SUCCESSFUL IMPLEMENTED CONDITION BASED MAINTENANCE CONCEPT FOR SWITCHGEAR

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SUMMARY

Increasing demands to fully exploit the capabilities of existing transmission equipment and systems and reducing exploitation costs requires the development of novel comprehensive diagnostics for high voltage equipment as an integrated part of maintenance concepts. A mixture of maintenance and measurement activities is covered by application of Condition Based Maintenance (CBM) technology.
This paper outlines the experiences of both Nuon InfraCore and Eneco of a successfully implemented CBM concept for a specific type of switchgear. For this switchgear CBM approach is used for reducing maintenance costs without worsening the technical condition of the switchgear by focussing the maintenance and measurement activities only on its critical components. Facts like: an increased age of the switchgear, high current maintenance costs, a long outage time for maintenance and a relative high failure frequency will increase the benefits of CBM approach significantly. More indirect benefits of CBM approach like condition data as an evidence in case of liability and postponing technical lifetime by applying trend analyses of condition data are not covered by this paper but have proved to be successful criteria in favour of implementation of CBM approach.
After choosing the type of switchgear for which a CBM approach is considered to be successful, a standardised Failure Mode Effect and Criticality Analyses (FMECA) is applied to determine the critical components of this switchgear. Cost and time reduction was achieved by firstly applying a combination of maintenance activities and condition measurements on only the critical components. Secondly optimisation was achieved by gathering condition data and using data mining approaches to gain more information about the aging process of the critical components. Data mining within the CBM process addresses both the knowledge about failure mechanisms as norms for the measurements and the required maintenance activities. This optimisation process resulted in both a reduction of measurements and maintenance actions as well as a decreased frequency of maintenance and measurement activities. The implementation of CBM for the switchgear as discussed in this paper resulted in a reduction of 35% of the current maintenance costs.

KEYWORDS
Condition Based Maintenance – FMECA- Data mining – Switchgear monitoring

INTRODUCTION

The significant pressures on utilities to reduce costs, taking into account an acceptable level of risk, has brought about the introduction of condition-based maintenance (CBM). In order to support the implementation of a CBM strategy Nuon InfraCore, a business unit of a Dutch utility, has developed an ISO 9002 certificated CBM implementation process, supported by a standardised FMECA approach, by software applications and by a data mining approach for circuit breaker (CB) performance monitoring. Within this CBM process there is a growing importance for the production, storage and analysis of data. The increasing use of computerised data storage and access techniques is providing ever-larger databases that contain, or can store, an enormous amount of useful information on the condition of electrical plant.

Fig. 1: Schematic structure of CBM implementation process and moments of benefit.

A complete CBM implementation process contains five different phases and has recognisable maintenance optimisation moments after the third and fifth phase. As shown in figure 1 the implementation starts with the decision making phase for the type of switchgear with the highest expected benefits. An optimised maintenance

program based on critical components derived by the FMECA phase 2 results in the first optimisation moment. Next phase (3) is the implementation of applications and rules to support and to standardise the condition based maintenance process. This phase is crucial for the validity and quality of produced maintenance and condition information that will be the input for the data mining approach. The growing importance of this approach necessitates a high level of standardisation and qualification to avoid a 'garbage in' – 'garbage out' situation. The outcome of the data mining process is being used for both optimising the maintenance and measurement activities as well as execution frequencies, and is also meant to create knowledge about aging process of critical components.
This paper addresses all the five phases by using illustrative examples from a specific type of switchgear.

1. DETERMINE SWITCHGEAR FOR APPLYING CBM

Because of the numerous types of switchgear it is impossible to implement CBM for the whole population at once. The criteria described below was taken into consideration upon deciding which type of switchgear was most attractive for the CBM approach.

1. Current maintenance costs per switchgear
2. Current outage time for maintenance
3. Risk for maintenance induced failures
4. Population size
5. Age and expected lifetime
6. Current failure behaviour and failure frequency

