# BENEFITS OF RELIABILITY CENTRED ASSET MANAGEMENT

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## ABSTRACT

*This paper provides an overview of risk and reliability assessment techniques, some which are available for distribution system operators, and others that are in the process of development. The main contribution of this paper is showing the possibilities and benefits of detailed risk and reliability analysis. Six samples of findings from research developed over the last decade within the RCAM group (Reliability Centred Asset Management) at the Royal Institute of Technology, Stockholm Sweden, are presented. The research is directly associated with risk and asset management applied to power systems. The first three examples are within developed research, followed by three areas where great potential is seen: 1) The value of accurate thermal models of transformers; 2) The impact of tariff regulation on asset management decisions; 3) Detailed interruption studies; 4) Dynamic rating; 5) Combined risk and reliability analysis of primary equipment and control equipment; 6) Systematic diagnostic measures for asset management.*

## INTRODUCTION

A number of trends and challenges are seen from the power system reliability perspective. This paper essentially identifies a number of these and highlights the value of improved analysis. The most apparent might be that the operation of local systems comes closer to the operation of transmission systems, recognized as the development of “Smartgrids”; grids that provide multiple options of control and measurement of apparatus condition, generation, power flow and storage for more stakeholders in the power system. One of the major motivations behind this development is increased reliability. That is a challenge in itself; introducing more options and increasing complexity for increased reliability.

Another trend and challenge is the preventive maintenance. Preventive maintenance puts a strain on the power system when performed offline and without proper knowledge about the reasons for doing the activity. More knowledge about degradation processes and how preventive maintenance counters these is crucial for doing the right activity at the right time. Directly connected to this is the research effort towards performing preventive maintenance with total system performance as the objective not the individual component reliability.

Power system reliability performance is to a large extent measured by unavailability measures, a very strong indication on that the power system function is taken for granted. The general trend is to put more and more trust in the power system, something which is reflected in an international tendency of increased regulatory pressure. Hence, studies of regulatory models and their consequences is an important part.

In this paper research from the RCAM-group is presented, the main focus is to highlight ongoing research with promising potential. The first three following sections of this paper is on developed research, while the three following cover areas that have been identified to have a significant potential in terms of reliability improvements.

## THE VALUE OF ACCURATE THERMAL MODELS OF TRANSFORMERS

Accurate thermal modeling of transformers is essential due to the fact that the most sensitive part of the transformer, the solid insulation, is sensitive to thermal stress. An increased temperature accelerates the deterioration of the solid insulation. Moreover, due to the fact that the temperature distribution over the transformer winding is inhomogeneous, there will be certain parts of the solid insulation which is warmer than the remaining part. The hottest part, which will deteriorate the fastest, is referred to as the hotspot. It has been suggested that, by tracking the temperature of the hotspot, it could be possible to estimate the consumed lifetime of the transformer. This could be done with the loss of life measure suggested by IEC [1].

Hotspot temperature measurements require optical sensors [2]. Unfortunately, optical sensors have only been installed on some of the transformers in the fleet. In particular, this technique is not available for those transformers predating this measurement technique for this purpose. This is when the use of thermal models becomes particularly important.

Thermal models of transformers are continuously undergoing improvements. Recent publications in this area are e.g. [3] and [4]. In order to determine the value of future research effort in this area, it is important to assess the value of this research effort in a quantitative measure such as a cost. This makes it possible to allocate a reasonable amount of funding devoted to this research area. In this paper, it is suggested that this value assessment could be done by combining life cycle cost analysis

(LCCA) and the loss of life measure provided by IEEE.

The first component of the suggested approach for research value assessment is the life cycle cost analysis. During an LCCA of the transformer, an economic analysis is performed that compiles costs and revenue for the transformer during its lifetime [5]. Having these costs it is possible to determine a factor $c$ that expresses cost per unit of life. The simplest way of doing this is to take the average of the cost and divide this with the average lifetime of the transformer type. However, more sophisticated approaches for this could also be chosen. The factor could be a function of maintenance strategy, operational strategy, and other related events.

The second component of the suggested approach is the loss of life measure [1]. The loss of life measure, defined by IEEE, is given by:

$$L = \int_T V\, dt, \tag{1}$$

where $V$ is the ageing rate, and $T$ is the studied time period. The ageing rate is given by the following expression:

$$V = Ae^{\frac{B}{\Theta_H + 273}}, \tag{2}$$

where A and B are constants, and $\Theta_H$ is the hotspot temperature. In the most common thermal models, the hotspot temperature is seen as a function of the load and the ambient temperature. Hence, the analysis needs to distinguish between load types for different seasons.

