in substations are described in [36]. Note that this is a flexible definition, which can be altered to cater for the variations in station designs and components. The required values of component reliability indices are provided and the possible ranges of false tripping probabilities are defined (0 to 1) in the theoretical simulation model initially, so that it can be ready to execute the logic of Equation 3.7. The same network framework for the data model is adopted in the simulation model so that the iteration ranges of i, j etc. in Equation 3.7 are established. At this stage, the theoretical simulation model is ready to plot the contribution term in system reliability indices (in this case which is System Average Interruption Frequency Index (SAIFI) contribution) against feeder distribution in busbar and station designs. The value of α , β and δ can be anywhere between 0 and 1 and the user, if required, can preset these values to see resulting trend. The expected behavior in the case of absence of false trips can be simulated by setting $\alpha = 1$, $\beta = 1$

and $\delta = 0$. The distribution and trend hence obtained is shown in Figure 3.3. Each data point denotes a busbar. Note that linear trends are observed here because of the structure of Equation 3.7. Combining Equation 3.7 with the data in Table 3.1, λ_{L_i} is taken as the dependent variable against the independent variable ‘number of feeders per busbar’.

3.3.2 Data model

As the simulation model is set as a flexible trend which can fit to various slopes, the system is ready to scan the actual trend plots from real world data. The distribution of α , β and δ affecting the performance of all practical distribution systems need to be analyzed from practical distribution station level performance and reliability data.

In a perfect distribution system, the presence and variations in the number of parallel feeders is not expected to degrade the performance of individual feeders. However, due to undesired false trips and secondary equipment failures, contingencies spread to neighboring lines. The investigation of fault registers from the distribution substations in Stockholm municipalities show that there are several cases of false trips and contingency escalation cases that have happened over the years. However, qualitative and quantitative assessment of these contingency escalations and respective probabilities has not been conducted in significant detail. The data for the modelling here hence consolidated the details of 9 different primary distribution substations in the Stockholm municipality, which vary in geographic locality, feeder and busbar architectures, number of customers and recorded performance reliability. Table 3.1 shows the consolidated data collection for modelling [36]. The stations in Table 3.1 are from different places such as urban and suburban areas. Exact locality information is avoided here due to utility data privacy requirements. Description of the three areas to which the stations belong is given in [36].

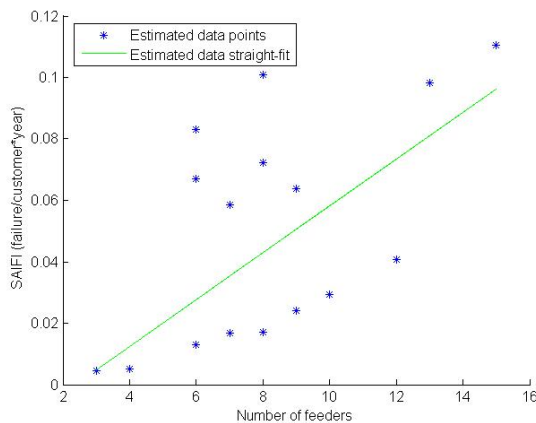


Figure 3.3: Simulated trend of busbar level SAIFI against number of feeders per busbar for a system with only active component failures.

3.4 OBSERVATIONS AND RESULTS

Initially, the theoretical trend line plot excluding false trip probabilities in the system is compared with the actual SAIFI contribution distributed over different systems with various 'number of feeders per busbar' distribution. The difference in the trends seen in Figure 3.4 strongly suggests the presence of false trips and contingency escalations in the grid as the real data shows poorer performance than the theoretical case with no false trips.

After confirming the disparity, the theoretical model is set free from prefixed values for α , β and δ . The model handshake sets the value in the theoretical model closest to the real data trend. This reveals the actual distribution of α , β and δ in the system studied. Note that, since active failures are the most frequent among the failure modes as discussed in the previous chapter, practical values of α and β should be closer to one than zero, whereas passive failures and overlapping failure events should be relatively rare and hence $(1-\alpha)$ and δ should be closer to zero than one. This knowledge can be used to prompt the simulation runs. However, it is not required to do so if the studied systems are a manageable data size. Figure 3.5 displays the model handshake point with the trend fit. The respective readings showing the hidden false trip probabilities in the system are $\alpha = 0.99$, $\beta = 0.82$ and $\delta = 0.038$.

Table 3.1 Substation, Busbar and Feeder Layout Data.

Substation	Total number of feeders	Station level SAIFI (failure/customer *year)	Average feeder length per station (km)	Net failure rate for feeder component (failure/year)	Number of separated busbars	Busbar	Number of feeders per busbar	Busbar level SAIFI (failure/customer *year)
1	43	0.134	1.467	0.02641	4	1	10	0.031163
						2	9	0.028047
						3	12	0.037395
						4	12	0.037395
2	44	0.602	2.047	0.03685	8	5	7	0.095773
						6	7	0.095773
						7	6	0.082091
						8	6	0.082091
						9	3	0.041045
						10	3	0.041045
						11	6	0.082091
						12	6	0.082091
3	48	0.103	1.303	0.02345	8	13	8	0.017167
						14	8	0.017167
						15	4	0.008583
						16	4	0.008583
						17	4	0.008583
						18	4	0.008583
						19	8	0.017167
						20	8	0.017167
4	15	0.271	3.169	0.05704	2	23	7	0.126467
						24	8	0.144533
5	12	0.192	6.062	0.10912	2	25	6	0.096000
						26	6	0.096000
6	18	0.456	2.156	0.03881	2	27	9	0.228000
						28	9	0.228000
7	30	0.418	4.057	0.07303	2	31	15	0.209000
						32	15	0.209000
8	26	0.451	3.796	0.06833	2	33	13	0.225500
						34	13	0.225500
9	14	0.158	5.513	0.09923	2	35	8	0.090286
						36	6	0.067714

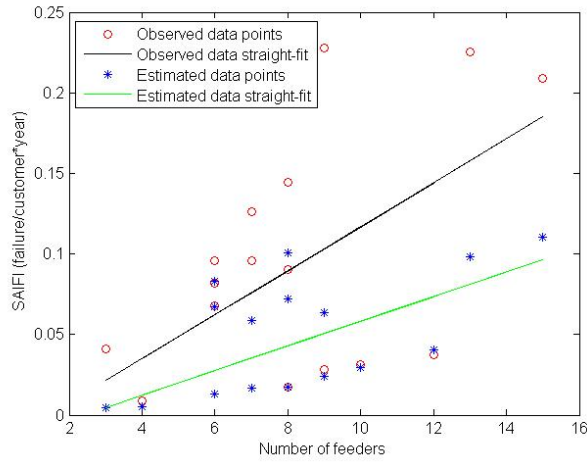


Figure 3.4: Observed trend of busbar level SAIFI against number of feeders per busbar from the data for the existing system along with the simulated data with only active failures in the system.

