VII WORKSPOT- International workshop on power transformers, equipment, substations and materials
RIO DE JANEIRO, RJ – NOVEMBER, 23 - 26, 2014

Trends in Risk-Based Substation Asset Management & Lifetime Monitoring

Ravish P.Y. MEHAIRJAN[1, 2], Johan J. SMIT[1], Dhiradj DJAIRAM[1]
[1]Delft University of Technology, Mekelweg 4, Delft, the Netherlands
[2]Stedin B.V., Blaak 8, Rotterdam, the Netherlands

SUMMARY

CIGRE Working Group WG B3.06 has been tracking changes in substation asset management over the last decade by several international study bodies and surveys. This has resulted into advices and best practices, processed and published in several CIGRE Technical Brochures (TB's). In general, three main topics related to substation asset management were recognized and investigated by CIGRE Taskforces (TF's), these three topics are: *Outsourcing of Maintenance (TF01)*, *Decision Processes for Asset Replacement (TF04)* and *Information Strategy for Asset Management (TF05)*. In this contribution summaries of the results from the group's investigations are presented. This initial work of well-over 15 years has yielded many insights into the development of trends in substation management. These developed trends should lead to the transition into future grid concepts. This particular aspect is the work that, currently, has been taken up by CIGRE WG B3.34, which is an extension towards asset management of future grid concepts. As an example of integral risk-based asset management for substation related assets, a case study is described of a risk linked *Reliability Centered Maintenance (RCM)* approach. In this case study a risk management business model has been linked to the RCM method in order to relook, for instance, the maintenance concepts of power transformers in substations. This risk linked RCM approach adopts the *Risk Priority Number (RPN)* to lead decision making. Risk management is one of the trends seen by the industry as leading principle for management and engineering. Furthermore, as an example of modern asset management developments, a second case study is described of future automated lifetime monitoring systems. In this case study dynamic loading of transformers is used to illustrate the concept. Thereto a framework of model-based optimization is included in the intelligent component. This framework consists of a *Predictive Health Model (PHM)*, which predicts the top-oil temperature and the hot-spot temperature based on the loading of transformer.

KEYWORDS - Substation, Asset Management, Maintenance, Risk Management, Information Strategy, Outsourcing, Predictive Health Model, Reliability Centered Maintenance, Decision-Making.

r.p.y.mehairjan@tudelft.nl , j.j.smit@tudelft.nl , d.djairam@tudelft.nl

INTRODUCTION

Firstly, in the following sections the work of WG B3.06 - TF01, TF04 and TF05 are briefly summarized. Secondly, an outlook of the topics of interest in the transition from existing to future grid concepts is shown as part of the current ongoing work of WG B3.34, illustrated in figure 1.

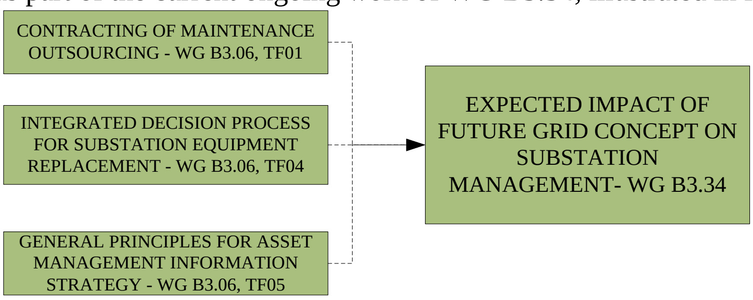


Figure 1: Researched trends in substation asset management as described by WGB3.06 and the extension towards future grid concepts that will be investigated by CIGRE WG B3.34. These investigated areas closely interact with each other.

Thirdly, a developed risk-linked RCM method is discussed and a real-life case study for an oil-filled 150 kV transformer bushing failure is used to demonstrate the principles of this method. Finally, a state-of-art lifetime monitoring case study based on predictive health modelling is elaborated.

CONTRACTING OF MAINTENANCE OUTSOURCING - WG B3.06, TF01

Undoubtedly, centralization of decision making within an asset management model is the prevalent response to business drivers introduced into utilities. In this context, the key driver for changing and relooking workforce management has been the liberalization of global power markets that has taken place over the last 25 years. This has led to increased contracting of work to external groups. The use of external service providers is a long established feature of life in Europe, Asia and Australia and a small upcoming trend in North America. However, maintenance outsourcing is not a simple task, particularly in core areas. In most instances it can be successful provided goals are not unrealistic, obstacles minimized and suitable management controls established. WG B3.06 (TF01) has developed various international surveys with the aim to track these changes. The surveys indicate significant concerns remain within utility engineers relating to flexible working, loss of skills and knowledge. The complete survey results and technical brochure are expected to be published in early 2015. A brief summary of a number of trends from these surveys are shown in figure 2.

