INVESTIGATION OF ECONOMIC FEASIBILITY OF MAINTENANCE STRATEGIES UNDER REGULATORY RESTRICTIONS

Qikai Zhuang[1 *], Wen Cao [2], Kai Wu[2], Dhiradj Djairam[1] and Johan J. Smit[1]
[1] High Voltage Technology and Management, Delft University of Technology, Mekelweg 4, 2628CD, Delft, the Netherlands
[2] State Key Lab. of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, West Xianning Road 28#, Xi'an, China
*Email: <q.zhuang@tudelft.nl>

Abstract: Regulators and stakeholders are imposing stricter restrictions on maintenance activities on high voltage components. Faced with this pressure, the asset manager should understand technical and financial implications of decreased maintenance and therefore apply proper strategies to balance performance and expenditures. In this paper, a probabilistic model is first introduced to illustrate the generic relationship between service life, health condition, diagnostic index and failure probability. The parameters of the model are linked with the pressure from stakeholders. Then we simulate the lifecycle cost of a cable fleet with time-based maintenance or condition-based maintenance applied. After repeating the simulation for different reliability and economic parameter values, it is concluded that condition-based maintenance is profitable only in certain scenarios of regulatory restrictions.

1 INTRODUCTION

Maintenance activities on high voltage components have societal impacts, such as environmental pollution, traffic congestion, risk to personnel safety, etc [1-4]. In recent years, these impacts are causing more public concerns. Consequently, regulators and stakeholders are imposing stricter restrictions on maintenance activities[5].

As a result, these restrictions add to the cost of maintenance activities and force the utility company to reduce the frequency and intensity of maintenance. Faced with this pressure, the asset manager should understand technical and financial implications of decreased maintenance and therefore apply proper strategies to balance performance and expenditures.

In recent years, it is commonly believed that condition-based maintenance provides more information about the health condition of components and achieves economic profits. However, the advantage of condition-based maintenance relies on several conditions.

In this paper, firstly in section 2.1, a straightforward reliability model is introduced for water tree aging of cables. Based on this, the life cycle cost (LCC) for time based and condition based maintenance strategies will be described in 2.2. As core assumptions of our investigation, we link several reliability and economic parameters with business factors of utility companies in Section 2.3. Based on these assumptions, the LCC of 10000 cables is simulated in section 3. We shall see that this leads to the conclusion that condition-based maintenance is more profitable than time-based maintenance only in a number of scenarios of the utility business.

2 SIMULATION MODEL AND PARAMETERS

2.1 Service life, health condition, diagnostic index and failure probability

There are three most important variables concerning the reliability of components and the following LCC assessment process. They are the service life, the health condition and the failure probability of the apparatus. During the aging of insulation, the relationship between these three variables is straightforward, as shown in Figure 1.

The focus of this paper is not the aging mechanisms of cables, but the economic feasibility of maintenance strategies. Therefore, we only consider the water treeing aging and disregard other mechanisms for sake of simplicity. In our previous research [6], a probabilistic relationship has been established as follows: a health condition *h*, defined as the maximum length of a water tree, follows a lognormal distribution as described in (1). The location parameter *μ* and scale parameter *σ* of the distribution increases with service life, as described in (2) and (3).

$$N_t(h) = \frac{1}{h\sqrt{2\pi \cdot \sigma(t)^2}} \exp\left[-\frac{\left(\ln h - \mu(t)\right)^2}{2\sigma(t)^2} \right] \quad (1)$$

$$\mu(k) = \ln(h_0 + t \cdot \Delta h) \quad (2)$$

$$\sigma(t)^2 = {\sigma_0}^2 + 0.01 \cdot t \quad (3)$$

The failure probability for a cable with health condition *h* satisfies a 2-parameter Weibull distribution, as is described in (4).

$$\mathrm{F}(h) = 1 - \exp\left(-\left(\frac{h}{a}\right)^b\right) \quad (4)$$

In the simulation, we use h_0=500, Δh=70, σ_0=0.618, *a*=9500 (µm) and *b*=4. These parameters are acquired through laboratory accelerated aging tests on cables in [6].

