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Industrial Electrical Engineering and Automation

Reliability Engineering Methods for Distribution Systems

Influence of differences between cable system and overhead lines

Anna Guldbrand

Dept. of Industrial Electrical Engineering and Automation
Lund University

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Anna Guldbrand
Lund University
anna.guldbrand@iea.lth.se

Abstract

One way to increase distribution network reliability is to replace traditional overhead lines with underground cables. To fully utilize these investments, network owners will have to adjust their reliability engineering methods to suit the new cable networks. In this paper different condition assessment methods as well as improved failure statistics for cable systems are considered. The paper is based on information from project reports and scientific papers. In addition a number of Swedish distribution network owners have been asked to share their opinion of reliability engineering work of today and the future.

The methods used for distribution system condition assessment change as overhead lines are replaced by underground cable. Visual inspections can no longer be used and diagnostic methods are instead introduced. The diagnostic methods are costly to perform. To become frequently used they must prove to be efficient enough to justify the financial means required. New, improved, diagnostic methods are under development and since most cable failures are related to component properties the use of diagnostic methods is likely to increase.

Statistics show that a majority of the cable system failures are ageing failures. The ageing failures do not to any large extent depend on environmental factors but on component properties. This implies that component lifetime standard deviation decreases as component data are related to the statistics, yet failure statistics is at present not related to component data. A majority of the network owners contributing to this paper agree that the nature of cable failures, except excavation failures, makes it interesting and useful to related cable data to failure statistics and to share the statistics with other network owners.

Several Swedish distribution network owners are in the process of installing new program for network analysis. One challenge is to decide which component data that shall be related to the failure statistics. Operational age, maintenance history, manufacturer and year of manufacturer are four manageable factors which influence on failure statistics is already established but yet not thoroughly evaluated. In addition the method of cable excavation is suggested as a fifth interesting factor related to cable system reliability.

1 Introduction

1.1 Increasing importance of reliability

The importance of distribution system reliability is increasing. During the last ten years the increase in cost of power interruptions in the Nordic countries, has exceeded the increase of consumer price index [1]. In addition, the storm Gudrun experience made the Swedish parliament, in December 2005, to pass a law regulating costumer compensation at power outages. The law entitles consumers compensations up to 300 % of their estimated yearly network tariff.

One way to increase the distribution network reliability is to replace traditional overhead lines with underground cables. Several Swedish distribution network owners plan to, during a near future, replace large amounts of rural overhead lines by underground cables. Urban distribution networks do already, to a large extent, consist of underground cable. The cablification will cost the distribution owners, and in the end the consumers, a significant amount of money. To make the most of the investments, the network owners will have to adjust their reliability engineering methods to suit the new cable networks.

1.2 Outline of the paper

In this paper the methods of reliability engineering in network with an extensive amount of cable is compared to the methods of reliability engineering in traditional overhead line networks. Actual networks differences and the reliability methods used at present are described. Further, possible future differences in the reliability engineering methods and effective use of statistics are discussed.

The paper is based on information from project reports and scientific papers. In addition a number of Swedish distribution network owners have been asked to share their opinion of reliability engineering work of today and the future. In this paper the questions are sometimes referred to as the survey. The distribution companies where all financing an Elforsk project studying consequences to the distribution network when replacing overhead lines by underground cable [2]. They are therefore considered to have interest in work related to cable networks.

1.3 Reliability engineering

Generally, distribution network owners recognise the importance of reliable power supply to the consumers. The opinions on how systemised, or academic, the distribution system reliability work shall be are however divided. One representative of a distribution company contributing to this thesis expressed his view on registration and storage of failure statistics as something like “I do not think one shall care to much about data storage. Problems concerning bad components will be recognized anyway.” This is not an expression of lack of interest in the reliability of the power supply, but an expression of scepticism towards the academic reliability methods demanding much information and computer work.

This paper focuses on how the introduction of more cable in distribution networks might increase the incentive of more systemised reliability work. An additional advantage connected to the introduction of systemised reliability work, not further mentioned in the paper, is the possibility to transfer experience from ageing personnel. A large part of the distribution network workforce is getting close to retirement and the companies risk losing valuable experience when senior staff retires.