Both the current maintenance costs as well as the outage time are related to direct maintenance costs. The risk for maintenance-induced failures however depends on the complexity of the switchgear and the technical impact of the preventive maintenance activities. In practice the preventive maintenance activities which are not related to critical components, will be skipped in the CBM approach.
Population size should be taken into account together with the costs for maintenance. A small population of very complex switchgear with high maintenance costs can be equally attractive for CBM as can a larger population of more simple switchgear. The criteria mentioned should be used both to define the ranking of the switchgear in the priority list for CBM benefits and to support the cost benefit analyses. Age and life expectancy criteria suggest both new and old switchgear to be remunerative for the CBM approach. New switchgear benefit from the CBM approach because of monitoring of their technical condition and quality control as defined and delivered by the manufacturer. Old switchgear work well with CBM because of the benefits which can be achieved by using the full technical lifetime of the switchgear based on condition data and data analysis. Because CBM addresses the critical components and the concept is continuously being updated by new failure information it can be effective to conduct CBM for switchgear with a high failure frequency.
The previous criteria are used to produce a priority list for switchgear to be involved in the CBM implementation process.
The average age of the HV switchgear as described in this paper is 35 years (population size is 270 bays) and up to now there is no apparent of reason to replace them on short notice. The outage time for maintenance per bay is 3,5 days and the switchgear had a risk for failures induced by the preventive maintenance of the complex hydraulic drive mechanism

2. FMECA APPROACH TO DEFINE CRITICAL COMPONENTS

After the definition of the specific type of switchgear to be involved in the CBM developing process a Failure Mode Effect and Criticality Analyse (FMECA) will be achieved to determine the critical components. Each different type of switchgear will have its own FMECA approach. For a structured execution of the FMECA process a switchgear is divided into different subsystems. Depending on the type of switchgear the amount of subsystems is about 5 or 6 per type. Mostly applied subsystems are mechanical-, dielectric-, primary-, secondary- and driving system. Each subsystem has its own unique primary function and contains all components that provides this function. For example: the dielectric subsystem contains all components like oil, epoxy and insulating materials that provides the insulation of the high voltage parts of the switchgear. The inventory of components and failure information is achieved by brainstorm sessions with technicians, by analysing event reports and archives, by visiting maintenance activities and by discussions with manufacturers.
All components and their failure behaviour are weighted by the four criteria as described hereafter. All criteria are defined from a technical and more practical point of view. Other criteria which are more related to risk based maintenance are not covered by this FMECA approach. This means that within the scope of this FMECA a switchgear situated in the city centre is of equal importance as the same type of switchgear situated in a small village or connecting an important industry to the network. The score for each component is achieved by using the Delphi method in brainstorm sessions.

Failure frequency

0. No failure has occurred yet
1. Failure incidentally occurs (< once a year)
2. Failure frequently occurs (> once a year)

Impact of failure on energy delivery.

1. No impact
2. Only has impact on the circuit which is directly connected to the switchgear.
3. Has impact on more than only the circuit which is connected to the switchgear.

Corrective costs

1. Nihil
2. < EURO 3.000,00
3. > EURO 3.000,00

Environmental impact

1. Only technical impact
2. Impact on safety

The final score for each component is achieved by multiplying the four criteria. The weight factors depend on a companies philosophy and are therefore changeable. For example in this case, the safety impact of a failure weighs twice as much as the technical impact but could be higher if a utility has safety as their main strategy. Another illustration is the failure of a protection relay which has no impact on safety but has consequences for the circuit which is connected to the switchgear.
Finally a classification should be determined according to detect-ability, diagnose-ability or item replace-ability. A component should be replaced on a regular base if its failure mode is not detectable or worthwhile to monitor. With respect to the detectable and diagnosable critical components an optimised inspection and diagnostic program can be determined including the specific inspection points and measurement types.

For the switchgear as described in this paper only one critical component had to be replaced on a regular basis. Based on its failure rate it had to be replaced every 10th year instead of every 3rd year as was practiced by the current maintenance program.
The failure occurrence of all the other critical components was covered by condition monitoring.

3. DEVELOPING MAINTENANCE AND MEASUREMENT PROGRAM

The maintenance and measurement program depends on the acceptable level of the FMECA score as described in chapter 2. For example, utilities with a high safety policy will take a score of 2, for safety, as a minimum level for components to be covered by a maintenance and measurement program. Besides the frequent replacement of non-detectable critical components the inspections and measurements should be performed to obtain data about the failure behaviour of these components. To monitor the condition of components, suitable parameters must be selected which give an indication of the component's health. Besides the results from the diagnostics, a reference figure is needed to interpret the data. From this reference level knowledge rules can be extracted with respect to the availability and remaining lifetime of components. Finally, specific levels (norms) should be defined to trigger inspection, maintenance or possible replacement actions.

1st BENEFITABLE MOMENT

Based on the FMECA approach cost and time reduction was achieved by firstly applying a combination of maintenance activities and condition measurement on critical components only.

