This paper propose a reliability-centred maintenance method developed to support cost-effective maintenance of electricity distribution systems. Electrical utilities, today active at the liberalized market need to incorporate methods, like this one, to fulfill requirements on reliability and cost. Results are shown for an application study of an urban distribution system and with different PM strategies applied to reduce failures for the cable component. The conclusion is that it is beneficial to apply PM strategies based on the results of quantitative systematic techniques such as the maintenance methodology developed and introduced in this paper, and that there exist incentives to provide the input data required.

INTRODUCTION

Today's electricity distribution systems operate in a liberalized market. These systems should therefore be able to provide electricity to customers with a high degree of reliability and be cost-effective for suppliers. The cost of maintaining system assets, especially through preventive maintenance (PM), is both a major and a relatively easy cost to see. This situation calls for improved PM strategies that can demonstrate both the benefits they provide in reliability and the total cost of implementation of the same. Reliability-centred maintenance (RCM) is a systematic method for achieving a cost-effective PM strategy by balancing between corrective (CM) and preventive maintenance (PM), and utilities are investigating how the method could be incorporated [1].

This paper introduce an enhanced RCM methodology that: (1) is based on a quantitative relationship between failure rate and PM activities. This can demonstrate both the benefits they provide in reliability and the total cost of implementation of the same. Reliability-centred maintenance (RCM) is a systematic method for achieving a cost-effective PM strategy by balancing between corrective and preventive maintenance and the use of optimal methods.

RCM principles and procedures can be expressed in different ways [1-6]. However, the concept and fundamental principles remain the same.

The RCM method developed

A reliability-centred maintenance method has been developed as a result of the experience from application studies [2]. The following three main stages can be identified for the RCM method:

Stage 1  **System reliability analysis:** defines the system and evaluates critical components for system reliability.

Stage 2  **Evaluation of PM and component behavior:** analyses the components in detail and with the support of necessary input data, a quantitative relation between reliability and PM measures can be defined.

Stage 3  **System reliability and cost/benefit analysis:** puts the understanding of the component behavior gained in a system perspective. The effect of PM on components is analyzed with respect to system reliability and benefit in cost for different PM strategies and methods.

There are however challenges to be overcome to accomplish an analysis following the proposed method. A main difficulty is related to supporting the method with required input data. This is a well-known problem area. However, the following application studies shows on one way to overcome the same. Another difficulty, and a main challenge in the method development is how to relate reliability and the effect of maintenance. This issue is treated by the two different approaches, presented as follows:

**Approach I** implies that a PM activity results in a percentage reduction in the causes of failures for affected components. Furthermore, it assumes that the failure rate is reduced by the equivalent percentage. The resulting model of the relationship between failure rate and PM is referred to as $\lambda_{PM}$.

**Approach II** implies that a functional relationship is established between failure rate and PM activities. This must be based on detailed knowledge and understanding of the condition of the components as well as the failure rate.
The resulting model of the relationship between failure rate and PM is referred to as $\lambda(t, PM)$.

### Reliability evaluation

A tool for reliability assessment of electrical distribution systems (RADPOW) has been developed within this work [2]. This is based on well known analytical methods as described in [7]. The output indices are measures of reliability at each load point (load point indices), and of average behaviour of the overall system (system indices).

**APPLICATION STUDY**

This section presents results from an application study for an urban distribution system (*the Birka system*), which is superposed a developed failure rate model for a cable component. The purpose is to show how the RCM method can be used to investigate the impact of maintenance strategy on cost and reliability of power distribution systems.
Stage 1 System Reliability Analysis

The Birka case system. The system studied is based on the 220/110 kV Bredängen station and 33/11 kV Liljeholmen station, connected via two parallel 110kV cables as shown in Figure 2. The only significant simplification in the system model, is that the double bus bar arrangements have been simplified to a single bus representation. To compensate for this the repair time of bus bars have been reduced to the effective switching time to transfer load from one bus to the other following a bus failure.

The customers are presented at one 11 kV load point (LH11). LH11 includes the customers connected to the 32x11 kV feeders outgoing from the Liljeholmen station with a total of 14300 customers.

The 11 kV cables are a mix of mass impregnated paper cables and cross-linked polyethylene cables (XLPE). It was assumed that each type has the same failure rate, based on disturbance statistics for the system [8-9].

Reliability evaluation of the system. System and load point reliability indices are evaluated with RADPOW. It is identified that the failure rate is significant at the 11kV level. Furthermore, that the 11kV underground cable component contribute the most to this. [10] Consequently, it has been identified that the 11kV underground cable (cable component) is the critical component for this system.

Stage 2 Evaluation of PM and Component Behaviour

Failure mode analysis. The cable component is investigated in further detail. The causes of failures are evaluated in the statistics and from experience, and the percentage contribution from each cause to the total failures is identified.

The results show that the causes of failures, which have significant impact on the 11kV cables are: "Damage" (16%), "Personnel" (12%), and "Material/Method" (59%). Of these could only "Material/Method" be affected by PM, and is therefore investigated in greater detail.

The statistics says that these percentages, are further known to be caused by “fabric and material” (14%), “lack of maintenance” (5%), “wrong method or instruction” (15%) (or not known). All of these could benefit by proper maintenance procedures. To find out the underlying causes of failures, the data survey was continued by placing the statistics in relation to practice, that is with the experience of 11kV faults in the Stockholm city network. Several discussions were held together with the personnel handling, on contract, the maintenance of the system. The participants included people both from the operation planning group and the electricians that perform the re-couplings, repairs etc, as well as from the utility. A full presentation from these discussions is given in [8], with a summary in [9].

A resulting output from the discussions was a list with underlying causes to cable faults. One of these was, water treeing. This is a tree like phenomenon which implies water penetration through the insulation, which occurred primarily in XLPE insulation cables produced in the mid 1970s.