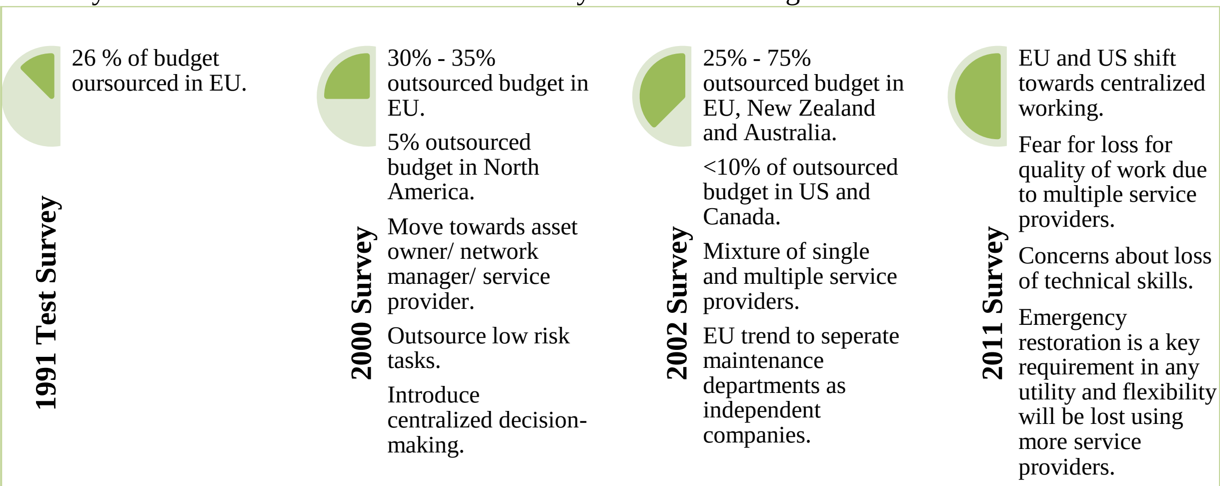
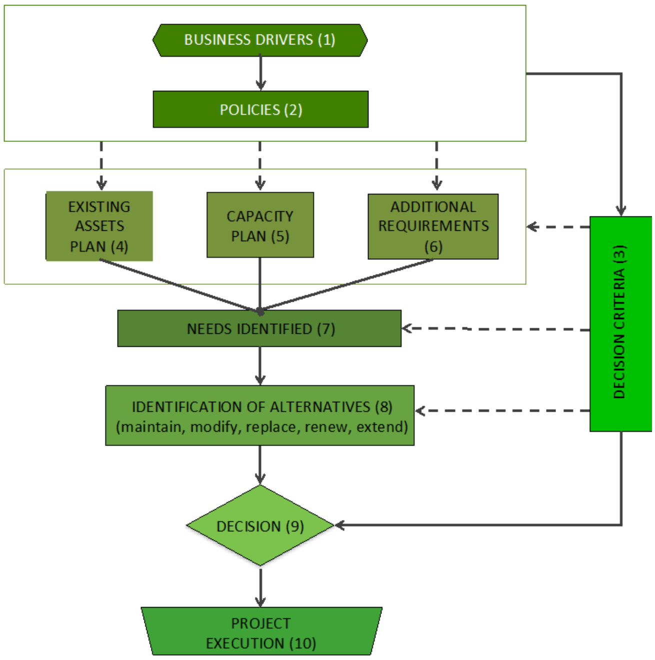


Figure 2: Summary of some concluding remarks from four survey results and their trends.