4. STANDARDISE MAINTENANCE AND DEFINE MEASUREMENT DATA TO BE STORED

Because of the growing importance of condition data for supporting and optimising the maintenance program the quality of produced data and consistency of the maintenance and measurement activities should be guaranteed. Therefore Nuon InfraCore developed the 'Inspector®' software application to support and manage the electricians in the field with the execution of the CBM activities (fig 2). This tool is directed at a consistent gathering of performance data and supports the execution of a standardized, human independent, maintenance and measurement program. The tool not only supports the complete execution of a maintenance program or concept, it also supports a standardised execution by means of help screens and information about developed standards and expert criteria.
The maintenance and measurement program as derived from the FMECA is translated in the 'Inspector®' approach and must avoid incorrect data to be put into the data mining system by the use of pull-down menu's and predefined multiple-choice answers as much as possible.
The 'Inspector®' supports and digitalizes the input of all required information directly at location in order to avoid human dependencies in translating handwritten checklists and event reports into the data mining system.

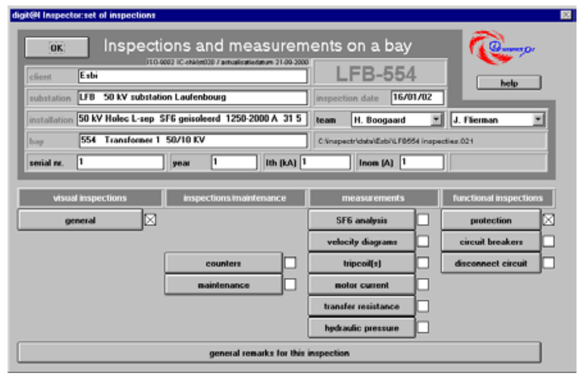


Fig. 2: Inspector® software application for supporting the execution of CBM.

With respect to the switchgear of this paper all maintenance, inspection and measurement activities were programmed in the 'Inspector®' including norms and instructions to make sure that every electrician carries out the same activities and has at his disposal the actual norms for a correct first line analysis.

5. DATA MINING APPROACH AND STORAGE

The full potential of condition and maintenance information cannot always be realised by using traditional techniques of data handling and analysis. There are often underlying trends or features of the data that are not evident from the usual analysis techniques. Such detail and trends can be important for the assessment of the equipment operation. There are also increasing demands from operators and asset managers to fully exploit the capabilities of this data in order to optimise the utilization of a high voltage electrical plant. The method of extracting full value from such extensive databases, using new analysis techniques, is commonly called Data Mining. In its basic essence, data mining is the application of relatively novel data-driven approaches to find patterns in data obtained from electrical equipment. The data mining techniques are then used to relate these patterns to the operational condition of the equipment and to provide new knowledge about aging mechanisms, norms, and required maintenance activities. In order to support the data mining process InfraCore applies the knowledge expert data base *i*-Core® in which all the measured data and failure information is stored and analysed. The general features of this approach are shown in Fig. 3. This process provides three outcomes (A, B and C) of the data mining approach. Outcome A refers to new knowledge about aging mechanisms of switchgear components and outcome B refers to recommended maintenance activities on switchgear components, resulting from the database analysis. Due to the large amount of measurement data stored in the software data system, operating norms and criteria are continuously updated and fed back to electricians in the field as determined by result C.

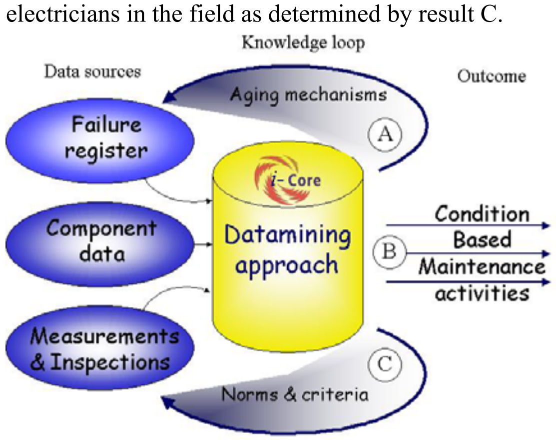


Fig. 3: Schematic structure of data mining process for condition-based maintenance of circuit breakers.

These three outcomes will be explained in detail by practical examples in the following paragraphs.