Based on the assumption that the research effort would yield an improved thermal model $\Theta_{H,\text{improved}}$, the difference to a reference model could be defined as the difference between the reference model and the improved model, i.e:

$$\Delta\Theta = |\Theta_{H,\text{improved}}\{t|t_1 < t < t_2\} - \Theta_H\{t|t_1 < t < t_2\}|, \tag{3}$$

for the time interval from $t_1$ to $t_2$. Having this temperature difference, it would be possible to estimate how much the lifetime estimate is improved in terms of consumed lifetime from Eq. (1). Finally, the value of this improvement, is the value of the research allocation, explicitly expressed as

$$C = c * L_{\Delta\Theta}. \tag{4}$$

## THE IMPACT OF TARIFF REGULATION ON ASSET MANAGEMENT DECISIONS

Tariff regulation has the role of providing incentives for cost-efficient operation with acceptable reliability and reasonable tariff levels [1] [7]. The impact from regulation and from other laws (e.g. customer compensation) has been studied which show on a significant impact on investments preferred [8]. For example, a recently performed description and evaluation [9] of the new Swedish tariff regulation (since 2012) shows that the method of evaluating the capital base has a large impact on asset management decisions (more than e.g. system reliability): Introducing more components is “rewarded”, while demolishing old components is “punished”.

The DSOs are rewarded for enhanced reliability of the power supply, and punished if the reliability decreases, but this has a significant smaller impact compared with the method of evaluating cost of capital employed which a recently performed M.Sc. thesis [10] has shown. However, a law of mandatory customer compensation for outages >12 hours has significant economic impact, potentially more than the tariff regulation and hence the reliability focus in Sweden largely focus on long outages. Economic consequences of outages as a function of time according to current Swedish regulation and laws are illustrated by Figure 1.

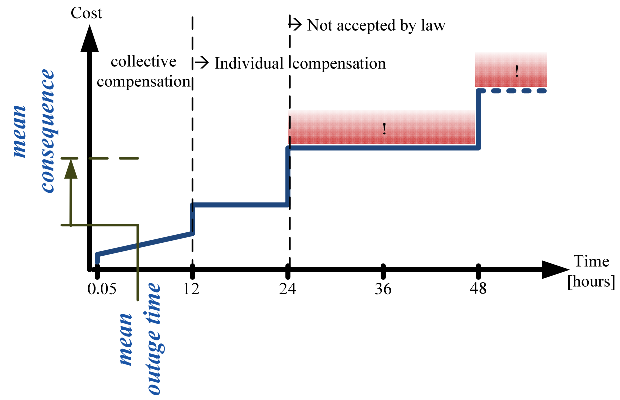


**Figure 1 – Illustration of economic consequences of current Swedish regulation, mandatory customer compensation for outages above 12 hours.**

## DETAILED INTERRUPTION STUDIES

Power distribution systems are mostly studied with average reliability indices. The problem is that the average situation seldom exists in real life. As seen in Figure 1, the consequence of an outage of mean length is not equal to the mean consequence of all outages since the consequence isn’t a linear function of time. This has motivated development of more detailed, and more realistic, reliability studies within the RCAM group [11].

To address the potential problem of using average values, significant more advanced analysis methods are not necessarily needed to be introduced. For example, it could be enough to divide one risk into two or more separate risks, e.g. to divide the risk of outages into three; short outages (0.05-12 hours), long outages (12-24 hours) and very long outage (>24 hours). That is using well tested methods but increasing the resolution. There is always a difficult balance between, on the one hand taking enough aspects into consideration and on the other hand developing methods that are realistic to use by DSOs (give more benefits compared to extra costs). This motivates a close collaboration between universities and companies.

## DYNAMIC RATING

Dynamic rating is identified by several companies as an important future opportunity and is e.g. proposed as a future research topic in a recently published report: "A vision on future research in electric power systems" [12]. In northern regions, the highest load is in winter when cold, hence coinciding with potentially increased load limits due to increased apparatus cooling. The aim of dynamic rating can be summarized as: "increasing the level of utilization". Power transformers, overhead lines and cables are probably of most economic interest to investigate. Protection equipments are also affected by temperature, but it is more about "optimizing dynamic settings".

Three stages of dynamic rating are identified:

1. Template levels, e.g. summer and winter: This is already introduced in some cases.
2. Template levels based on weather forecast: clear improvement, implemented to some extent, mainly on transmission systems.
3. Online measurements: relatively expensive and results in big data, rare as of today.