INTEGRATED DECISION PROCESS FOR SUBSTATION EQUIPMENT REPLACEMENT - WG B3.06, TF04

WG B3.06 TF04, sheds light on the current practice of an integral decision process for asset replacement purposes, as applied to substations. This work is published in CIGRE TB 486 (2011). The integral nature of the decision process (top-down) results from the consideration of both the maintenance needs of existing assets (due to aging), as well as of the requirements by the capacity plan (due to grid enlargement or structural changes). This integral approach to substation asset replacement is obligatory in order to ensure that high-level, general business drivers are systematically applied to all levels of individual replacement projects. This decision path should be incorporated into an overall asset management concept such as described in *PAS 55* or *ISO 55000*. According to the WG experience the decision process for asset replacement is commonly organized into ten steps, as shown in figure 3.

In *step 1*, the corporate *business drivers* are included as primary scope for any decision that follows. In *step 2*, proper asset replacement or maintenance *policies* need to be established. Well-defined policies provide general guidelines which ensure consistent decision making. In *step 3*, *decision criteria's* are set, which are used to evaluate and quantify the performance of the alternatives with respect to the general business drives. These criteria's are risk indicators as part of risk management. In *step 4*, the *existing asset plan* (renewal, replacement, long overhauls, etc.) for maintenance of already installed assets is considered. In *step 5*, *capacity plan* results from middle and long term grid planning and investigates situations beyond "business as usual". Integration of the capacity plan into asset replacement decisions is an important feature of the proposed decision process. In *step 6*, *additional requirement* of external factors are taken into account. In *step 7*, individual *needs* of each asset are *identified* for the maintenance, the capacity plan and additional requirements. Next, in *step 8*, the identified needs are used to develop decision *alternatives*. Each alternative should be defined as a project with a clear scope and budget along with assumptions made.

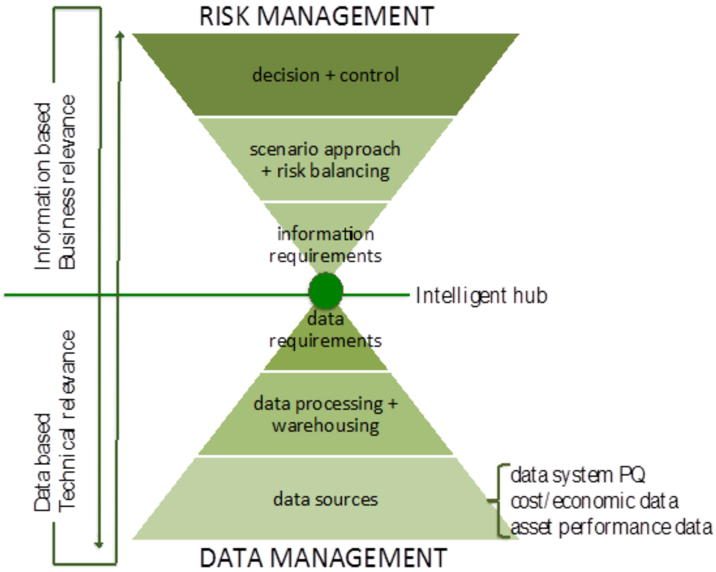


In *step 9* the *decision-making* takes place. Prior to decision making, the performance of each alternative with regard to the decision criteria has to be evaluated. Comparing the respective risk indicators with and without project execution demonstrates the compliance of an alternative with the general business drivers. Moreover, risk exposure due to postponement of decision making should be taken into account in order to identify urgency.

Figure 3: A 9 step integral decision process for substation equipment replacement and maintenance.

GENERAL PRINCIPLES FOR ASSET MANAGEMENT INFORMATION STRATEGY - WG B3.06, TF05

Integrated decision processes require information strategies to support them. In other words, risk based integrated decision process require data in mixed strategies. This means matching technical, economic and social data from a holistic point of view. Utilities require a data management model that is capable of linking them to the risk management decision-making model. WG B3.06 (TF05) identified that, worldwide, utilities still need to settle for less than ideal circumstances when it comes to asset information to support risk-based decision making. The international survey shows that this is mainly due to the, still existing, strong focus on technical data and less on economic and social data. This WG instigates in filling the gap between data management, through information strategies, and the link with risk based decision-making. This work has been published in CIGRE TB 576 (2014).



A model, referred to as an *hourglass model*, is proposed. In general, such a model should assist utility leaders to be aware of a potential gap and make a link between risk management (decision-making requirements) and data management (data and information requirements). This model is conceptually shown in figure 4 and comprises of two essential parts, which are:

- Risk management: this helps in utilizing and addressing the requirements on asset data.
- Data management: this supports the decision making process through constructing a system to acquire, warehouse and transmit data.