2 Background

Reliability is often related to in terms of failure rate and outage time. Cigré defines reliability in the context of power system as “A general concept encompassing all the measures of the ability to deliver electricity to all points of the utilization within acceptable standards and in the amount desired” [3]. Individual condition monitoring of all equipment installed in distribution systems would be time consuming and costly. Effective statistical methods is therefore of high importance for distribution system reliability.

2.1 Influence of component reliability on system reliability

The general power system reliability concept can bee seen as a combination of three factors; *Reliability relating to the performance* of a piece of equipment or a part of the system, *maintainability*, which is the possibility to detect failures and to reach and restore the components and the *security of the maintenance*, i.e. spare parts, maintenance equipment and the ability of the maintenance staff. The power system reliability concept and parameters of importance are illustrated in Figure 1 [4][5]. All three areas are affected when underground cables replace overhead lines.

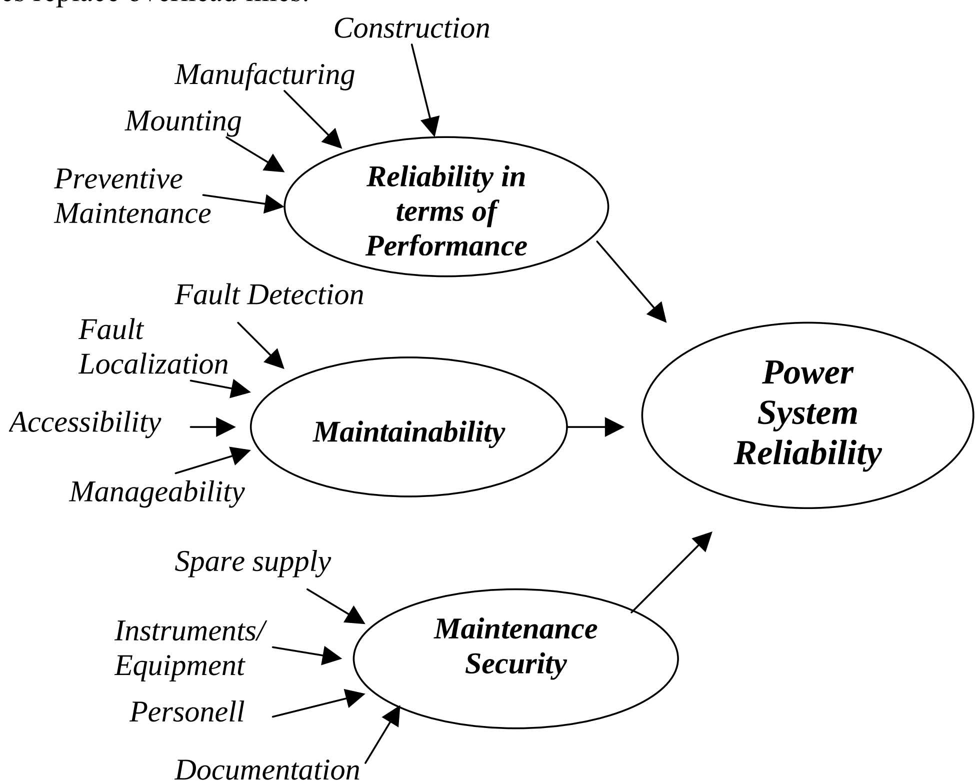

Figure 1, Power system reliability is a combination of equipment performance, maintainability and maintenance security, all three governed by different parameters

80 % of the failures in distribution network are related to the electrical components, i.e. overhead lines, cable systems, secondary substations or medium voltage switchgear stations [6]. These components are made up of different parts of which all have a probability to fail. Cable system faults are not only faults on the cables but also on joints and terminations. In addition to the condition of individual components, network topology and environmental factors influence the ability of the system to performance a required function.

2.2 The reliability engineering process

One approach to the reliability engineering is to divide the process into four basic steps; past system behaviour, reliability calculation methods, calculation of reliability indices and prognosis of future system [3]. It is mainly the activities in step one, the collecting of data in order to create models of outages and failures, that differ between networks with an extensive amount of cable and traditional overhead line networks. The failure rates of different components, calculated in step one, are used in the subsequent steps of the engineering process.