Thus, the results are in the practical range, which reveal significant information regarding the studied system. An extracted view of false trip related SAIFI contribution (passive breaker openings, breaker operation failure and sympathetic trips) among the total set was also generated and the distribution shows that about 36% of the failures are associated with false trips and protection system faults [36]. Even though the results given by the model are specific to the data analyzed, the approach and range of results are generalizable. Paper [36] further discusses the validation and value of the results.

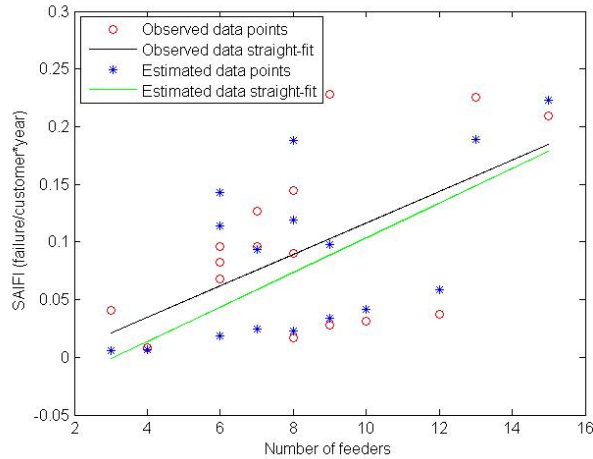


Figure 3.5: Curve fitting optimization of estimated trend with the observed data; $\alpha_1 = 0.99$, $\beta_1 = 0.82$ and $\delta_1 = 0.038$.

3.5 SYSTEM PERFORMANCE SENSITIVITY TO VARIATION IN PROBABILITIES OF FALSE TRIPS

As mentioned before, each data point in Figure 3.3 to 3.5 denotes one busbar with certain number of connected feeder lines. A closer view of the expected variations in the reliability and performance of these busbars for a range of variation of false

tripping probabilities is discussed here. Also, variations in System Average Interruption Duration Index (SAIDI) contributions are observed. Data regarding one busbar and connected feeder details were collected first. Similar data is also of interest in the discussions in the next chapter. There, the layout of the whole station of which the busbar studied here is a part, is investigated for re-configuration possibilities. The system is described by the coordinate layout in Figure 3.6 and the data given in Table 3.2. Paper [37] discusses the case study in detail with a general architecture layout for the busbar, feeders and secondary stations.

Note that, here the passive failure probability of feeder breakers are neglected as they are found to be very low in the analysis. Equation 3.7 excluding failures in breakers, is modelled here with the data from the Table 3.2, as the focus is on grid failures.

Equation 3.7 relating the dependent variable, λL and the independent variable 'number of feeders per busbar' gives simplistic linear variations in the expected system reliability indices when probability of one of the overlapping events is varied keeping the other at the measured value. Two sample figures with the simple linear trends are shown here and [37] shows two more. See Figures 3.7 and 3.8 to see how impacts of various failure modes add up to give the total SAIFI and SAIDI contributions.

An approximate distribution of number of events from various failure modes from the fault statistics of 10 different distribution substations over a period of less than seven years is presented in Section 2.4 of the project report and displayed in Figure 2.2. The respective combination of sympathetic tripping probability and breaker operation failure probability is shown in Figure 3.9 based on estimations. Among the stations in Figure 2.2, those which have not experienced either any sympathetic trips or any breaker operation failures during the period of study are distributed directly on the axes lines in Figure 3.9. The rest of the stations have experienced both sympathetic tripping failures and breaker operation failures during the analyzed years. The data points denote the stations.

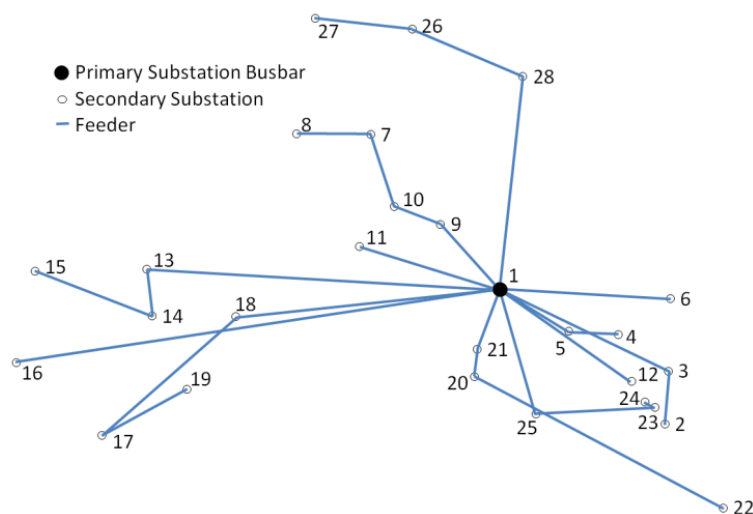
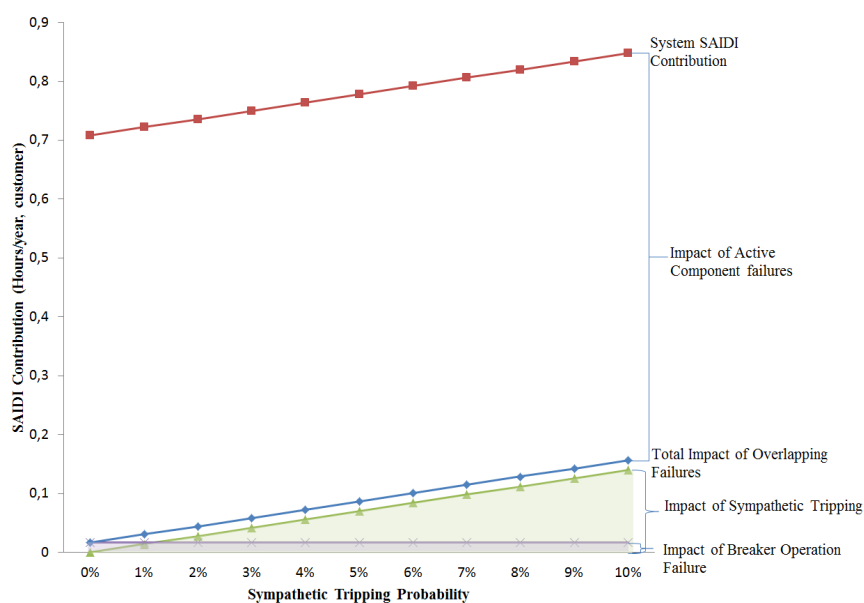