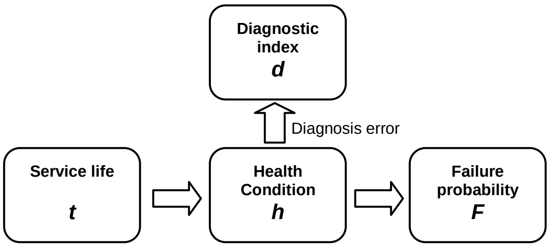

Figure 1: Relationship between different parameters in the simulation model

The length of water tree is a physical variable growing with service life and it influences the failure probability and, consequently, the remaining life. Unfortunately, it cannot be observed directly from field components. Alternatively, diagnostic indices, such as partial discharges, are frequently observed as an indicator of health condition based on given knowledge rules. We label it as *d* in Figure 1. However, this observation has errors. In reliability statistics, the confidence bounds on lifetime or health condition are commonly modelled with lognormal distributions[7]. Therefore, in our qualitative study, we assume that the ratio between the diagnostic index *d* and the health condition *h* satisfies a lognormal distribution with location parameter equal to 0 and scale parameter *η*.

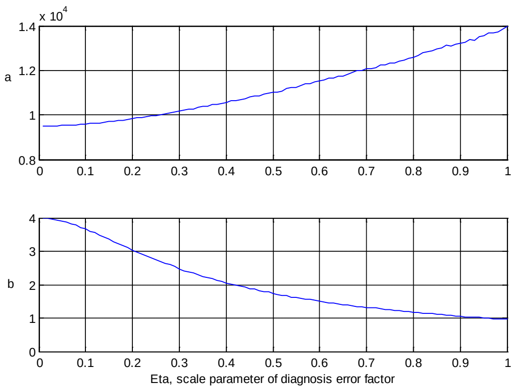

Figure 2: Effect of increasing diagnosis error on the scale parameter *a* and shape parameter *b* of the Weibull failure probability

The relationships of diagnostic index *d* with service year *t* and failure probability have the same form with those of the health condition *h*. If we replace the variable *h* in Equation (1) to (4) with *d*, the parameters σ_0, *a* and *b* of the probability distributions will be changed simultaneously by the diagnosis error indicator *η*. Given *a*=9500 and *b*=4 for *h*, σ_0, *a* and *b* for *d* will be as Figure 2 and Equation (5) shows.

$$\sigma_0{}^2 = \sqrt{0.618^2 + \eta^2} \quad (5)$$

2.2 Maintenance strategies and costs

Three types of maintenance strategies are generally applied for cables[8] and many other high voltage asset systems. They are corrective maintenance, time-based maintenance (TBM) and condition-based maintenance (CBM). Corrective maintenance means that replacement is only conducted after failure occurs. In TBM, each component is replaced after serving for a predetermined period. In CBM, diagnosis is performed periodically. When a certain diagnostic index of a component exceeds a certain threshold, the component will need to be replaced.

Three types of costs are included for each maintenance strategy: the failure loss (FL), replacement expenditure (RE) and diagnosis expenditure (DE). The difference between different types of repairs and partial replacements are neglected. Nor do we consider disposal. The FL includes multiple damages, risks, loss of energy and unplanned replacements. Since a replacement is included, FL is always larger than RE. In the simulation, RE is always normalized to 1. FL is set to 20 according to the case of cables in [9] and DE is 0.05 according to [6].