5.1 Aging mechanisms (Outcome A)

As mentioned before in the Netherlands the average age of circuit breakers is about 35 years. Because of the expected re-investment wave there is a growing need for determination of aging models of circuit breaker components. A large amount of data, stored in the *i*-Core® database system is being used for an investigation of the aging process of an insulation material called "Coqolite". This material is applied in a large number of this 35 year-old switchgear and is pointed as a critical component because of the cost of replacement and the consequences for environmental safety in case of a failure (Due to the potential for problems caused by the oil insulation). For measuring the condition of the coqolite a loss current (tg δ) measurement is being applied and if tg δ is above 10%, the coqolite must be dried in a furnace. If tg δ is above 23% the circuit breaker may not be used again and the coqolite is looked upon as irreparably damaged. The ultimate goal of the research of this aging process was to find the different parameters of the failure mechanism of coqolite using data mining techniques.

Because the coqolite is enclosed by insulation oil a correlation was expected between the moisture level of the oil and the tg δ of the coqolite. As shown in Fig. 4 there is an increased influence of oil on the aging mechanism when the moisture level is above 11 ppm and a destructive influence above 24 ppm.

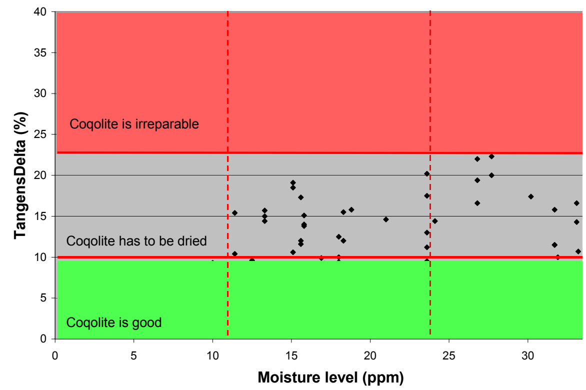


Fig. 4: Correlation between moisture level in the oil and the tg.δ of coqolite.

However this figure also shows a large deviation in the section between 24 and 30 ppm. This means that other parameters besides moisture level also influence the aging process of the coqolite. Further research made clear that the substation location also influenced the aging of coqolite because of the variety of groundwater in different regions in the Netherlands. Fig. 5 shows the correlation between the moisture level of the oil and the aging of coqolite in a region with a high groundwater level.

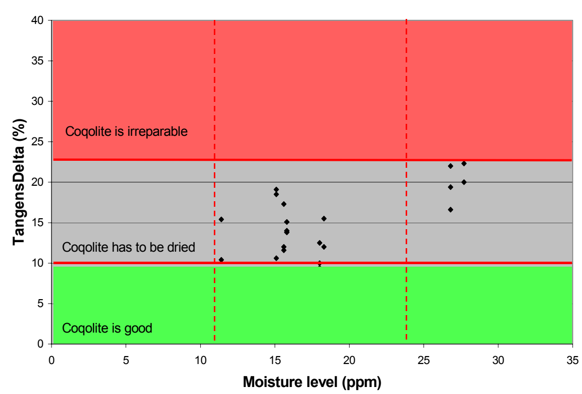
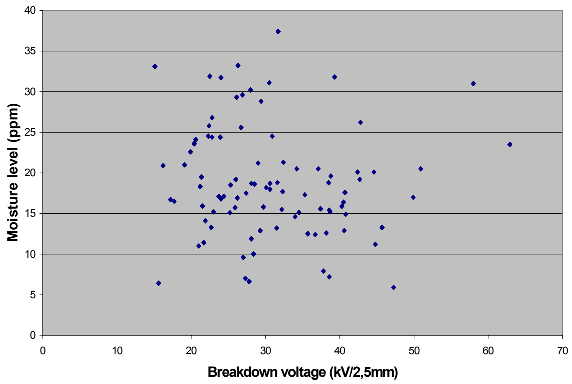


Fig. 5: Correlation between moisture level in oil and tg.δ of coqolite in high moisture level areas.

Normally only the breakdown voltage of the oil insulation of this type of circuit breaker was measured frequently. However the known influence of the moisture level of the oil on the aging of the coqolite requires also a frequent moisture measurement. If a correlation could be found between the moisture level and breakdown voltage of the oil the extra moisture level measurement could be excluded. However as shown in figure 6 there is no correlation between the breakdown voltage and moisture level of the oil in this circumstances. The lack of a correlation between breakdown voltage and moisture level is probably caused by the relatively low moisture level (< 30ppm) and the temperature of the oil (15-20°C). As described in the literature[1] a significantly decrease of breakdown voltage will occur above a temperature of 20 °C and a moisture level above 30ppm. Because of the importance of a low moisture level for this specific type of switchgear with coqolite parts the lack of correlation means



that both breakdown voltage and the moisture level should be measured.