Figure 3.6: Nodal layout of the grid section; related data in Table 3.2.

Table 3.2 Data regarding primary Station Busbar and the Secondary Stations.

Substation	Linking Feeder	Customers Connected	Power Demand [kVA]	Connecting cable length [m]
1		Total = 9527		0
2	1	301	690	4471
3	1	315	282	3198
4	2	1109	1250	1591
5	2	150	70	1050
6	3	216	513	1054
7	4	162	552	1498
8	4	82	483	1880
9	4	10	690	615
10	4	76	2400	893
11	5	41	900	1144
12	6	25	980	1164
13	7	788	518	1941
14	7	584	690	2352
15	7	137	492	3105
16	8	861	624	3943
17	9	859	730	2582
18	9	175	690	1382
19	9	1148	1040	3163
20	10	506	380	685
21	10	262	242	476
22	10	412	807	2261
23	11	323	1247	3062
24	11	42	870	3187
25	11	558	586	1926
26	12	115	621	3924
27	12	206	414	4737
28	12	64	828	2816

**Figure 3.7:** Variation in SAIDI Contribution with Sympathetic Tripping Probability; $\beta=0.82$.

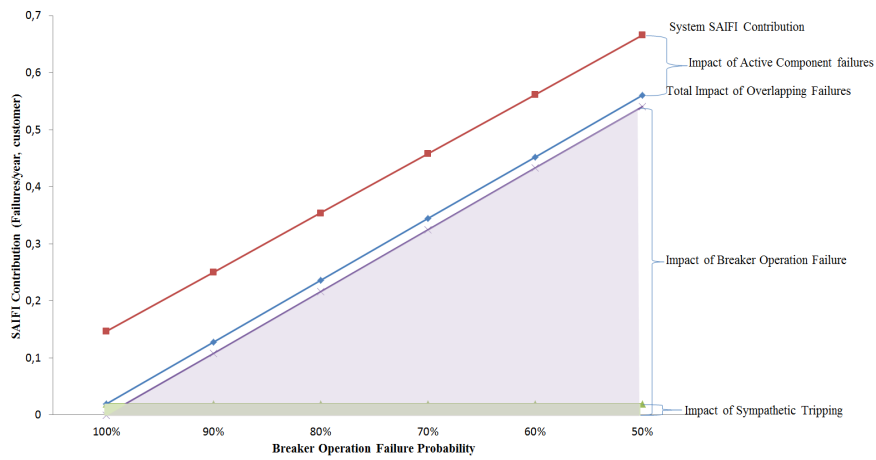


Figure 3.8: Variation in SAIFI Contribution with Breaker Operation Failure Probability; $\delta=0.038$.

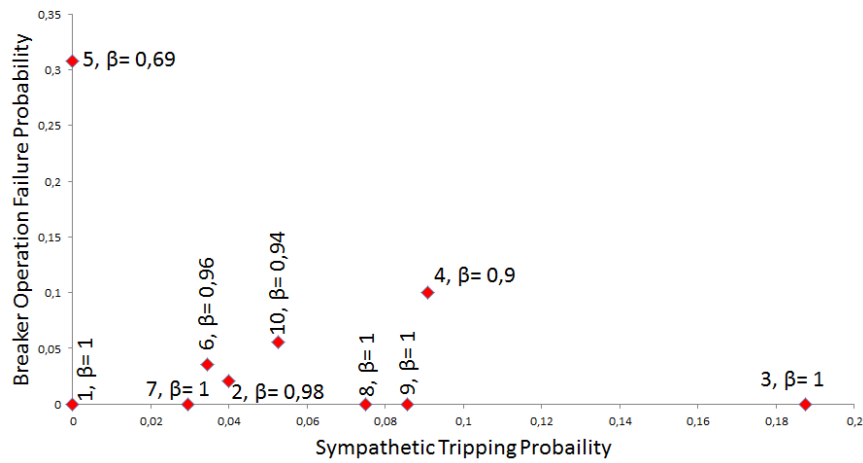


Figure 3.9: Overlapping Failure Probability Distribution in Actual Station Performance

4 Network Reconfiguration Optimization

This chapter discusses the objective of using reliability impacts of various network configurations in planning effective improvements in distribution systems. The objective is addressed with a cost optimization approach in which both the investment for reconfigurations in the network and the expected cost of outage in the resulting suggestions are considered. Optimization is conducted on a real world substation model. The following sections introduce the reference network, the optimization model, the set of constraints and the necessary relational equations. The results and analysis of the calculations follow afterwards.

4.1 REFERENCE MODEL FROM STATION CASE STUDY

A real-world distribution station and feeder network from the Stockholm municipality area in Sweden is used as a reference model case study here. A busbar section derived from this model is used in the case study in [37] and presented in Section 3.5.