Figure 4: The "hourglass model", which expresses the need to align the translation of data into information according to the risk-based decision process.

The international survey was carried out in 2006/2007 and reached out to 19 utilities from Europe, North America, Middle East and Australia. A number of conclusions from this survey are:

- Majority of utilities own a large volume of digital records regarding daily operation and maintenance on a wide range of substations components.
- Data processing is mainly focused on technical aspects.
- Hand-based data collection is still common practice nowadays (68% of respondents).
- Integration of technical and non-technical systems is not common in the power sector.
- An increased automatic collection and storage in digital format is expected.
- On Enterprise Resource Planning (ERP) a significant increase on adding those to the existing system landscape can be seen.
- Systems for Enterprise Asset Management, planning/scheduling systems (not ERP), MS office and specific systems and proprietary databases are most commonly (> 50% of the respondents) used.

EXPECTED IMPACT OF FUTURE GRID CONCEPT ON SUBSTATION MANAGEMENT-WG B3.34

The electricity grid will revolutionize at a fast pace into a highly interconnected, more complex network of power systems utilizing telecommunications, internet and electronic applications. It is highly probable that, if not all, many elements of the power system will include sensors, communication and compatibility abilities. In order to investigate what will be the expected impact of these future features of power systems on substation management, CIGRE WG B3.34 is initiated as a natural extension of WG B3.06. In this context, WG B3.34 takes up the task to create more insight on the impact of the above mentioned challenges for future grids and substation management.

RISK BASED MAINTENANCE MANAGEMENT MODEL – CASE STUDY

As an example of the integral decision-making process, we introduce a recently developed risk-based maintenance model at a Dutch DSO. This model introduces a risk incorporated *Reliability Centered Maintenance (RCM)* method. In this method, the traditional *Risk Priority Number (RPN)* has been expanded in order to deal with the consequences of asset failure modes on multiple corporate business values (business drivers). In doing so, the aim is to develop a practical yet sufficiently accurate method for risk-based maintenance management. A complete and extensive description of this method can be found in [9]. Here a brief overview of this method and its application is shown.
In this approach, the RCM process follows the following three main steps:

1. *Failure Mode and Effect Analysis (FMEA)*, which provides an initial RPN of the failure mode.
2. *Failure Effect Categorization (FEC)*, which provides a method to categorize the failure modes according to their effect in a uniform way. This helps with selecting an effective and proper maintenance strategy in the next step.
3. Task Logic, which provides, on basis of the FEC, means to define a maintenance strategy for each failure mode. Maintenance strategies such as, preventive (scheduled) maintenance, condition based maintenance or run-to-failure can be selected.

The traditional RPN formula is:

$$\boldsymbol{RPN} = \boldsymbol{S} \times \boldsymbol{O} \times \boldsymbol{D} \qquad (\mathbf{1})$$

With, *Severity (S)*, which is a rating for the severity or consequence of each potential failure effect. *Occurrence (O)*, which is a rating of the likelihood of occurrence of each potential failure cause. *Detection (D)*, which is a rating of the likelihood of detecting the failure cause.

Three main difficulties are seen in practice when using the tradition RPN approach. These are:

1. Ability of multiple scenarios for consequences of failure occurrences.
2. Data availability to extract required failure occurrences (probabilities).
3. An (sufficiently) accurate procedure for calculating the Severity and Occurrence

The above mentioned shortcomings are made clear by means of a conceptual overview in figure 5.

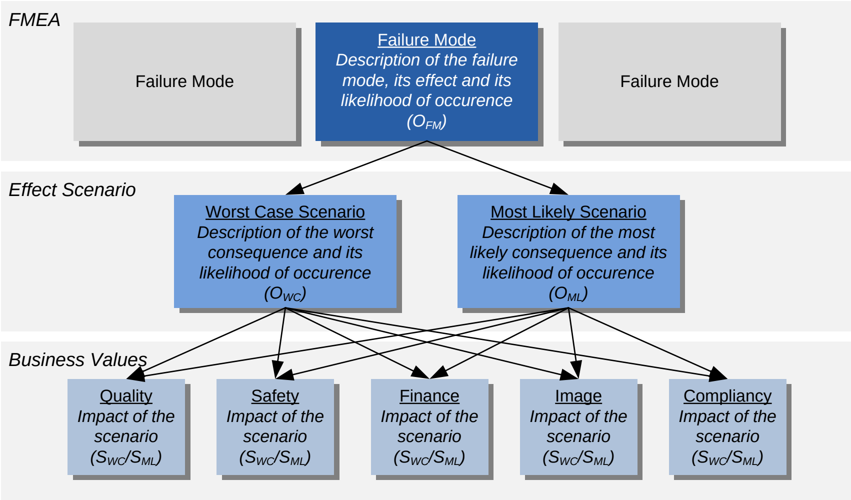


Figure 5: The interrelated issue with multiple business values for two effect scenarios for an identified failure mode.