Power system investments are often costly. If dynamic rating calculations results in that an investment can be avoided it provides direct savings, but even if the investment "only" is postponed, it can still constitute a significant saving [13]. For instance when postponing expensive investments, the net value saving is calculated as follows:

$$Saving = C1_I - \frac{Ci_I}{\left(1+\frac{z}{100}\right)^i}, \quad (5)$$

where $C1_I$ is the investment cost today and $Ci_I$, is the investment cost year $i$; $Z$ *[%]* is the internal rate of return and $i$ is number of years the investment can be postponed. For example; if an investment of 2 000 000 EUR is postponed 10 years, and the investment cost is assumed to increase 25 %, an internal rate of 9%, result in savings of ~1 056 000 EUR (52.8 %).

## COMBINED RISK AND RELIABILITY ANALYSIS OF PRIMARY EQUIPMENT AND CONTROL EQUIPMENT

Most of today's research on risk and reliability are handled as two separate entities for primary equipment and control equipment. By combining risk analyses of primary and secondary equipment, the total risk and cost can result in more efficient investments especially in the coming generation of distribution grids [14].

One example to highlight the value and importance of combined and improved reliability analysis can be illustrated with the power outage event experienced in parts of Stockholm on the 3rd of December, 2012. The outage at its peak affected more than 80 000 customers including the subway [15]. This happened due to two major reasons: relatively cold weather (high load) in combination with that, one out of three transformers was under repair. The estimated interruption cost, including customer costs, came close to 28 million SEK and an estimate of 45 man-days of repair (360h).

The maintenance arrangement practiced in this system runs according to a scheduled plan, based on input from both manufacturers and station specifics in accordance with best practice in the industry. The transformer maintenance is carried out as planned in every six years with 4 to 6 man-days spent per transformer. Also the maintenance schedule followed for the control equipment is about 5 man-days per station in every 4 to 6 years [16]. This clearly suggests to investigate for additional developments over the state of the art maintenance methods now a days followed by distribution companies. Effective methods observed and studied include applying the concept of dynamic rating in combined reliability analysis. A Situational Adaption Maintenance (SAM) is proposed as a development, considering the requirements of the situation.

The application of the concept of dynamic rating in this particular case might have changed the outcome, together with the situational preventive maintenance of the transformer. This might enable the rated specific control setting that triggered the outage (max current), to be dynamically (temporarily) raised to withstand the high load. The complication is to do this with respect to the risk of failure and lifetime consumption of the two live transformers given that the third is under repair. In this case with the extent of customers affected and the resources for the repair, it indicates that the SAM approach would have been beneficial. However, if the approach is beneficial from a total business perspective is yet to be determined and requires more methods to be developed.

## SYSTEMATIC DIAGNOSTIC MEASURES FOR ASSET MANAGEMENT

The cost of maintenance can be divided into three parts: equipment, work and cost of interruption. The last factor, in terms of getting approval for disconnection, has increased during the last years in the Swedish transmission system, as the capacity for disconnections are constrained by other activities.

Hence, it is important to decide when to carry out maintenance. With little specific knowledge of the equipment, maintenance could be scheduled based on time or on the number of operations carried out since the last maintenance. It can be useful to utilize more condition indicators of a component in order to plan the maintenance efficiently.

Two studies [17] and [18] are about reliability of circuit breakers and they have dealt with 1 546 respective 2 137 breakers. In [18] there are data about the number of fault operations per year. For the bulk oil circuit breakers at 34.5-138 kV the values are between 0.05 and 2 with a median of 0.5 fault operations per year. For the 345 kV circuit breakers the number of fault operations per year was between 0.2 and 2 with a median of 2. The number of failures is naturally lower, 0.047 respectively 0.08984 failures per unit-year. As the number of fault operations varies with at least a factor 10 between breakers of the same type, it strongly indicates on the usefulness of measuring breaker condition

In [17] there are estimates of the Weibull distribution for three parts (close-operation lock, open-operation lock and the remaining parts) of one type of circuit breaker. The shape parameter is 1.8, 2.1 and 1.6 respectively, which gives a quotient between the standard deviation and the mean of the distribution between 0.35 and 0.54. For example the mean life for the close-operation lock is 1 962 operations. The standard deviation is then 890 operations, which means that about half of the breakers handle between 1 000 and 3 000 operations before corrective maintenance.

These two studies show that the variation in remaining life of circuit breakers is fairly high. Hence a significant value lays in the condition assessment of each circuit breaker in order to schedule its next preventative maintenance, as it may be possible to postpone it to a suitable interruption for another purpose.

## CONCLUSTION

In conclusion this paper shows on a number of fields that can provide significant advantages in the operation and planning of distribution systems. Some examples have been presented from methods that are ready to be employed by industry others show benefits of continued research and development.

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