3 Data collection and the idea about statistics

3.1 Reliability simulation programs

Modern asset management methods require information about component reliability. Most methods, such as reliability centred maintenance, RCM, depend on reliability simulation programs. The input variables required by the programs are general statistic quantities as failure rate and outage time [7][8]. To be able to provide the input variables users must have some knowledge about the reliability of the individual components in the distribution system. The programs are constructed to calculate load point reliability and system reliability indices. Standardised system reliability indices such as SAIDI, System Average Interruption Duration Index, SAIFI, System Average Interruption Frequency Index, and CAIDI, Customer Average Interruption Duration Index, are comparable for all type of network structures.

More than one of the companies taking part in the survey for this paper, are in the process of installing new computer program for network analysis. They emphasise the importance of computer programs that are easy to use and can handle the large amount of information in an efficient way

3.2 Specific component statistics

Access to reliable statistics is a key factor for distribution network performance. One area that is emphasized in the Nordic OPAL project is the importance of relating failure statistics to network components [1]. The failure rate and outage time of different components varies considerably depending on factors like operational age and manufacturer. In reliability simulation programs failure rate is coupled to a specific piece of equipment. Provided that the owners have the necessary information about the network components, it will be possible to simulate the reliability using statistics that is specific for their network components. It might however be difficult to find enough data to generate reliably detailed statistics with several factors involved.

One additional reason to relate component data to failure statistics is to be able to identify problematic components. To be able to calculate the failure rate of a specific manufacturer or age of the components it is also necessary to keep record of healthy network components since a relative measure as the failure rate is based on a total number of components.

3.3 Present report of failure statistics

Not all distribution network owners believe in the use of detailed failure registration in order to perform reliability analysis. National failure statistics has been questioned since they show the national average failure rate. Different environmental factors such as climate and landscape are not discernible in the statistics. There are however two registration system to which most Swedish distribution companies at present report failure statistics. The EMI, Energy Market Inspectorate, is part of the Swedish Energy Agency. EMI demands annual reports from all Swedish local and regional network owners. The reports include some failure statistics. The statistics are not for individual components but refers to an entire division. The statistics includes interruptions with duration of at least three minutes. Interruption frequency and average interruption time due to failures in the own network is reported as well as interruption frequency and average interruption time due to failures in overlaying networks [9]. Since the statistics does not refer to components or cause of failure but to the systems, it is not very useful for simulating reliability in computer programs. It seems rather to be an instrument to compare the performance of different network owners.

The Swedish power distribution trade association Svensk Energi (Swedenenergy) keeps a more detailed record of failure statistics of their members. The statistic is compiled in a system called DARWin. 112 of 180 Swedish distribution network companies reported failure statistics to DARWin during 2005. These companies deliver power to 91 % of the Swedish power consumers [10]. The statistics are detailed in terms of cause of failure, duration and number of costumers affected. The category of the faulted component, i.e. cable, transformer or overhead line, is reported. Any further information about the component, as age or manufacturer, is however not included in the report. Some of the distribution companies answering the survey for this paper keep their data registration and storage exactly according to what EMI and Swedenenergy demand. A few of the companies register the faulted component if the component is considered to be the main cause of the failure. They do however not yet use this information to differentiate any failure rates in reliability analyses.

4 Differences of cable and overhead lines failures

Component failures can be characterized as teething failures, random failures or ageing failures relating to the well-known bathtub curve. Teething failures are normally found by on-site test and handled when the components are first connected to the system [6]. Random failures are caused by external factors such as weather conditions or excavator work. The random failure rate is constant over time. Ageing failures are caused by electrical, thermal, mechanical and environmental stress. The ageing failure rate increases over time.

One major difference between overhead lines and underground cables is the insulation material. Air insulates overhead lines from earth. Since the insulation is not a part of the overhead lines the conductors are exposed to environmental factors. Modern underground XLPE cables are insulated by polyethylene, while older cables are paper and oil insulated. The ageing of the insulation material in underground cables is a major contributing factor to cable system failures. Degradation of the insulation material often results in partial discharges, PD. If measures are not taken to prevent failure, the partial discharges will eventually cause insulation breakdown.

4.1 Fault Localization

The fault localization time depends on a number of factors. Among these are the localizing method, level of distribution automation, size of the network and whether it is a cable system or an overhead line system. Visible components generally make the location of the fault easier and faster. Most cable failures, except excavation work, are not visible. The fault location time is a major reason the outage time is much longer in overhead network than in cable systems [11]. In addition, after the fault has been localized, it is complicated to reach the fault and replace or repair the cables. This is particularly critical during the winter when the ground is frozen.