This brings us the extended version of formula (1), which has been used in our practical application.

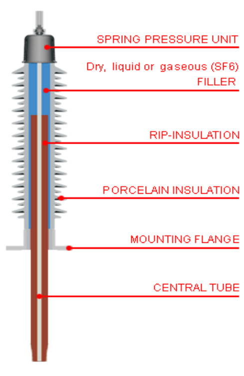
$$\boldsymbol{RPN}_{\boldsymbol{worst\ case}} = \boldsymbol{S}_{\boldsymbol{business\ value}} \times \left(\boldsymbol{O}_{\boldsymbol{business\ value}} \times \boldsymbol{O}_{\boldsymbol{failure\ mode}}\right)_{\boldsymbol{worst\ case}} \times \boldsymbol{D} \qquad (2)$$

$$\boldsymbol{RPN}_{\boldsymbol{most\ likely}} = \boldsymbol{S}_{\boldsymbol{business\ value}} \times \left(\boldsymbol{O}_{\boldsymbol{business\ value}} \times \boldsymbol{O}_{\boldsymbol{failure\ mode}}\right)_{\boldsymbol{most\ likely}} \times \boldsymbol{D} \qquad (3)$$

The RPN calculations are made using unified risk management ranking tables for each parameter *(S,* $O_{business\ value}$, $O_{failure\ mode}$, *D)*. When the RPN's are calculated, each failure mode can be individually ranked from high to low risk. This ordering of RPN's will provide a priority ranking for choosing maintenance tasks to mitigate and control the occurrence of failures. It is desirable to revise the initial risk assessment based on the assumption (or the fact) that the recommended maintenance actions have been completed. To calculate revised RPN's, a second set of revised ratings of *severity*, *occurrence* and *detection* for each failure mode are multiplied. The *initial* RPN's can be compared to the *revised* RPN's. This offers an indication of the usefulness of certain maintenance actions. In addition, an assessment can be made of the implications on risk exposure when certain maintenance tasks are not performed (i.e. in case OPEX budget cuts).

As a practical application of the developed method, this model is applied on a case study for 150 kV transformer bushings (oil filled condenser type) of which a summarized FMEA result is shown in table 1.

Table 1: Typical FMEA results for high voltage transformer bushing for a failure mode.

Component Hierarchy	*Function*	*Functional Failure*	*Failure Mode*	*Failure Effect*
 *Source: mosizolyator.com*	Provide an isolated connection between the transformer windings and cable termination.	Short circuit between transformer tank and conductor.	Low oil level, which can be caused by not on time filling or leakage due to a leaking gasket.	Short circuit will lead to disconnection of the transformer from the grid. Loss of the bushing and possibility of fire.

A recent failure of a transformer bushing is used to assess this method. These types of bushings are indicated as “sealed for life” and thus not refillable. On the one hand, due to degradation of gaskets, leakages can occur. On the other hand, these bushings do not have oil level inspections windows. In case of oil leakage, the oil level is lower than a certain critical level, the occurrence of a short circuit will become inevitable. In an independent failure report, it was reported that due to this failure mode a short circuit to ground potential caused an explosion of the bushing with fire outbreak on the transformer as a result. An analytical assessment of the impact of such a failure on each business value can be done by calculating an initial RPN. For this study, two failure scenarios were identified by experts:

- Worst case: *Power transformer burn, major injury, article in local newspaper.*
- Most likely: *Transformer is switched off by protection, bushing explodes, burn damage on the transformer, transformer repairable, no injuries (nobody present).*

The experience of the actual failure is used to make an estimation of the occurrence of the failure mode (1 time in 30 years). Originally, there is no detection measure for the failure mode and therefore the detection is ranked as no detection (highest rank). With the $O_{failure\ mode}$, $O_{business\ value}$, S and D, the RPN’s for each business value are calculated. For mere study purposes, we have developed an inspection task (yearly) for the oil levels of the high voltage bushing. With the oil level inspection, the failure mode can be detected preventively. With this revised detection possibility, the *revised* RPN for the most likely scenario is calculated. In figure 6, a combination of *initial* and *revised* RPN’s is shown.