Detailed data collection from utility sources was conducted on the primary station and the respective feeder lines. The data includes the design of the MV grid, geographic coordinates, the number of customers connected to all secondary stations, the respective load demands at the secondary stations and actual lengths and distribution of cables. The reference model is adopted such that the network design can be used as a graph theory model with all station locations denoting nodes and feeder cable connections between stations denote links. Figure 4.1 represents the existing system with all the nodes and links. Note that direct single-line connection links between nodes are displayed, not the actual cable paths in the geography. The actual cables take longer runs though the underground cable channels in the municipality area.

The reference network consists of one primary substation feeding 52 secondary stations through the MV grid. In the existing network, there are 24 feeder cables having a total cable of about 60 km, originating from the primary station and feeding one or more secondary stations through the length of the feeder. Certain simplifications and assumptions are made on the reference model to assist the optimization exercise and to respect the utility's data privacy requirements.

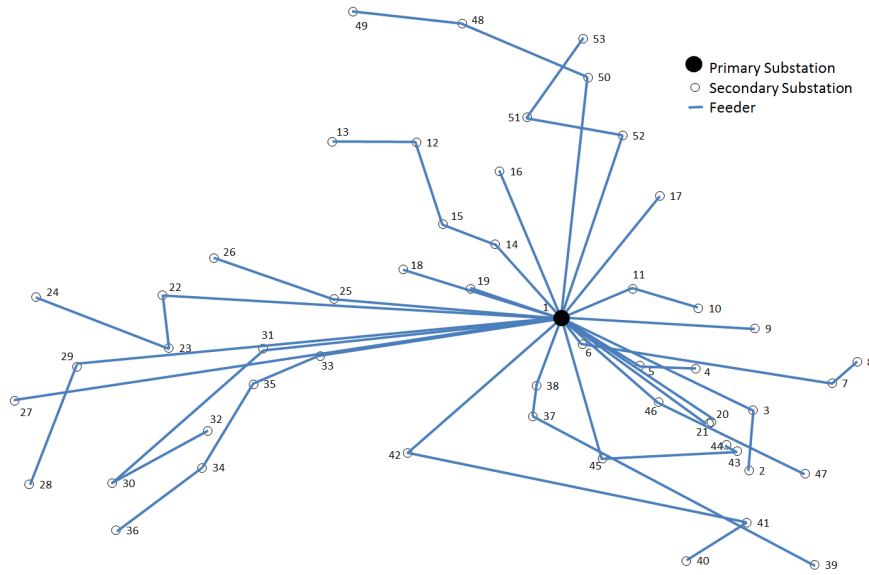


Figure 4.1: Existing coordinate network structure of the MV grid

The optimization, to make use of the graph theory model, should consider all possible cable lengths between all possible node connections. From the network, only existing cable lengths are known as actual values. Hence, a reference model specific multiplication factor is calculated as an average, comparing all existing cable section lengths to the two-dimensional distance between respective geographic coordinates. This multiplication factor assists in estimating the practical lengths of cable required to connect those nodes in the studied system where no actual links exist as of now. This gives a basis for the calculation of investment cost. The multiplication factor obtained from the calculation is 1.79. This means that a coordinate distance of one meter in this system requires approximately 1.79 meters of cable to connect those coordinates.

From the reported peak demands at the secondary stations over the years, the power demand of the sink nodes (the secondary station positions) are assumed, which in the studied system varies from 70 to 2400 kVA. Although it is an extreme case to assume peak demands as node requirements, it helps testing if the power transfer capacities of the feeder cables are always respecting the possible peaks. Along with this, from the utility practice, a safety margin for the power transfer capacity of the cables was calculated as shown below, prior to settings the constraints of optimization. Apparent power capacity [32],

$$S_{cap} = \frac{\sqrt{3} U I}{1000} \text{ kVA} \quad (4.1)$$

where, U denotes the voltage level in the feeders (10.7 kV MV grid) and I denote the current capacity of the cables. (Most of the system consists of 'PEX' model cables with current capacity 385 A). Also, as per the utility practiced safety margin the cables are allowed to operate up to half the current carrying capacity; hence 192.5 A rating is allowed in the calculation.

Since the system is already operating in the existing state, the supply node that is the primary substation is assumed capable of serving the power demand of all sink nodes. Technologies such as distributed generation and storage are not considered in the scenario as the goal is to optimize configuration investment cost that should be able to handle the system demand without other sources than the primary substation.

4.2 TOTAL COST OPTIMIZATION

Here, the optimization is run as a GAMS program algorithm where possible combinations of node connections are investigated considering both investment cost and operational outage cost. The combination of node connections are iterated by the program and corresponding reconfiguration investment cost is calculated by the product of total new cable length in the investment state and a standard investment cost per unit length of cable. The optimization which minimizes the total investment and operational outage cost satisfying the load demand at sink nodes and radial connectivity without power transfer capacity violation is described below.

$$\begin{aligned} \min_{\{x(i,j)\}} \quad & \sum_{i=1}^N \sum_{j=1}^N RCost(i, j) + \sum_{i=1}^N OCost(i) \\ \text{s.t.} \end{aligned} \quad (4.2)$$

$$RCost(i, j) = x(i, j) \cdot CCost(i, j) \quad (4.3)$$

$$OCost(i) = \lambda_N(i) \cdot L_a(i) \cdot (k(i) + c(i) \cdot r(i)) \quad (4.4)$$

$$\lambda_N(j) = \sum_{i=1}^N x(i, j) \cdot (\lambda_N(i) + \lambda_L(i, j)) \quad (4.5)$$

$$\lambda_N(s) = \lambda_s \quad (4.6)$$

$$x(i, i) = 0 \quad (4.7)$$

$$\sum_{i=1}^N x(i, j) = 1, \quad \forall j \neq s \quad (4.8)$$

$$x(i, j) + x(j, i) \leq 1, \quad i \neq j \quad (4.9)$$

$$\sum_{j=1}^N x(s, j) \geq 1 \quad (4.10)$$

$$LF(i, j) = x(i, j) \cdot LC(i, j) \cdot 0.5 \quad (4.11)$$

$$\sum_{j=1}^N LF(j, i) = L_a(i) + \sum_{j=1}^N LF(i, j) \cdot (1 + loss), \quad \forall i \neq s \quad (4.12)$$

where,

$x(i, j)$ Binary variable which is equal to 1 if the potential line between nodes i and j is constructed and 0 otherwise