Fig. 6: Correlation between moisture level and breakdown voltage.

Detailed data analysis as described has thus increased the knowledge about the aging process of critical components of circuit breakers. Extra attention for the moisture level of the oil of circuit breakers in areas with high groundwater level should extend the technical lifetime of critical components like the coqolite. The re-conditioning of the oil above a moisture level of 11 ppm in these areas can be looked upon as a precautionary measure for slowing down the aging process and the postponement of re-investment costs.

5.2 Maintenance activities (Outcome B)

To find a balance between cost reduction and environmental and personnel safety, condition-based maintenance is used world-wide to give support to these asset management responsibilities.

[1] M. Beyer, W. Boeck, K. Möler, W. Zaengl, 1986, Hochspannungstechnik

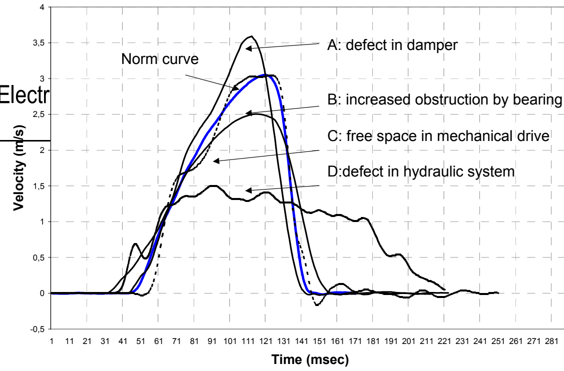
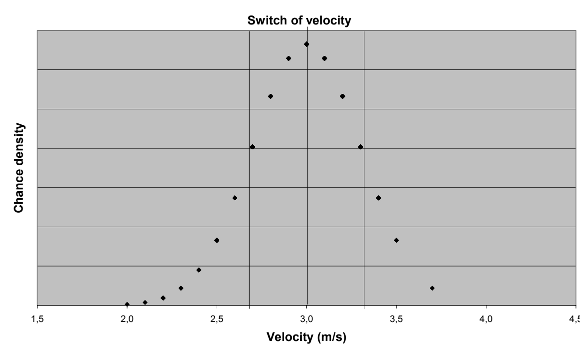


Fig. 7: Deviations of the contact velocity curves

Preventive maintenance activities are controlled by the results of condition measurements. In addition to man-made inspections, computerized contact velocity measurement has been shown to be one of the best tools to implement condition-based maintenance for circuit breakers.

Velocity and acceleration curves give information about the condition of the driving system by showing any deviation, obstruction or incorrect damping during the switching operations. In practice most information is retrieved by comparison of the measured curve with standard curves stored in the monitor's database. As shown in figure 7, many mechanical faults can be recognized and the proper maintenance action can be initiated on a detailed level. Now a total overhaul of the circuit breaker is not necessary anymore and is being replaced by condition-based maintenance activities at component level.

5.3 Norms and criteria (Outcome C)

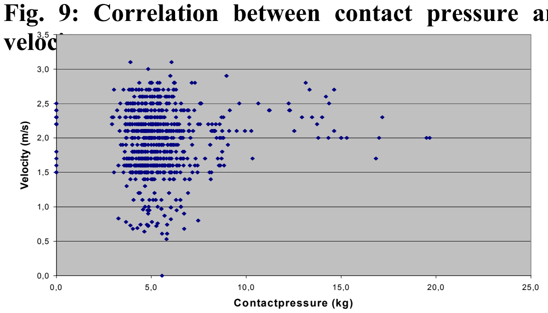


Due to the growing importance of measurements as an initiator for maintenance activities, the need for reliable norms and criteria increases significantly.

Fig. 8: Probability density curve of switching velocity.

Database analysis support thus requires the continuous improvement of norms and criteria. In the case of new measurements and diagnostics, this is often the only way to create reliable norms, due to the relative lack of detailed knowledge of manufacturers with regard to the new and evolving techniques.
Fig. 8 shows the determination of a norm for the switch velocity of a specific type of circuit breaker. From different speed curves, key quantities have been derived, including switching time, velocity and acceleration. Each quantity is put into probability curves for calculating a norm based on the average value and standard deviation as shown in the figure. In this case a norm for the velocity of 3.0 ± 0.3 m/s is derived.
An example of updating norms for contact pressure of circuit breakers is shown in Fig. 9. Due to uncertainty about the influence of a high contact pressure on the switching velocity of the circuit breaker, a database analysis was applied to find the correlation between the two quantities.