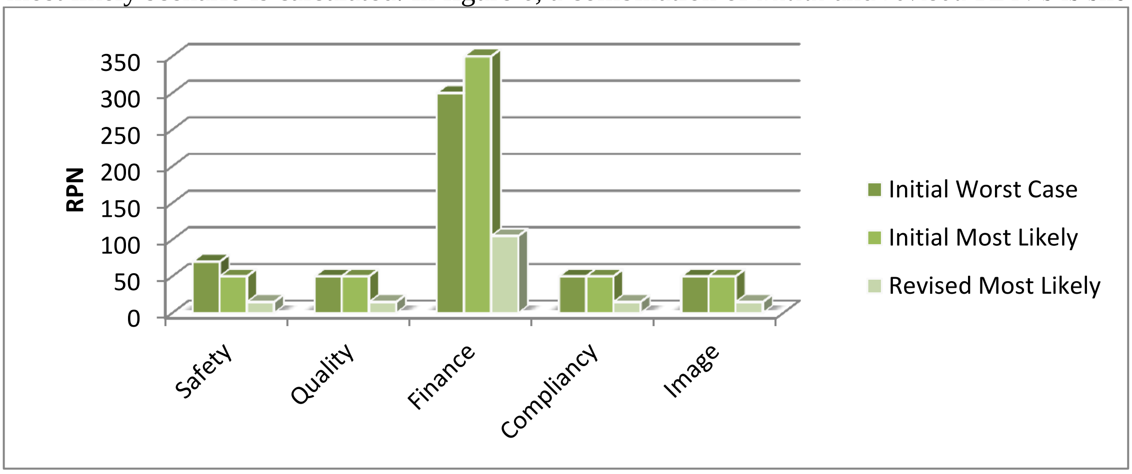


Figure 6: Business value for initial (both scenarios) and revised RPN’s.

With this, the benefit in terms of business value risks for a maintenance or inspection task can be assessed. In practice, this developed tool is immensely improving the RCM team in addition to preventing solely technical judgements to prevail the follow-up maintenance strategies. Moreover, we find that the technical experts are actually, gradually, developing an improved social-technical understanding of re-examining the traditional maintenance beliefs. For more details, please refer to [9 , 12].

PREDICTIVE HEALTH MODEL – CASE STUDY

As another example of modern asset lifetime management, we will now briefly discuss an application of a newly developed predictive control framework, schematically shown in figure 7, in which electric power is proactively rerouted based on calculated future operating temperatures in transformers of a grid. These temperatures, top-oil and hotspot, are calculated using a prediction of the load.

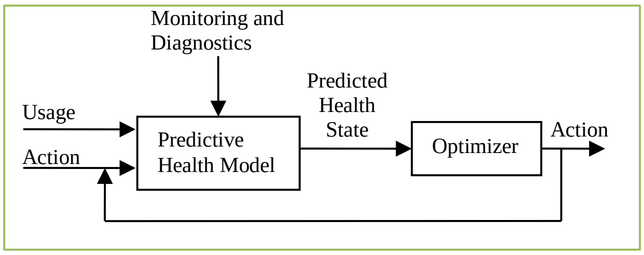


Figure 7: Schematic overview of the predictive health management control framework.

If transformers operate at a temperature higher than the rated level, accelerated aging will occur which, in turn, will lead to a lifetime shorter than the specifications of the manufacturer. By rerouting the power proactively based on the predictions, the stresses on the transformers will be distributed in such a way that the total aging of all the transformers in this part of the grid is minimised.