As in [6], the life cycle cost is calculated with the net present value (NPV) to take the interest rate into consideration. The interest rate is fixed to 5%. 10000 components are initially installed in 10000 places, called connections. Each connection is used continuously for 100 years, despite how many components have been replaced on it. In equation (6), our life cycle cost, named the "Expected Cost of One Connection" (ECOC), is defined. N_f, N_r and N_d means respectively the total number of failures, replacements and diagnoses within the 10000 components in year *i*. Correspondingly, the number of connections 10000 in the denominator means the expected cost is calculated from the simulated failures, replacements and diagnoses. The simulation is performed for 100 years; a duration of approximately 2 life cycles for each connection. Due to the effect of $(1+0.05)^i$ from NPV, the ECOC will not be significantly different if the simulation period is increased.

$$ECOC = \sum_{i=0}^{100} \frac{FL * N_f(i) + RE * N_r(i) + DE * N_d(i)}{10000 \cdot (1+0.05)^i} \quad (6)$$

2.3 Regulatory restrictions

The parameters introduced in 2.1 and 2.2 are typically influenced by stakeholders in three different ways:

(1) Costs of failures, replacements and diagnosis

Additional costs are added to failures, replacements and diagnosis. In general, FL, RE and DE will all be increased, but the ratio between them depends on the stakeholders. When loads are growing, the network is less redundant and the risks of outages will increase. When environmental issues are more of a concern, penalties on failures and additional approvals for maintenance will be applied. Both of them will lead to increasing costs of large-scale asset management activities, i.e. increased FL/RE and RE/DE. On the other hand, shortage of workforce will increases the costs of maintenance activities, especially those with higher “ranks of requirement on skill” listed in [4]. In this situation, FL/RE and RE/DE will be decreased.

(2) Limited volume of maintenance

Several factors can limit the maximum volume of asset management activities. Firstly, reliability and availability of the network act as constraints on outage-necessary replacements. Secondly, local governments limit the frequency of maintenance to control their effects on the environment. Thirdly, the population of aging components outnumbers the capability of the workforce.

(3) Quality of diagnosis

The quality of diagnosis is determined by many technical factors, such as the precision of the sensor, the readiness of the knowledge rule, etc. From a societal aspect, the shortage of workforce, especially experienced asset workers, can also lead to large diagnosis errors. This error is indicated by the scale parameter η introduced in 2.1.

3 SIMULATION RESULTS

3.1 Optimal parameters of maintenance strategies

Interval of replacement and diagnosis should be chosen properly for TBM and CBM. For CBM, the knowledge rule, i.e. the threshold of health index above which the components should be replaced, should be optimized. Figures 3 and 5 show the optimal TBM and CBM strategy for our default reliability parameters (h_0=70, Δh=50, σ_0=0.618, a=9500 (µm) and b=4) and economic parameters (FL=20, RE=1, DE=0.05).

Figure 3 shows the ECOC when TBM is applied with different replacement intervals. The optimal replacement interval is 23 years. However, this optimal choice is flexible, because TBM with intervals ranging from 17 to 29 years produces less than 105% of optimal ECOC, as the top edge of the dashed rectangle shows in Figure 3. The left part of ECOC is steeper than the right part, which means that lower-than-optimal replacement intervals tend to increase costs more than higher-than-optimal ones.

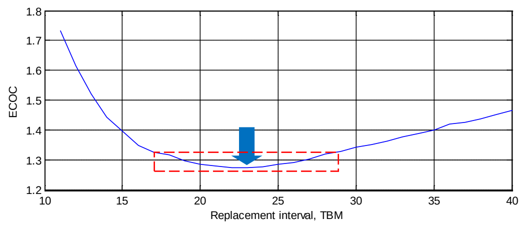

Figure 3: Expected cost of one connection when TBM is applied with different replacement intervals (optimal replacement interval at 23 years, as the pointer shows)

The threshold of the health index to replace components determines the number of replacements and consequently ECOC. For each diagnosis interval, the threshold with the lowest ECOC is calculated and shown with a circle in Figure 4. We fit the optimal thresholds into a polynomial curve. The residuals of this fitness is around +/-100, which means a ±100 difference on the threshold is acceptable.