$RCost(i, j)$ The reconfiguration cost associated with the construction of the potential line between nodes i and j (SEK)

$OCost(i)$	The outage cost associated to the disconnected consumers at node i (SEK)
N	Number of all nodes in the system
$CCost(i,j)$	The construction cost of the potential line between nodes i and j (SEK)
$\lambda_N(i)$	The failure rate of node i (f/yr)
$L_a(i)$	The amount of average load at nodes i (MWh/h)
$k(i)$	Cost constant at node i (SEK/f,kW)
$c(i)$	Cost constant at node i (SEK/kWh)
$r(i)$	The amount of repair time at node i (h/f)
$\lambda_L(i,j)$	The failure rate of potential line between nodes i and j (f/yr)
L	Number of potential lines among all nodes in the system
s	The node number for the substation node
λ_s	The failure rate of the substation node s (f/yr)
$LF(i,j)$	The amount of load flow in the potential line between nodes i and j (MWh/h)
$LC(i,j)$	The amount of line capacity for the potential line between nodes i and j (MWh/h)
$loss$	The amount of power losses in potential lines (%)

In these formulations, the objective function (Equation 4.2) includes the summation of all reconfiguration and outage costs. Equations 4.3 and 4.4 respectively define the reconfiguration cost of constructed lines and outage cost of disconnected customers. Equation 4.5 is adopted from [33]. Equation 4.5 describes the failure rate of each node based on the failure rate of upstream node, while the failure rate of the substation is set in Equation 4.6. Equation 4.7 prevents a lines being considered from and to the same node. The constraint in Equation 4.8 guarantees that each node has only one upstream node. Equation 4.9 limits the start node and end node for each constructed line. The connection of the other nodes to the substation node is assured in Equation 4.10. Equation 4.11 calculates the maximum load flow in each line, whereas Equation 4.12 guarantees the power balance at each node.

It should be noted that Equation 4.5 is nonlinear since it includes the multiplication of binary and continuous variables. This equation could, however, be replaced with linear equations such that the whole optimization problem is solved as mixed integer program (MIP) as follows:

$$\lambda_N(j) = \sum_{i=1}^N z(i, j) \quad (4.13)$$

$$z(i, j) \leq M \cdot x(i, j) \quad (4.14)$$

$$z(i, j) \leq (\lambda_N(i) + \lambda_L(i, j)) \quad (4.15)$$

$$z(i, j) \geq (\lambda_N(i) + \lambda_L(i, j)) - ((1 - x(i, j)) \cdot M) \quad (4.16)$$

$$z(i, j) \geq 0 \quad (4.17)$$

where,

$z(i, j)$ Auxiliary variable used for problem reformulation

M A considerably large number

Note that cost translation of cable length to investment cost is by using the system owner's approximate investment cost per unit length of cable for new investments. For different systems, the cost of cable installation can widely vary depending on the type of cable, geographic locality, installation charges and other factors. Here, as the existing system is a viable solution to satisfy the load demands without violating transfer capacity limit and without additional investment, the optimization should specifically include the willingness to invest so as to make improvements in system performance. This is modelled by making a range of operational cost on the existing system so that the investment options can compete with cost of operating and continuing with the existing system. For existing cables, a range of values from 10 to 50% of the cost of new cables is calculated from respective lengths, in steps of 10%. This range is expressed from here onwards as willingness to invest. The observations are discussed in the next two sections. Note that the increase in the percentage value denotes relatively high costs of using existing system and thus appreciates further investments at optimal positions.

4.3 PRIOR OBSERVATIONS

Before the optimization considering willingness to invest, a minimum possible cable length that could connect the nodes in the reference model was estimated, ignoring the capacity limits and impact of operational outage cost of cables. The result hence is a practically non-viable and less reliable construction. However, it expresses the possible minimum length of cable that the system can have. Figure 4.2 is the representation of the system for this condition. The corresponding total cable length is approximately 25 km. Note that the existing system has a total cable length of approximately 60 km.

The willingness to invest is considered within the range 10 to 50%. In practical cases, there always exist limitations in the number of investments and changes that can be made on a working grid. Hence, suggesting several changes by forcing the optimization to do so is not very significant. Here, the range of willingness to invest for > 50 % is not presented, though the program can have any range. However, if expansion of an existing network needs to be done to a new area, or when a new network is being constructed from scratch, such analysis can be used if the nodes of secondary station locations are decided. If the reference case study model was such a case where there are no existing cables and the nodes are intact,

then the optimization gives the suggestion as shown in Figure 4.3. Comparing the layouts in Figures 4.1 and 4.3 shows that in an optimal design the number of feeder sections can be half that of the existing system. The reduction is cable length and possible routes for fault escalation the system reliability and performance can be enhanced. Since the analysis here is based on an existing system, this case is not discussed further, as it demand a very high investment.