5 Condition assessment

5.1 From inspections to diagnostic methods

Individual condition monitoring of every piece of equipment installed in distribution systems would, as mentioned above, be time consuming and costly. Condition based preventive maintenance will however become increasingly important as the distribution network reliability demands increase. Condition assessment covers both diagnostic methods and inspection. Diagnostic methods, involving measurement equipment, are referred to as objective assessment while inspections depends on the experience of the inspector and are referred to as subjective assessment [4]. As the amount of cable increases in the distribution networks, the objective assessment is likely to become increasingly popular, compared to the subjective methods. There are technical as well as financial reasons to explain this translation.

More than half of the failures in cable systems are ageing failures [12]. These failures depend on the condition of the components. The number of failures can therefore be decreased by diagnostic methods that find the damaged components before the failure occurs. Random failures such as excavator work or lightening, on the other hand, are caused by external factors and will not be prevented by diagnostics methods.

The random failures dominating the overhead line failure statistics do, to a large extent, depend on the landscape surrounding the conductors. Inspection of the vegetation, animals and lightning related equipment close to the conductors can, to a certain extent, prevent random failures of overhead lines [13]. Cables are located underground and inspection of the cables is therefore not possible during operation.

Costs associated to network failures increase as the failure duration or component replacement time increase. Cable systems are more reliable than overhead lines systems, but the average duration of a failure in a cable system is considerably longer than a failure in an overhead system [11]. Consequently the incentive of the distribution network owners to prevent a cable failure is large and the expenses related to the diagnostics tests can be justified.

5.2 Condition assessment methods

5.2.1 Inspection

All distribution companies contributing with information to this work perform visual inspection of their overhead lines and inspect the wooden poles for damage caused by decay. The line inspections are either performed from air, using a helicopter, or from ground using four-wheelers and, during wintertime, snowmobiles. The inspectors look for trees that threat to fall into and break the conductors, and corrosion. At least one of the companies uses video cameras during the inspections. The films can later be watched several times to analyse the systems. Acoustical inspections can be used for corona and surface discharges [14]. Acoustical methods are also usable to inspect cable joints.

Traditionally, network companies have a deterministic approach to the inspections; the results are compared to defined limits. If the results exceed the limits, actions are taken. Trees that grow closer to the conductors than what is stated in the regulations will, for example, be cut down. An alternative approach is inspection based condition rating [13]. The idea is to give the network components ratings that reflect the importance of the components. The ratings combined with results of the inspections, are to be used in reliability analysis. This probabilistic method would demand extensive computational resources, quite contrary to the easy applicable deterministic method.

Underground cables cannot be visually inspected while in operation. After a breakdown the faulted cable can however be inspected to increase the understanding of insulation defects that cause failures.

5.2.2 Diagnostic methods

The increasing interest for diagnostic methods is reflected in numerous project and articles relating to the field. As mentioned in Chapter 4 the insulation degradation process in many cases leads to partial discharges before the actual insulation breakdown. Since the partial discharges can be detected it is possible to act on the degradation before failures occur. There are insulation defects, such as formation of water trees, that cannot in time be detected by PD diagnostics. The partial discharges will not be detected until after the water tree has developed in to an electrical tree, which in many cases is too late to prevent failure [12]. Water treeing is a common cause of failure in the Nordic countries. Resources are therefore put into the development of new methods to detect water trees at early stage [4].

Diagnostic methods are either online or offline. Online methods are used on cables in operation while offline methods require the cables to be disconnected from the system and energized from an external source. The water tree detection methods available today are offline methods generally referred to as dielectric spectroscopy, DS. Dielectric spectroscopy, as tan δ or Double's method, is applied to a cable radial, whose losses and capacitance are measured and compared to the values of a new cable. Since treeing can be a local phenomenon the fact that dielectric spectroscopy analyses the entire cable radial is a disadvantage of the method [14]. Online diagnosis requires permanent connection to the network [16]. This is costly but opens for the possibility to detect treeing at an early stage. One of the methods under development, intended to become an online diagnostic method, is time domain reflectometry, TDR, [14]. By injecting a pulse to the cable and measuring reflections along the cable it will be possible to locate the treeing.