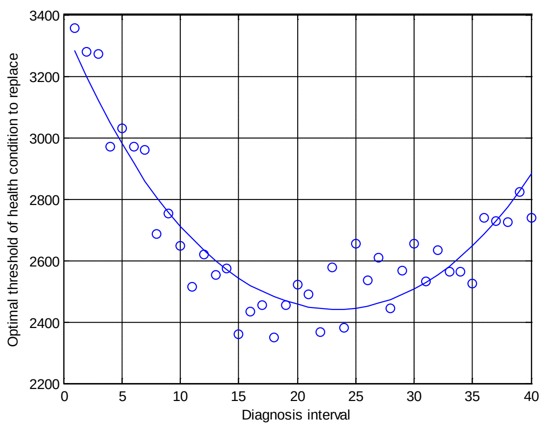

Figure 4: Optimal threshold of health index when different diagnosis intervals applied for CBM

With the optimal thresholds shown in Figure 4, the lowest ECOC for each diagnosis interval can be calculated and plotted in Figure 5. The optimal diagnosis interval is 8 years. Intervals between 5 and 10 years will produce less than 105% of optimal ECOC, as the top edge of the dashed rectangle shows in Figure 5.

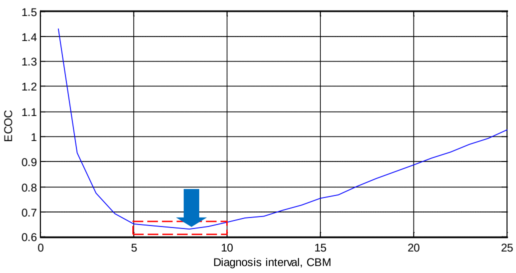

Figure 5: Expected cost of one connection when CBM is applied with different diagnosis intervals and their optimal thresholds (optimal diagnosis interval at 8 years, as the pointer shows)

3.2 Life cycle costs of maintenance strategies

Section 3.1 introduced the optimal parameter for TBM and CBM strategies with given reliability parameters h_0, Δh, σ_0, a and b and economic parameters *FL*, *RE*, *DE* were introduced in 2.1 and 2.2. In this section, the optimal TBM/CBM strategy and corresponding ECOC are calculated for various combinations of reliability and economic parameters, in order to simulate the regulatory restrictive scenarios listed in 2.3.

In our reliability model, the quality of diagnosis is indicated with the “scale parameter of the diagnosis error” η, as Section 2.3 introduced. Figure 6 illustrates the ECOC of CBM with different to η ranging from 0 to 3. The optimal diagnosis interval for CBM keeps 8 when η below 1.5, but increases to 11,14 and 16 when η is 1.5, 1.8 and 3.

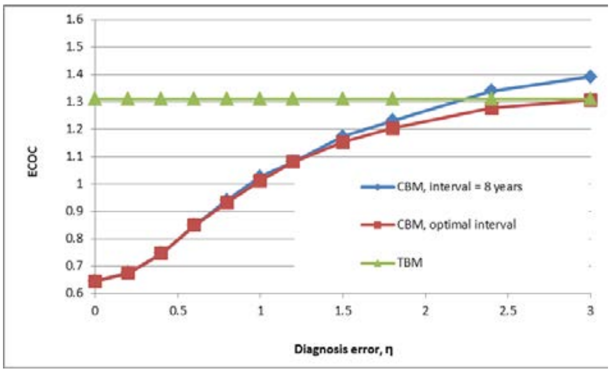

Figure 6: Expected cost of one connection of condition based strategy with different levels of the diagnosis error (h_0=500, Δh=70, *FL*=20, *RE*=1 and *DE*=0.05)

Apparently, the diagnosis error parameter has significant influence on the ECOC of CBM. With our default economic parameter, CBM loses its advantage of ECOC to TBM when η is increased to 2.4. CBM with diangosis interval fixed to 8 years can have a ECOC higher than TBM. Comaretively, the CBM with optimal interval is essentially the same TBM when η is above 2.4. This is because: (1) The optimal threshold tends to decrase to small values below 1000, i.e. nearly all diagnosed comonents are replaced. (2) The optimal diagnosis interval is approaching the 23 year optimal replacement interval of TBM.