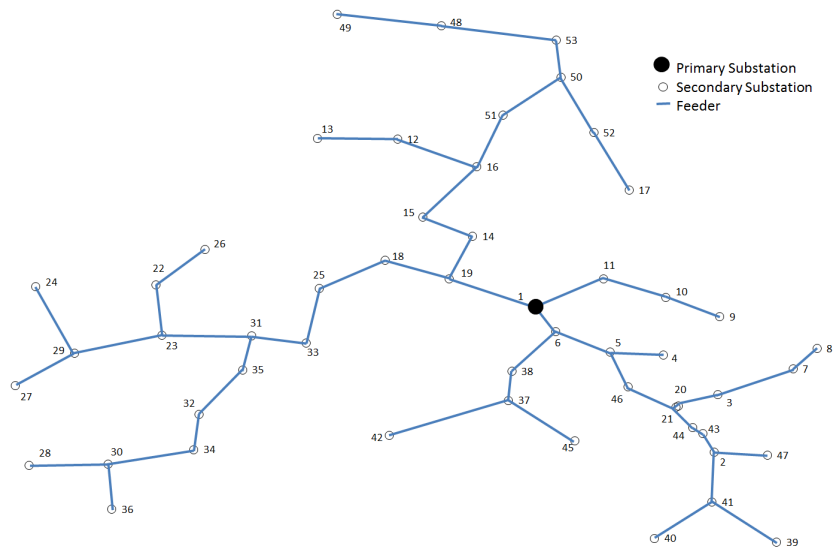


Figure 4.2: Possible minimum cable layout ignoring transfer capacities and system reliability. (~25 km)

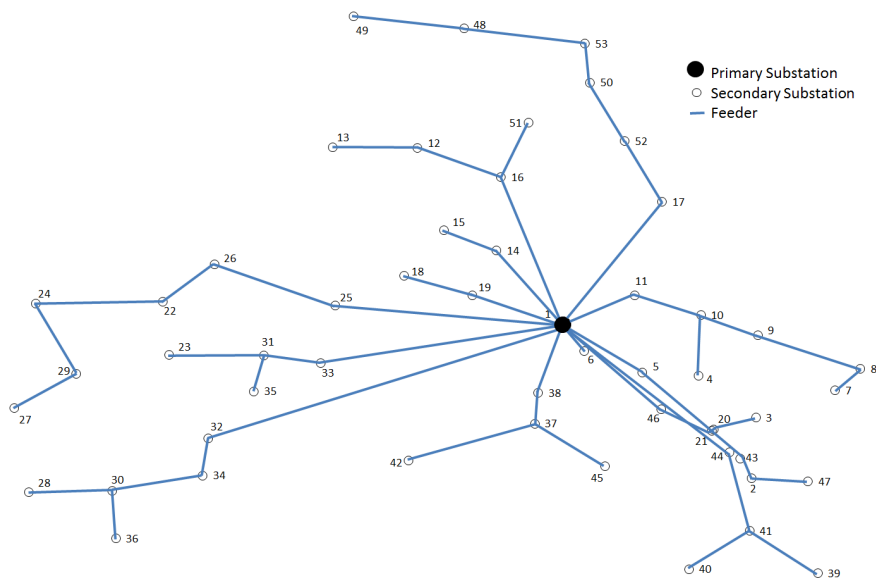


Figure 4.3: Network suggestion for the reference nodes for constructing a new system with same nodes, from scratch.

4.4 INVESTMENT ALTERATIONS COMPARED TO EXISTING SYSTEM

The results from the assessment of optimal system reconfigurations when the willingness to invest is increased are discussed here. Five cases are shown in Figures 4.5 to 4.9. For ease of understanding while displaying the resulting layouts, only the feeders with a suggested change from the optimization are shown. The investment suggestions are shown in red lines connecting nodes. The existing lines in the feeders in which any change has happened such as a new connection or an ignored connectivity is also shown in the respective figures. However, the connections where no change is suggested by the optimization are not displayed and those sections should be assumed to exist as in Figure 4.1.

Table 4.1 has the results from the optimization where the total cable length in the system after investments, the length of cable that needs to be installed, the cost units corresponding to the cases and the number of actions suggested by the investment are shown. The considered range of willingness to invest brings forth approximately 96% to 67% reduction in total cable length in the system. The increase in total cost compared to the previous case diminishes as the willingness to invest moves from 10% to 50%. The transition from 20% to 30% case has only 3% reduction in total cable length at the cost of 28% increase in investment cost. This transition hence has less worth even though only one additional action is required. Whereas, the next transition step from 30% to 40% holds more value with 17% saving in cable length at the expense of 20% increase in cost. However, 9 more additional actions are required. Figure 4.4 is a graphical representation of the above observations. The changes in the layout suggested compared to the existing system is presented afterwards.

The purpose of the network reconfiguration optimization is to formulate a method that is applicable to distribution networks for forecasting the requirements and advantages of potential investment options in the network. Hence, more than the system specific observations, the focus here is on the utility of the approach introduced. The effectiveness of the approach is tested using an actual case study.

Table 4.1 Data regarding investment alternatives.

Willingness to invest	Number of investment actions	Total Cost [million SEK]	Total cable length in the system [metre]	Installed cable length [metre]
0%	0	0	59955	0
10%	2	42.4	57739	6327
20%	5	74.7	51511	11709
30%	6	104.4	49877	16664
40%	15	130.3	42398	20967
50%	17	149.7	39998	24207

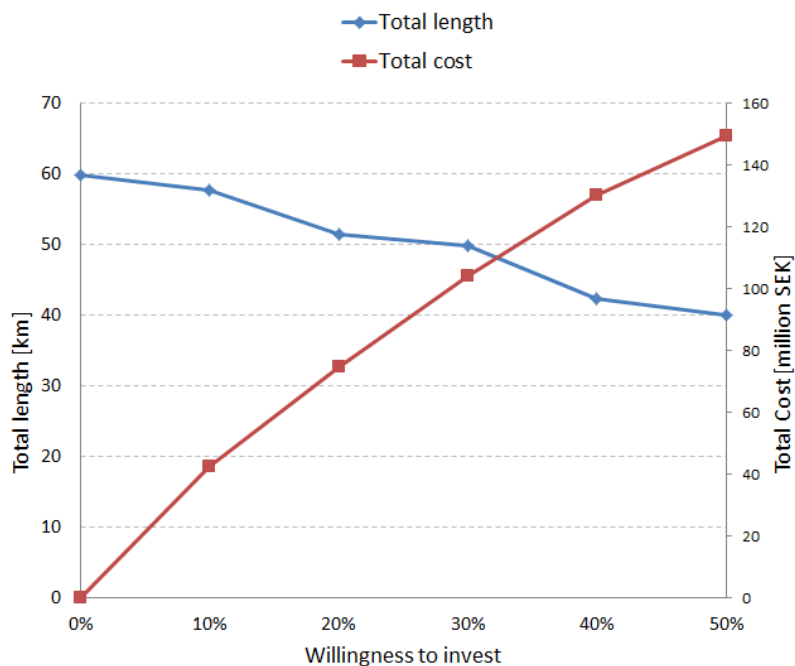


Figure 4.4: Saving in total cable length and increase in total cost for the investment options