Fig. 9: Correlation between contact pressure and veloc



The correlation figure shows that there is no negative influence of a high contact pressure on the velocity of the circuit breaker contacts and so there was no reason to make the maximum norm for contact pressure dependent on the velocity. The energy of the drive mechanism has no problem with the obstruction of the contact pressure.

2nd BENEFITABLE MOMENT

By applying data mining techniques it is possible to fit maintenance and measurement activities much better to aging mechanisms of critical components.
Based on the outcome of data mining studies as described in the previous paragraphs a second maintenance optimisation was achieved for the switchgear of this case study. Both the amount of measurements and the execution frequency was decreased by a deeper understanding of the aging mechanisms and relations between measured quantities. The maintenance and measurement frequency was changed in every 6th year with exception of the moisture measurement which will still be carried out every 3rd year but only in relevant areas.

6 COST BENEFIT ANALYSES

Total maintenance costs were euro 4.200,00 per bay and maintenance was conducted every 3rd year. Average maintenance costs were euro 1.400,00 per year per switchgear.

First benefit moment

With respect to the switchgear of this paper a reduction of maintenance activities resulted in a decrease of total outage time of only 1 day in stead of 3,5 days. This RCM based optimisation process achieved a cost reduction of euro 1.200,00 per switchgear bay each 3rd year meaning a 29% reduction of the euro 4.200,00 for the 3,5 day maintenance program. The cost reduction was not proportional with the current maintenance duration because of the increased engineering costs for the CBM approach.

Second benefit moment

The second cost reduction was achieved by analysing the stored condition data and another optimisation of the maintenance and measurement program. This resulted in an average cost reduction of another euro 325,00 per switchgear per year to euro 675,00.

Extra costs for CBM

Extra costs were induced by the implementation project of CBM, the use of software applications, increased engineering activities and additional measurement equipment. Although the costs per switchgear will decrease if the total amount of switchgear involved in the CBM program increase, the extra costs for the switchgear addressed in this paper are estimated at euro 235,00 per year.

The whole CBM approach resulted in a cost reduction of euro 490,00 per year per switchgear which is a reduction of 35% compared to the current 3,5 day preventive maintenance program.

7 CONCLUSIONS

Due to the pressure on utilities to reduce costs, taking into account an acceptable level of risk, an important change is brought about by the introduction of the condition-based maintenance strategy. For support the CBM processes, standardisation and data mining has become an important component of power system operation. Based on a large amount of condition data, data mining techniques can give both new information about ageing mechanisms of components and act as a support for the initiation and optimisation of maintenance activities and can also be used to update standard norms. CBM process as described in this paper should not be regarded as a finite process but as a structured way of gathering more and new knowledge about circuit breakers behaviour. This information will emphasize the need for maintenance in a responsible way even if it would not result in major cost savings.

REFERENCES

[1] A.J. McGrail, E. Gulski, E.R.S. Groot, D. Allan, D. Birtwhistle, T.R. Blackburn, *"Data mining techniques to assess the condition of high voltage electrical plants"*, Cigre session, Paris 2002

[2] Ph Wester, J.J. Smit, J.J. Oestergaard, J. Corbett *"Development of Asset Management Services",* Cigre session, Paris 2002.

[3] R.D. Damstra, E.R.S. Groot, Ph. Wester, C.M. Ackerman, H.E. Dijk, J.J.Smit *"The impact of a condition based maintenance strategy on network system operators",* Cigre symposium , London 1999.

[4] J.J. Smit, J.A.W. de Croon, E.R.S. Groot, Y.F. Fu, E. Gulski, W.R. Rutgers, H.F.A. Verhaart and Ph. Wester *"Decision making experience with maintenance diagnosis of high voltage equipment",* 37th Cigre session, Paris 1998, paper 15-105.

[5] D. Kopejtkova, H.P. Ott, H. Röhsler, F. Salamanca, J.J. Smit, A. Strnad, Ph. wester *"Strategy for condition based maintenance and updating of substations",* 36th Cigre session, Paris 1996, paper 23-105.