In addition to the of η, value of the economic parameters FL and DE are also changed. Their relationship with ECOC are shown in figure 7 and 8. From Figure 7, we learned that FL only enlarges the difference between CBM and TBM. In Figure 8, CBM is profitable only in the range of DE<0.2 and η<3. These results imply that DE and η have much larger effect on the decision between TBM and CBM than FL has.

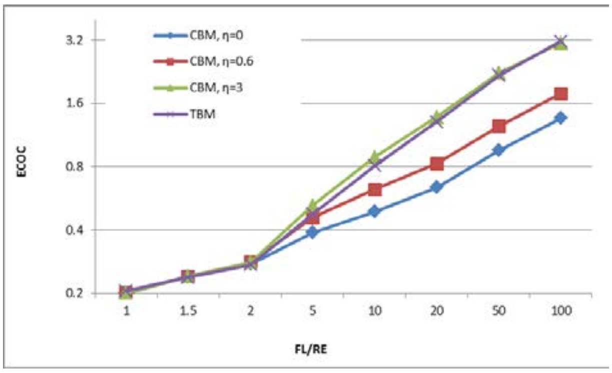

Figure 7: Expected cost of one connection vs. failure losses (h_0=500, Δh=70, A=9500, B=4, RE=1 and DE=0.05)

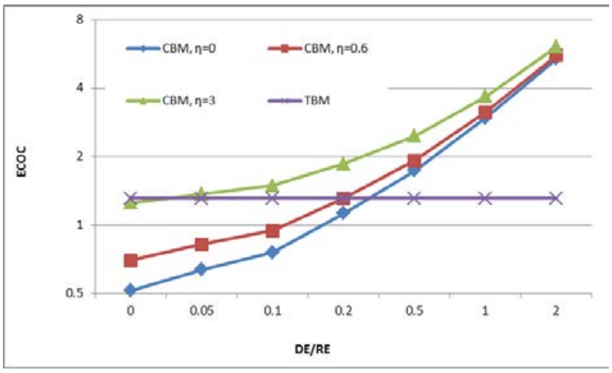

Figure 8: Expected cost of one connection vs. diagnosis expenditures (h_0=500, Δh=70, *RE*=1 and *FL*=20)

3.3 Limited volume of maintenance

In most situations, resources necessary for maintenance can be obtained from the market. Limited resources can be purchased at higher prices, which simply add to the life cycle cost. In some cases, however, the politically driven regulations impose restrictions on maintenance activities. In this section, a typical political restriction, namely the limited number of replacements, is discussed.

For simplicity, the reliability and economic parameters are fixed as following: h_0=500, Δh=70, σ_0=0.618, a=9500, b=4, FL=20, RE=1 and DE=0.05. Since the limit is applied on annual number of replacements, it is improper to assume that all components were installed in the same year. Alternatively, the original installation is distributed evenly into 20 years, i.e. 500 components are installed each year, from year 1970 to 1990. This is similar to the aging distribution described in [10].

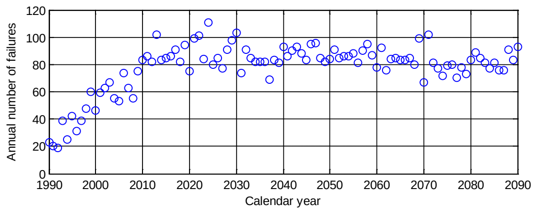

Figure 9: Annual failure and replacement number for corrective maintenance

Figure 9 shows the annual failures from the year 1990 to 2090 when corrective maintenance is applied. The growing failure rate from from 1990 to 2020 indicates the "aging wave" which has been stressed in many utility companies [10]. From 2020, the number of annual failing (and hence replaced) components eventually stablizes in the range of average 70 and maximum 90. This is the minimum number of replacements required to maintain the system.