Both PD and DS measurements are crucial for cable system reliability. Simultaneous measurements carried out with the same instrument would make the diagnostic more efficient. A combined system for PD and DS measurements is at present under development at the Royal Institution of Technology [17].

Cables are generally tested at commissioning while diagnostic methods for cable condition assessment are still considered too expensive to use on regular basis by most companies in the survey. One of the companies has, at two occasions, used dielectric spectroscopy on old cables that are of particular importance to the reliability of the system. The test results have differed between the occasions and are therefore considered slightly confusing by the company. One diagnostic method that in contrast to partial discharge detection and dielectric spectroscopy is widespread is the use of thermo cameras. The cameras are used to take pictures of for example cable joints in order to find areas with extensive losses.

6 Reliability influence of component factors

The cause of failure on cable systems and overhead lines differs considerably. Figure 2 and Figure 3 illustrate the cause of failure in cable systems and overhead lines. According to the Swedenenergy DARWin statistics [18], 35% of cable system failures are reported as material related failures, i.e. ageing failures. In addition, the component ageing is of significant relevance to the load related failures, i.e. overload, reconnection of load and fuse melting, that are reported to cause 11.5 % of cable system failures. 29 % of the cable system failures are due to external factors such as excavation work or sabotage. The dominant part, at least 70 %, of the overhead line failures is random failures due to environmental factors [19].

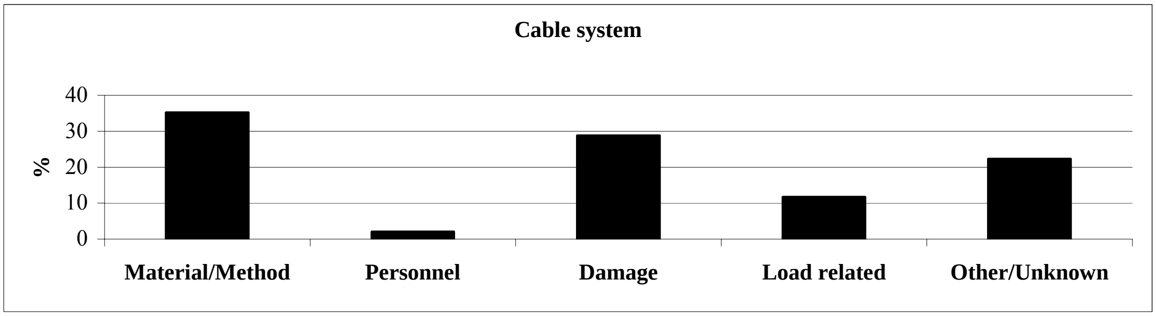

Figure 2, Failure statistics of cable systems 2005 [18]

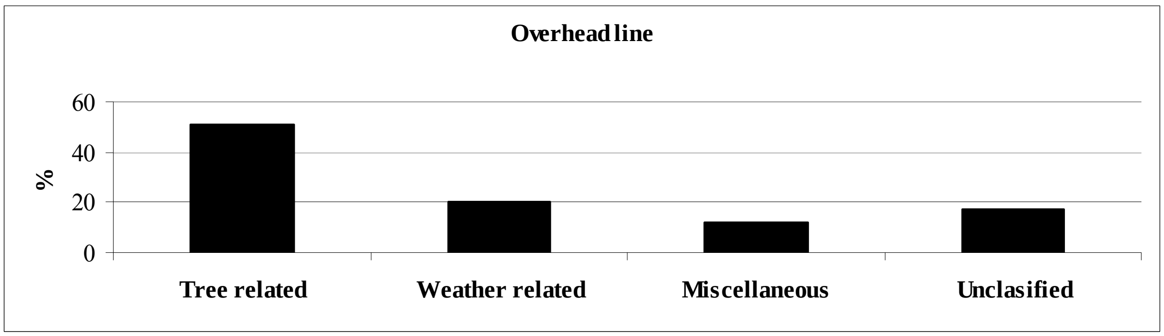

Figure 3, Failure statistics of overhead line systems [19]

One major reason the companies in the survey do not systematically relate component data to failure statistics is that they experience excavation work to bee the dominant source of failure. These are random failures, which are not related to component factors and cannot be prevented by diagnostic methods. This view differs from the DARWin statistics according to which, 26.5 % of the cable failures are due to excavation work. Since failures due to excavation work do not depend so much on environmental but on human factors, it is possible to bring down the number of failures. A majority of the companies participating in the survey agrees that the nature of cable failures, except failures due to excavation work, makes it interesting and useful to related cable data to failure statistics.