Model the effect of PM on reliability (approach I). The knowledge gained from the statistic survey about percentage contribution of different causes of failures, for this specific system, is used for estimating the effect of PM.

Sensitivity studies have been made to see the effect at the system level if each of these causes of failures could be decreased individually or in combination. The different cases are as follows:

1. base case,
2. fabric or material faults =14%,
3. lack of maintenance =5%,
4. wrong method or instruction =15%,
5. total of (2-4) =34%, and
6. total for (material and method) = 59%.

The difference between the two last cases (34% and 59%) lies in the reported failure causes “material and method” that has no further level of classification. This indicates the need for greater focus on completing fault reports with as much detail as possible in order to facilitate the establishment of effective PM programs.

Figure 3 shows the benefit of these different cases on system indices. It has been assumed for each case that the causes of failures can be eliminated by the maintenance activities. Thus the corresponding failures would be eliminated and the reliability indices influenced. The results show that PM measures to reduce individual causes of failures, for a critical component in the system, can have a significant impact on the system reliability.

Figure 3 Effect of reducing the causes of failures in 11kV cables showing results for load point LH11.

Model the effect of PM on reliability (approach II).

The knowledge gained from the statistic survey together with the discussions with maintenance personnel about underlying causes of failures, is used for estimating the effect of PM. However, to possible establishing a functional relationship between failure rate and PM measure more information is required. For one of the identified causes to cable faults, enough data to support such a model is successfully identified. This relates to failures due to water treeing. It is important to remark that this is not a typical cause of failure for the analysed system, since these type of cables now have been replaced. However, for other systems cables still exist with these type of failures, and the main purpose of the study is to show on the possibility to estimate a relationship with support of required input data.

Data related to this failure cause is collected and selected. These include: disturbance statistics [11], measurements and modelling of the cable condition [12], and PM of the cable by rehabilitation (by silicon injection) [13]. Based on these real data a functional relationship for the failure rate function has been defined for the cable component, which specific relates to failures caused by insulation degradation due to water treeing. A detailed presentation of the modelling of this failure rate model is provided in [2].

The composite failure rate function for the cable component is estimated as the sum of failures caused by water treeing (from the developed failure rate model) and other failures (which is adjusted to be superposed on the Birka system 11kV cable here assumed being effected by water treeing).

Three different situations of PM are identified as follows:
- the PMsi rehabilitation method,
- the PMrp replacement method, and
- the CM or “no-PM” method.

Functional relationships for the failure rate function impacted of the different PM situations are defined. The effect of applying PM at different times are evaluated (results are shown for years 9, 11 and 12).

Figure 4 Effect of PMsi using different strategies for the 11 kV average cable in the Birka system.

Figure 4 shows the effect of two different strategies for PM on the composite failure rate. With S1, 10% of the cables are rehabilitated on the three maintenance occasions, and with S2, 30% of the cables are rehabilitated on the three maintenance occasions. This means that with the first strategy a total of 30% of the total population of cables are changed within the period compared with 90% for the second. Consequently, the figure shows a span for the probable effect of the maintenance strategy that is the benefit in the composite component failure rate.

Stage 3 System Reliability and Cost/ Benefit Analysis (approach II)

The effect of PM on system reliability. Strategies are defined for PM of the cable component in the system, and within the time period t [0,30] that includes:
• how many times PM is applied (results shown for three times),
• the times PM is applied (results shown for years: 9,11,12 ),
• which PM methods that are applied (for this study PMrp or PMsi),
• what percentage of the cable components that are affected by each measure (that are 3x10 (S1) or 3x30 % (S2) for shown results).

The failure rate model developed, for the cable component, when affected by the defined PM strategies (S1 and S2) is evaluated. This implies to estimate the resulting average composite failure rate functions. This failure rate function provides input data on the cable component to the system reliability model.

System reliability analysis is made running RADPOW repeatedly to achieve the effect of time. The output is the system and load-point reliability indices that show the different effects of the PM strategy (S) on the system.

The effect of PM on total cost. The following three different yearly cost functions are defined, modelled and evaluated:

a) cost of failure, Cf, this costs refers to the total cost of repairing components causing system failure,

b) cost of PM, CPM, this cost refers to the total cost of PM measures applied to the system within the different strategies, and

c) cost of interruption, Cint, which is evaluated at a load point (here at the average 11kV load point LH11, as shown in Figure 2). This cost takes into account: the customer cost of interruption, based on input data as presented in [14], the inflation rate, and energy not supplied (E).

Figure 5 shows yearly cost results for cost of failure functions. The three different cost functions represent the different PM situations (PMsi, PMrp or CM). Furthermore, the results are shown for the two PM strategies S1 and S2. The results show on the general impact of maintenance to reduce the cost of failure. The trend in the increase of cost due to the interest rate can also be seen.

The total annualized costs are evaluated. This implies for example that the costs of PM activities are spread annually (in connection with the three times for measures). Based on these present values are evaluated. This implies that the economic effect of that money available today is of greater value than money available tomorrow, is taken into account which provides an incitement to delay the time to apply PM measures. The cost-effective solution is the PM strategy that provides the lowest present value of all the strategies analyzed.

CONCLUSIONS

Conclusions from this study shows that it is beneficial to apply PM strategies based on the results of quantitative systematic techniques such as the RCM methodology developed. It is also identified that extensive input data are required to support such a method, and proven that it is possible to provide the same.

ACKNOWLEDGMENTS

The authors express their gratitude to: several persons at Fortum Distribution (former Birka Nät) and Fortum Service (former Birka Service) involved in making this application study possible, and to the sponsors of this project, the Competence Centre of Electrical Power Engineering at KTH with associated reference group.

REFERENCES