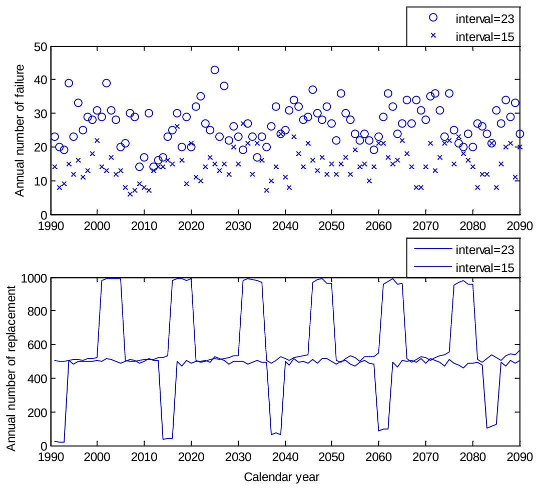

Figure 10: Annual failure and replacement number for TBM, with different intervals of replacement

When TBM is applied, the annual failures and replacements will be as shown in Figure 10. Two replacement intervals are simulated: the optimal interval 23 years, and a shorter interval 15 years simply to demonstrate the "over-reliable" situation. The annual replacement numbers of both intervals have a "peak season" and "idle season", because original installation of the connections concentrated within 20 years.

The "seasons" of replacement tasks can be utilized to tackle the restriction of "maximum number of replacement". In each year, especially the "peak season", the oldest components have the priority to be replaced. When the maximum number of replacement is reached, the replacements of relatively younger components are delayed. Surviving components younger than the replacement interval, 23 or 15 years in our case, will not be replaced. This can be regarded as a "service age based" life extension strategy.

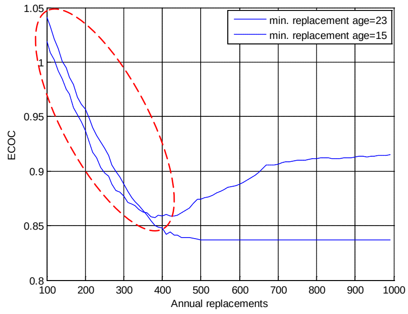

Figure 11: Expected cost of one connection vs. maximum annual number of replacement, when TBM is applied.

The effect of this strategy on the ECOC is plotted in Figure 11. Because the maximum annual replacement for 23-year is 500 in Figure 10, the ECOC of 23-year interval remains a constant 0.84 when annual replacement is above 500. This 0.84 is the optimal ECOC of TBM. On the other hand, the ECOC for 15-year interval tends to decrease when the upper limit of annual replacements decreases from 1000 to 400. This implies the fact that this 15-year interval is shorter than optimal and over-reliable. A critical point can be identified at 400 annual replacements, which is approximately the component number 10000 divided by the optimal replacement interval 23. When the annual replacement is below 400, the ECOC curve becomes very steep, as we marked with a dashed ellipse in Figure 11 i.e. significant losses on ECOC will be caused compared to the optimal ECOC 0.84.

CBM without diagnosis error requires much fewer failures and replacements, as shown in Figure 12. The result proves that CBM is a better solution to the "limited volume of maintenance" than TBM. For the optimal CBM strategy (interval=8, threshold=2500), the annual replacements are between 200 and 300, 3 times that of corrective maintenance. This number can be further reduced through increasing the threshold, which allows more failures but requires less replacements. This leads to larger ECOC. Figure 13 shows the relationship between annual replacements and ECOC when threshold is changed from optimum. At the top-left of the figure, 30% reduction of replacements leads to 20% more costs. This reduction is larger than what can be realized with TBM with the same loss.