Distribution network companies that are positive towards ambitious registration and systemised reliability work as well as companies that are not, emphasis the importance to recognize the experience of operators and other personnel.

6.1 Cable systems

Data collection and systemized reliability work take a lot of effort from the distribution network companies. It is therefore important to be able to justify the component factors that are to be included in failure statistic reports. The failure statistics imply that the importance of relating component data to failure statistics is higher for cable system than for overhead lines. In addition, since regional differences is of less importance to the cable statistics, it becomes more interesting to share failure statistics with network owners in other parts of the country.

Four component specific factors; *operational age*, *maintenance history*, *manufacturer* and *year of manufacture*, is mentioned as having influence on reliability in several different reports and papers, among them [1] and [20]. A fifth factor, the *method of cable excavation*, has been mentioned in the company survey and is in this paper considered of relevance to the component reliability. There are additional interesting reliability influences such as operational stress. It must however be manageable to keep a record of the influencing factor for it to be of any statistical use. In this paper the influence of operational stress is not considered manageable and therefore not further treated.

6.1.1 Component operational age

The operational age of the component has an obvious influence on the component reliability. As mentioned above 59 % of the cable system failures are age related. Consequently, the cable system failure rate increases considerably as the age of the system components increases. Component age is comprehensive and the most important component factor to be used in cable system failure statistics. Age dependency will decrease the standard deviation of the cable system failure rate considerably. A majority of the distribution network owners taking part in the survey claim to register their components. The extent of the registration varies but all companies that keep a register include age, which implies that the importance of component age is recognised.

The age dependence is related to both environmental factors and manufacturing. It reflects the average component age dependence. Since the age dependence of the components often differs from the average age dependence, additional factors are useful to further improve the reliability of cable system statistics, i.e. decrease the failure rate or component lifetime standard deviation.

6.1.2 Manufacturer and year of manufacturing

The failure rate and failure rate age dependence may differ considerable between different manufacturers as illustrated in Figure 4 [1]. The figure includes approximate failure rates based on actual statistics.

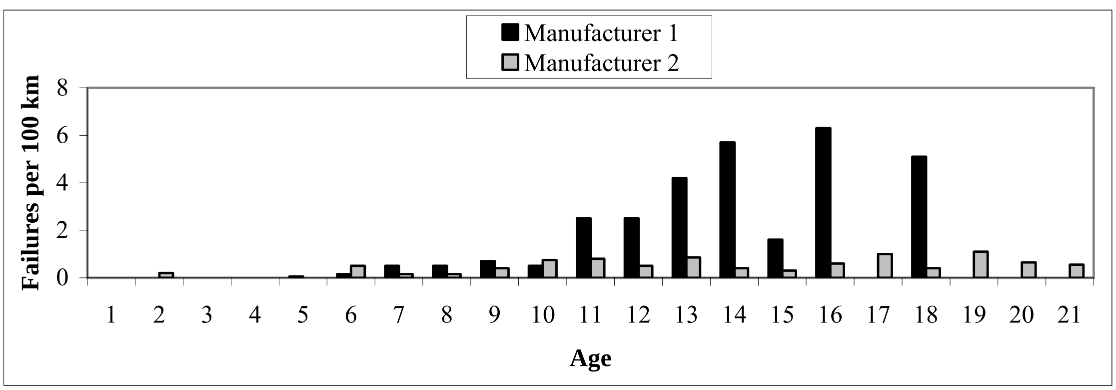

Figure 4, Component age dependence: XLPE failure rate per 100 km cable, two different manufacturers

In addition to produce reliable failure statistics, one major reason to relate component data to failure statistics is, as mentioned in Chapter 3.2, to be able to identify problematic components. Early XLPE Cables, for instance, increased failure rate in the Nordic distribution networks during the eighties. It was the manufacturing technology that caused rapid ageing on the cables. Most of these cables are now replaced but similar manufacture related problems are not unlikely to happen again. The forced cablification of Swedish rural distribution networks has led to large demand of distribution cable. The increased paste in which the manufacturing now takes place might influence the quality of the cables. It is therefore additionally important to keep a record of the distribution cables manufactured at present. In the future it might be possible to notice a difference in the failure rate of cables manufactured during these years.