The method discussed can be adopted by utilities and calculations can be done using directly accessible data. One of the primary requirements of the approach is the position of supply and load nodes. The distance, failure rate, cost etc. of all possible links in the network can be individually defined, and hence the method can be used to test the value of new technology investments. The use of willingness to invest as a decision variable helps prioritization of investment alternatives. Depending on the preferences of the grid owners, the possible options limited by investment cost, number of alterations etc. can be investigated.

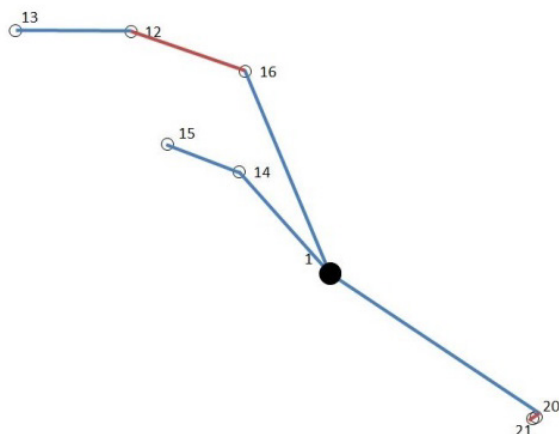


Figure 4.5: Changes suggested compared to existing system for 10% willingness to invest.

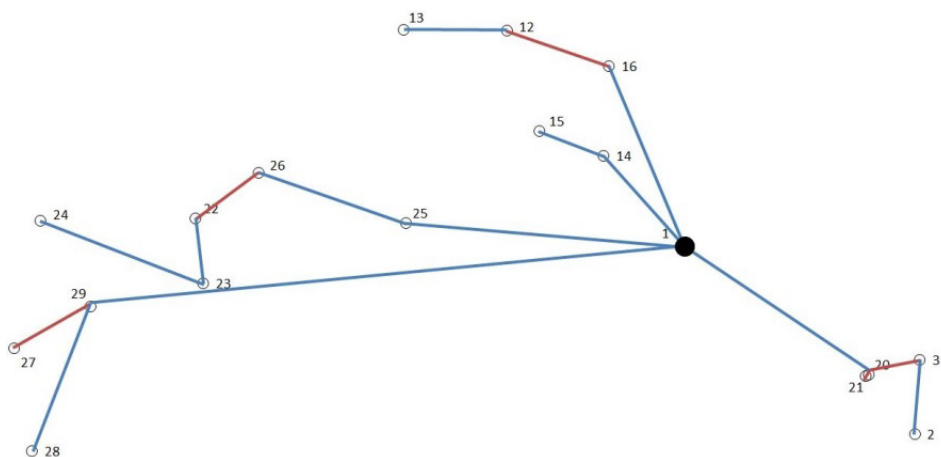


Figure 4.6: Changes suggested compared to existing system for 20% willingness to invest.

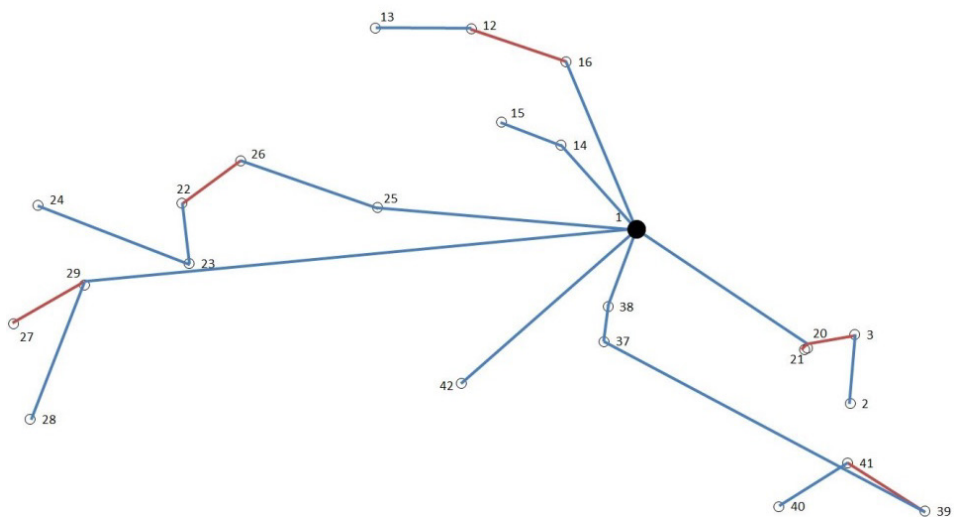


Figure 4.7: Changes suggested compared to existing system for 30% willingness to invest.