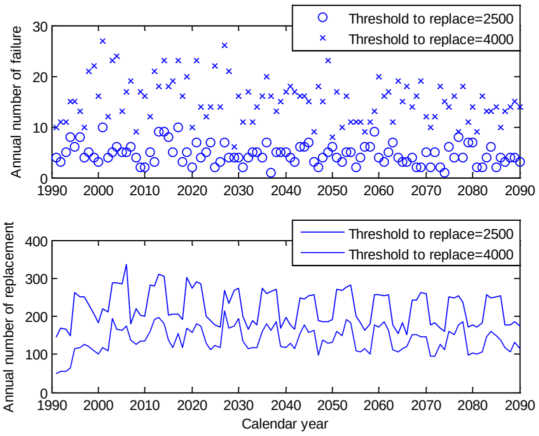

Figure 12: Annual failure and replacement number for CBM, with optimal diagnosis interval 8 years and different threshold of replacement.

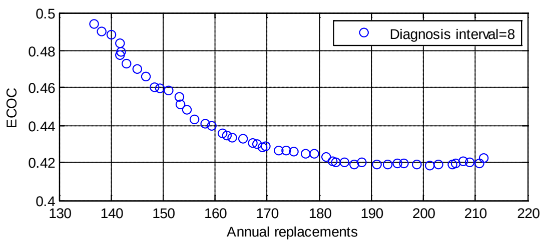

Figure 13: Annual failure and replacement number for corrective maintenance

3.4 Summary

With the simulation results described from sections 3.1 to 3.3, we retrieve the discussion about regulatory restrictions in 2.3 and summarize the links between them as follows:

(1) Economic advantage of CBM relies heavily on the diagnosis quality. While this quality mainly depends on technical factors, relevant societal factors, such as workforce availability, should not be neglected.

(2) When the diagnosis error level is controlled, the cost of diagnosis determines the choice between TBM and CBM. The loss of failure does not change the decision on strategy, but enlarges the gain/loss of the decision. Pressures from external stakeholders, such as environmentalists, suppliers and consumers, normally values larger events (increases FL/RE and RE/DE). Thus they tend to select condition based strategies. On the contrary, internal stakeholders such as personnel tend to decrease FL/RE and RE/DE and consequently favour selecting time-based strategies.

(3) Both CBM and TBM can provide certain degree of freedom for annual replacement numbers when an upper limit is set by stakeholders. Given certain amount of extra cost, the range CBM can provide is larger than TBM. In other words, CBM is more suitable to tackle political restrictions from external stakeholders.

4 CONCLUSION

This paper performs simulations on life cycle cost time-based and condition-based maintenance strategy, in order to study their economic feasibility under emerging regulatory restrictions on utility companies. The results show that condition-based maintenance is profitable only in several scenarios: (1) the diagnosis error is controlled technically, (2) workforce on assets is sufficient, (3) external stakeholders are imposing higher demands and stricter restrictions on the maintenance. If a contrary scenario occurs, time-based maintenance will become favourable. The simulation parameters are based on cables, but the process can be applied to other type of high voltage assets.

5 REFERENCES

[1] "Remaining Life Management of existing AC Underground Lines," *Cigré Technical Brochure 358,* 2008.

[2] "Asset Management Performance Benchmarking," *Cigré Technical Brochure 367,* 2008.

[3] "GIS: State of the Art," *Cigré Technical Brochure 381,* 2008.

[4] "Guide for Transformer Maintenance," *Cigré Technical Brochure 445,* 2011.

[5] K. Froehlich, "Strategic Directions 2010-2020," *ELECTRA,* vol. 249, 2010.

[6] W. Kai*, et al.*, "Investigation of Economic Feasibility of Different Rules of Insulation Diagnosis," *Dielectrics and Electrical Insulation, IEEE Transactions on,* vol. 16, pp. 909-916, 2009.

[7] W. Q. Meeker and L. A. Escobar, *Statistical Methods for Reliability Data*. New York: John Wiley & Sons, Inc., 1998.

[8] "Maintenance for HV cables and accessories," *Cigré Technical Brochure 279,* 2005.

[9] B. Quak, "Information strategy for decision support in maintaining high voltage infrastructures," EWI, Delft University of Technology, Delft, 2007.

[10] "Aging of the System, Impact on Planning," *Cigré Technical Brochure 176,* 2000.