According to the company survey carried out, it is not common to relate manufacturer and manufacturing year to failure statistics. Not until it becomes normal to store this data, the influence of the parameters on failure statistics can be thoroughly evaluated and the level of influence will appear. Figure 5 illustrates cable system failure rate manufacture year dependence. The dependence differs between different cable manufacturers. The rates are approximate but based on actual statistics.

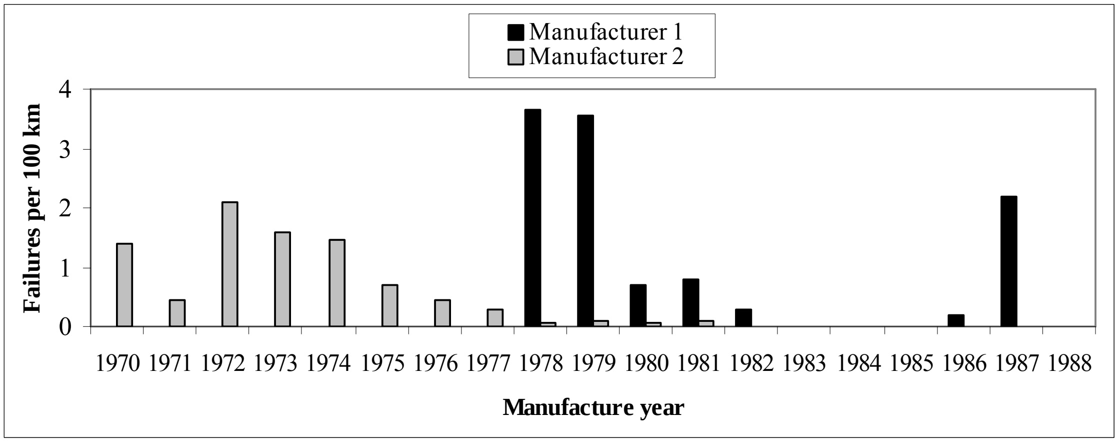

Figure 5, Manufacture year dependence: XLPE failure rate per 100 km cable, two different manufacturers, Manufacturer 1 data 1978-1988, Manufacturer 2 data 1970-1981

6.1.3 Maintenance history

Average failure rates do not reflect the impact of maintenance and are therefore not useful for reliability centred maintenance [13]. Maintenance history must be included in both cable systems and overhead lines failure statistics, for the statistics to be used in maintenance management.

6.1.4 Method of cable excavation

The present, forced cablification of the Swedish rural distribution network influences the method of cable excavation. Since the speed of the excavation is important, plows are widely used to get the cables in the ground. It is not possible to control the interface between the surrounding material and cables that are plowed in to the ground; objects such as small rocks in the ground might end up very close to the cable and gradually destroy the cable insulation. It is useful for future reliability work, to study whether or not the excavation method influence the cable failure rate.

6.2 Overhead lines

Overhead line failure rate depends, to a large extent, on the numbers of trees in the distribution area. The failure rate used for reliability calculations can be adjusted to reflect this. It is however not necessary for the companies to relate the failure statistics to the number of trees in the area [21]. Instead mathematical models have been developed to convert the average overhead line failure rate to a tree dependent overhead line failure rate. In addition the geographical location, average temperature and annual rainfall are relevant factors to overhead line failure statistics.

6.3 *Improvement of failure rate standard deviation*

The national failure statistics represents a geographical average. The cable system average failure rate is comparable nationwide. The failure rate standard deviation does therefore not increase when the statistics are combined to an average national failure rate, Figure 6:1. A small standard deviation is to prefer since this corresponds to actual values that do not differ much from the average value, i.e. the failures are easier to predict. When the failures statistics are related to component data the average rate is differentiated, i.e. there will be a number of different rates. The standard derivation from the specific rates decrease compared to the standard derivation from one average rate, Figure 6:2.