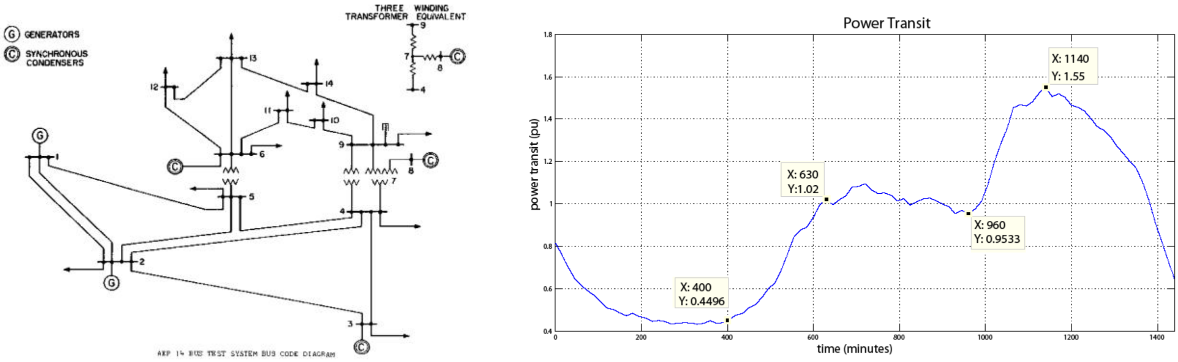


Figure 8: Left-hand side: IEEE-14 bus network. Right-hand side: daily load profile

In this case study, a typical daily load profile is applied at a specific node in an IEEE-14 bus network. This causes one specific transformer (5-6) to be overstressed as shown in figure 8 by the fact that the ageing factor (green/blue lines) crosses the red line.

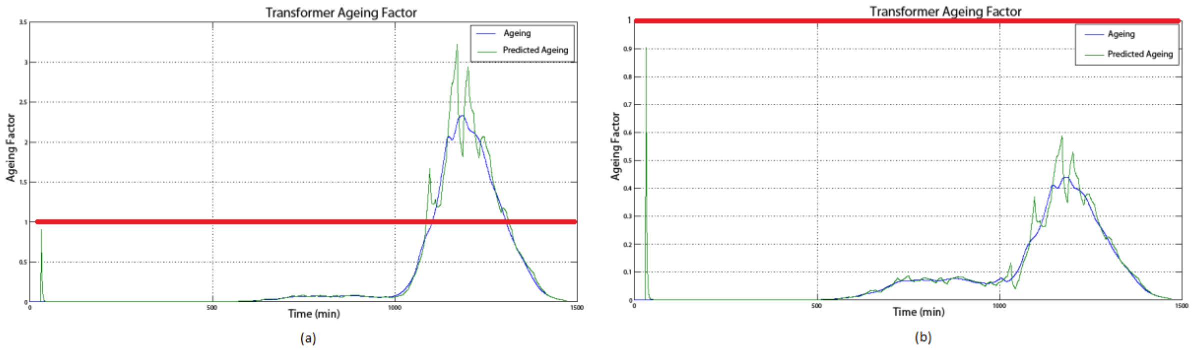


Figure 9: Ageing of the most stressed transformer. The red line represents the ageing at rated level according to manufacturer, i.e. ageing factor of 1. (a) Uncontrolled situation where the ageing factor goes significantly above 1. (b) Controlled situation where the ageing factor is maintained well below 1 by the control framework.

The red line represents an ageing factor of 1, which corresponds to ageing due to operation at the rated level according to the manufacturer. In a situation controlled by the PHM framework, the power is proactively rerouted to the other transformers thus reducing the ageing of the most stressed transformer 5-6 as shown in 9.

The numerical results of this simulation are shown in Table 2. The most important part is the ageing for transformer 5-6 during the uncontrolled (orange) and controlled (green) situation. We can see that the number of ageing minutes is reduced from 458 to 95 minutes.

Table 2: Ageing of the transformers in the IEEE-14 bus network. Transformer 5-6 is the most stressed transformer. Left-hand side in orange: uncontrolled situation. Right-hand side in green: controlled situation.

Trans former	ageing (min)	predicted ageing (min)	error (%)	power flow (pu)	ageing (min)	predicted ageing (min)	error (%)	power flow (pu)
4-7	0.225	0.229	1.5	267.4	0.595	0.229	4.2	315.4
4-9	$1.825 \cdot 10^{-3}$	$1.837 \cdot 10^{-3}$	0.7	152.2	$2.915 \cdot 10^{-2}$	$2.997 \cdot 10^{-2}$	2.8	182.2
5-6	457.53	490.19	7.1	585.7	94.82	97.75	3.1	509.3

We can conclude that the PHM framework is able to play a significant role in extending the lifetime of components compared to the situation where the future health state of the components is not taken into account. For more details, please refer to [10, 11]

BIBLIOGRAPHY

Ravish P.Y. MEHAIRJAN, is with Stedin B.V. in the Netherlands involved in various roles, especially on maintenance management, condition monitoring, statistical life data analysis and risk-based management. He also works part-time towards a PhD degree at Delft University of Technology at the High Voltage & Asset Management group on the topic of risk-based maintenance within asset management. He has a BSc (2008) and MSc (2010), both cum laude, in electrical power engineering from University of Suriname and Delft University of Technology, respectively. He is member of CIGRE WG B3.06, B3.34 and secretary of WG D1.39.