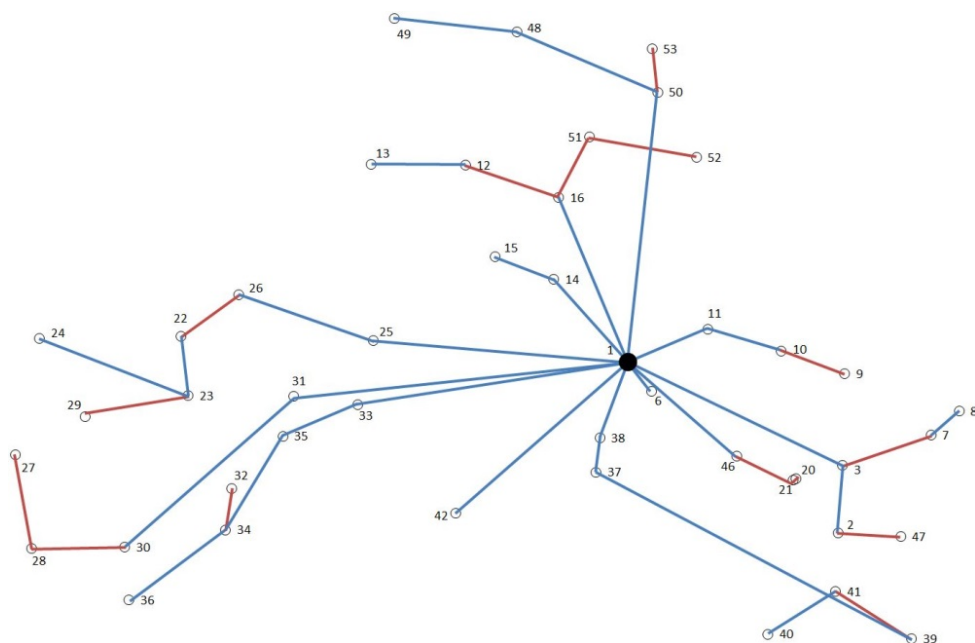


Figure 4.8: Changes suggested compared to existing system for 40% willingness to invest.

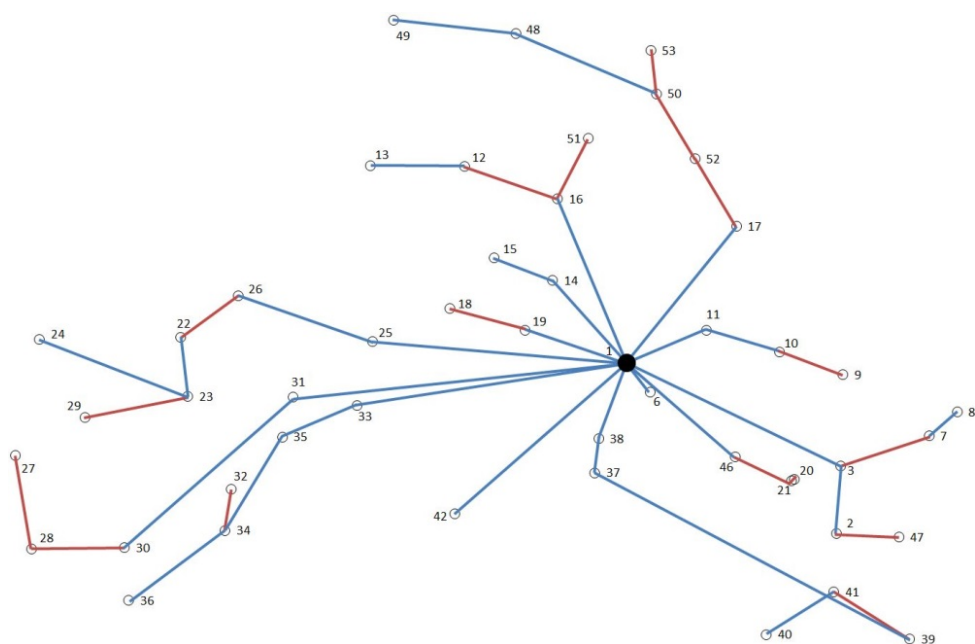


Figure 4.9: Changes suggested compared to existing system for 50% willingness to invest.

5 Conclusion and Future Work

This project report handles two key objectives within the scope of power distribution system reliability.

Identification, quantification and impact assessment of correlated failure events and combined reliability analysis of primary and secondary equipment is the first objective. The distribution of correlated events associated with the combined impact of circuit breaker and protection systems operation is observed from power utility fault registers using analysis of contingency escalation. The direct estimation model proposed for utility application is based on degree of contingency escalation, comparing the connected customers in the different feeders with the number of customers affected by various faults in feeder conductors. The design of distribution systems varies widely, and hence the modelling can be improved from system specific approaches to more generalizable methods, making better understanding from directly available failure related data.

The estimation practice is followed by an accurate quantification approach where templates of theoretical models using RBD were formulated to handle distribution grid performance statistics and data. The analysis hence conducted on real-world case studies reveals the respective distribution of hidden false tripping probabilities. The share of protection system faults among the total number of recorded faults was found to be in the range of 36% in the studied system. These results are tested and verified. The practical variation ranges of correlated failure probabilities in systems with various degrees of automation were observed. The capabilities and calculation accuracy of the correlated failure probability calculation tool developed can be enhanced by considering system specific trend plots. The curve fitting at the optimum gives more accurate readings of fault escalation probabilities where there is room for improvement.

The second objective of the project report is the use of network topologies in calculating system reliability and thus the investigation of potential improvements in configuration of the system. The analysis considering system reliability impact was done to make important observations. The optimization included the constraints such as load demand at customer nodes, power transfer capacity of the existing system, etc. The trend of number of new cable installations required with increasing investment cost was observed along with optimizing the total cable length to be installed. This analysis helps budget-constrained decision making, in prioritizing alternate investment options.

The reconfiguration example was done based on existing systems with nodes already determined. The optimization can be improved to have the capability to suggest optimal positions for the placement of secondary station transformers if such actions are of significant advantage. It can also be extended to handle non radial architecture. Although these are currently rare in distribution systems, this ability would progress the scope of the tool to transmission system planning, inclusion of distributed generation etc. Hence, the extension and development of the works discussed in this project report have significant value and application in system reliability improvement.

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RELIABILITY EVALUATION OF DISTRIBUTION SYSTEMS

This report presents developed approaches to quantify and analyze the complex correlated failure probabilities of different failure modes in distribution networks.

A theoretical simulation model that relates to real world data to measure false tripping probabilities is developed and tested. More simplified approaches that utilities can exercise with readily available data in fault registers are also established. Optimal configurations that could improve system performance and respective investment costs are analyzed and savings in system reliability at the cost of grid investments are modelled. The optimization helps in prioritizing the most critical investments by considering the system impact of re-configurations focusing on meeting customer demands and respecting transfer capacities of weak links.

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