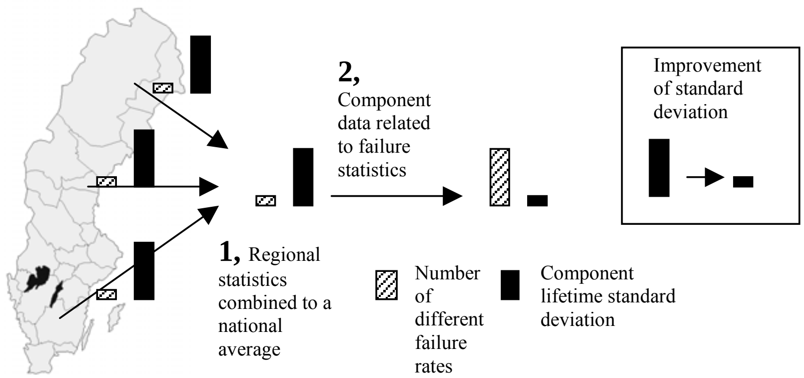

Figure 6, Schematic picture of national cable system failure statistics: National co-operation and failure statistics related to component data considerably improve the standard deviation of estimated lifetime of cable system

For cable systems personnel and financial means required for data collection and statistic reports can be justified since the work will result is more accurate statistics, i.e. decreased standard deviation.

Figure 7 schematically illustrates that for overhead lines the situation is quite different.

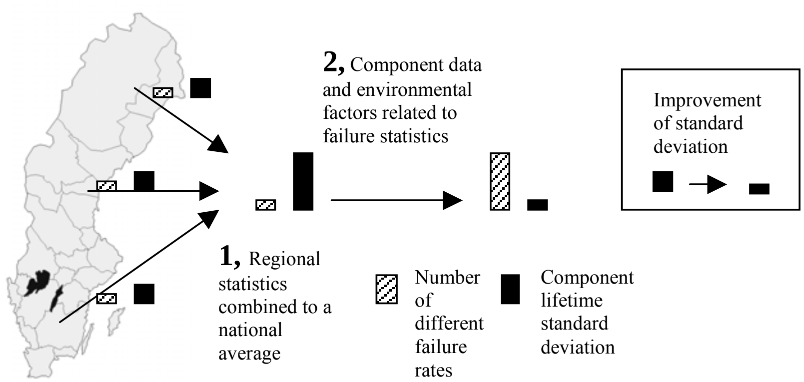

Figure 7, Schematic picture of national overhead line system failure statistics: National co-operation and failure statistics related to component data do not, to the same extent as in the case of cable systems, improve the standard deviation of estimated lifetime of overhead lines

The average failure rate depends on regional factors. The standard deviation will therefore increase when the statistics are combined to an average national failure rate, Figure 7:1. When component specific and regional factors are related to the statistics the number of different failure rates increase and the standard derivation from the specific rates decrease, Figure 7:2.

The result might not be a very large improvement, in terms of standard deviation, compared to the original regional statistics. The required personnel and financial means are therefore harder to justify.

7 Conclusion

The dominant cause of failure differs between overhead line systems and cable systems. Statistics show that a majority of the cable system failures are ageing failures while a majority of overhead line failures are random failures. The ageing failures do not to any large extent depend on environmental factors but are related to component data and are, in contrast to random failures, possible to prevent by the use of diagnostic methods. These are however costly to perform and most companies claim they cannot justify the financial means required. New, improved, diagnostic methods are under development and since visual inspections, widely use for overhead line systems, cannot be used on cables, the use of diagnostic methods is likely to increase.

The characteristics of cable failures imply that component lifetime standard deviation decreases as component data are related to the statistics. In addition the statistics are similar nation wide. None of the companies participating in the survey systematically relate component data to failure statistics at present. One major reason for this is that they, in opposite to the statistics used in this paper, experience excavation work to bee the dominant source of failure. A majority of the companies agrees however that the characteristics of cable failures, except excavation work failures, makes it interesting and useful to related cable data to failure statistics and to share the statistics with other network owners. Some of the distribution network owners do not believe that the result justifies the required means and will probably not relate their cable failures to component data unless EMI and Swedenenergy demands this information.

Several companies are in the process of installing new program for network analysis. They emphasise the importance of computer programs that are easy to use and can handle the large amount of information in an efficient way. One challenge is to decide which component data that shall be related to failure statistics. Operational age, maintenance history, manufacturer and year of manufacturing are four manageable factors which influence on failure statistics is already established but yet not thoroughly evaluated. In addition the method of cable excavation is suggested as a fifth interesting factor related to cable system reliability. Since it might influence the cable system reliability the high pace in which overhead lines are now replaced by underground cables, further increase the interest of component data registration.

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