Johan J. SMIT, received his Ph.D. at the State University of Leiden in 1979. Since 1996 he is fulltime professor at the Delft University of Technology (NL) for High Voltage Technology and Management. He chairs the foundation for Knowledge Sharing and Research on Asset Management of Electrical Infrastructures. Earlier he was employed at KEMA T&D for 20 years, and member of the supervisory board of the power transmission company of South Holland. Also he is IEC-TC112 WG6 convener on Electrical Insulation Systems Evaluation, and for CIGRE TC-honorary member, past SCD1 chairman on Materials & Emerging Technologies, convener of D1 advisory bodies and WG B3.34.

Dhiradj DJAIRAM, received his Master degree in Applied Physics from Delft University of Technology in 2002. From 2004 to 2008, he conducted his PhD research into the feasibility of an electrostatic wind energy converter and successfully defended his thesis in 2008. From 2008 onwards, he has been a staff member of the High Voltage Group at Delft University of Technology. His research interests are in the fields of renewable energy, intelligent grids and asset management based on future conditions. He is also significantly involved in the education of B.Sc. students of the Faculty of Electrical Engineering, Mathematics and Computer Science, both in teaching and education development.

REFERENCES

[1] "International Survey of Maintenance Policies and Trends ", CIGRE JWG 23/39 brochure N°152, February 2000.

[2] “Outsourcing of maintenance in view of market liberalization” T. Eyles, P. Wester, G. Brennan and A.Wilson. CIGRE Session paper, 2002, 23-39-10.

[3] “Maintenance Outsourcing Guidelines”, CIGRE JWG 23/39 brochure N°201, 2002.

[4] “Outsourcing of maintenance –a review of world experience” A.Wilson, K. Doernnemann, E.Olid-G, J.Lica, P. Renaud, I. Kinnis, J. Corbett, CIGRE Session paper 2004, B3-106.

[6] “International Trends and Structural Changes in Substation Management”, N. Barrera, J. Smit and A. Wilson. Paper at 79th International Conference of Doble Clients, Boston, USA, 2012.

[5] “Integral Decision Process for Substation Equipment Replacement” CIGRE WG B3-06 brochure 486, February 2012.

[7] “Integrated Substation Life Management and Asset Information Strategy” J.J. Smit, N. Barrera, A. Wilson, R. Mehairjan, P. Leemans, N. Fantana, P. Myrda, I. Portugues, J. Bednařĺk, N. Kaiser, B. Bakka, G. Balzer, T. Kobayashi, A. Mackrell, S. Läderach. CIGRE B3 & D1 Colloquium, Brisbane, Australia 9–11 September 2013.

[8] “IT Strategies for Asset Management of Substations - General Principles”, CIGRE WG B3-06 TF05 brochure 576, April 2014.

[9] “Risk-Based Approach to Maintenance Management Applied on Power Transformers”, Ravish P.Y. Mehairjan, M. van Hattem, D. Djairam, J.J. Smit. 9th World Congress on Engineering Asset Management (WCEAM) 2014, Pretoria, South Africa, October 2014.

[10] “Multi-Agent Model-Based Optimization for Future Electrical Grids”, G. Bajracharya, PhD dissertation, Delft University of Technology, the Netherlands, February, 3rd, 2014..

[11] “Framework of Model-Based Health Optimization on the Electrical Power System”, R. Grizonic, MSc thesis, Delft University of Technology, April 9th , 2013.

[12] “Organisation-Wide Maintenance & Inspection Improvement Plan: A Dutch Electricity & Gas Distribution Network Operators Approach”, Ravish P.Y. Mehairjan, Martin van Hattem, Remco Manuel, Rini Krijgsman, Faouzi Bouthari, Joep Weerts, IET International Asset Management Conference, London, 2012.