ASSET MANAGEMENT TECHNIQUES

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Abstract – Deregulation and an increasing competition in electricity markets urge energy suppliers to optimize the utilization of their equipment, focusing on technical and cost-effective aspects.

As a respond to these requirements utilities introduce methods formerly used by investment managers or insurance companies. The article describes the usage of these methods, particularly with regard to asset management and risk management within electrical grids. The essential information needed to set up an appropriate asset management system and differences between asset management systems in transmission and distribution systems are discussed.

The bulk of costs in electrical grids can be found in costs for maintenance and capital depreciation. A comprehensive approach for an asset management in transmission systems thus focuses on the "life-cycle costs" of the individual equipment. The objective of the life management process is the optimal utilisation of the remaining life time regarding a given reliability of service and a constant distribution of costs for reinvestment and maintenance ensuring a suitable return.

In distribution systems the high number of components would require an enormous effort for the consideration of single individuals. Therefore statistical approaches have been used successfully in practical applications. Newest insights gained by a German research project on asset management systems in distribution grids give an outlook to future developments.

1 INTRODUCTION: FUNDAMENTAL ASSET MANAGEMENT TASKS

Asset management means operating a group of assets over the whole technical lifecycle guaranteeing a suitable return and ensuring defined service and security standards.

Distribution and transmission network operators are facing many different and partly even competing targets. It is their task to find a balance between the requirements of the customers concerning product and service quality at affordable prices as well as the shareholder demands for suitable returns on the capital they invest. Also potential regulatory impacts on revenues and changes in the political perception of e.g. renewable energy have to be focussed. To optimize between these demands network operators have to develop and extend “best practices” in asset management. The main question is not “Which network design will provide the best service quality?” but instead, “Which network design will provide better-than-required service quality while maximizing financial performance?” [1]

Asset management in electrical grid companies plays a key role in the detection and evaluation of decisions leading to long-term economical success and best possible earnings. For asset management to live up to these expectations, it has to meet a number of challenges. The four key challenges are (a) alignment of strategy and operations with stakeholder values and objectives; (b) balancing of reliability, safety, and financial considerations; (c) benefiting from performance-based rates; and (d) living with the output-based penalty regime. [1]

For this reason fundamental asset management tasks cover aspects from technical issues like network planning or the definition of operational fundamentals to more economical themes like planning of investments and budgeting, and end up in strategic planning issues.

Causal loop diagrams can be used to visualize the relationship between the elements of the system. Starting on the left side, Fig. 1 shows that the network condition degrades over time due to fundamental ageing processes. This has an impact on network performance which leads to investments if internal performance targets are not met any more. Investments depend on availability of money which directly results from the demands customers are willing to pay for. Finally investments (Capital expenditure “CAPEX”) or operational expenditure (“OPEX”) improve the network condition.

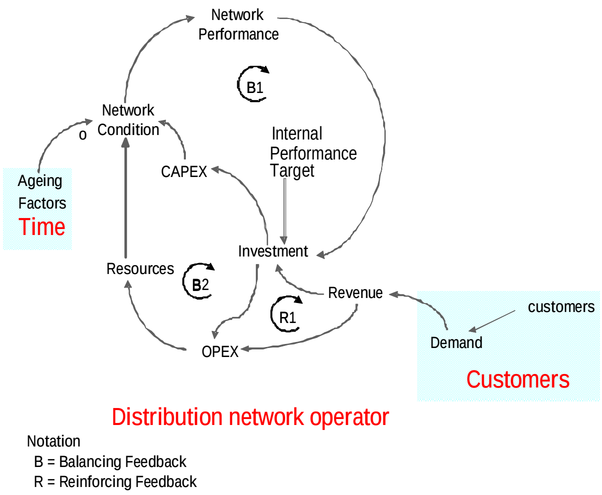

Fig. 1: Causal loop diagram

In the following chapters some of the most important strategies and management techniques actually in use by grid operators are described. These are:

- maintenance strategies
- determination of component condition
- asset simulation
- statistical fault analysis and statistical asset management approach (distribution)
- life management (transmission)

There is growing concern that the pressure for short-term efficiency targets and customer satisfaction has placed asset engineering in a background role. The time constants inherent in asset degradation and the delays between asset investment and realised benefits are sufficiently long to reduce asset investment without unduly affecting short-term performance. Additionally they are much longer than the tenure of the regulator and his political masters. Therefore, such strategies could lead to an irreversible time bomb situation with a degree of asset condition degeneration that might shatter the benefits current regulator policy seeks to achieve.

In order to make the right decisions it is therefore very important to develop the ability to analyse the complex dependencies between maintenance and renewal actions and the costs and the quality of service. The ability to assess different scenarios for the whole grid or parts of the grid having the same structure or technology is a major competence in asset management. These assessments provide extensive knowledge about the effects of alternative strategies on the asset base. By using this knowledge asset managers can actively develop the grid and spend the money in a way that the long term goals as well as the short term budgets are met.

2 MAINTENANCE STRATEGIES

Maintenance strategies can be divided into different approaches which lead to varying maintenance costs and asset availability.

One common way to classify maintenance strategies is to distinguish whether the condition of the component is considered on the one side and whether the importance of the component is considered on the other side. Figure 2 gives an overview of this classification. Both the condition and the importance of components can be defined in many ways, depending on the desired level of detail and the availability of appropriate data. For example, the definition of importance may be oriented at quite simple aspects like e.g. the number of feeders of a substation, or at more sophisticated indices like e.g. the share of the energy not supplied in time caused by failure of each respective component.

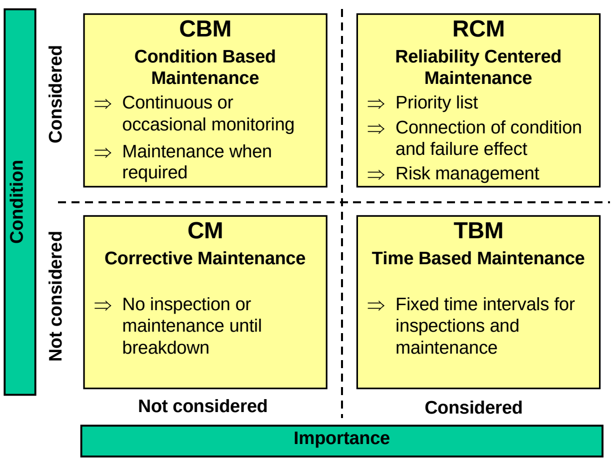

Fig. 2: Classification of maintenance strategies

The most simple maintenance strategy according to this classification is the so-called Corrective Maintenance. In fact, there is no preventive maintenance at all in this strategy – the component is operated until it fails. Then it is decided whether the component can be repaired or whether it must be replaced. In general, this strategy is not the maintenance strategy causing the lowest total cost, as the damages caused by the failures of the components may create more cost in the end than a different and more appropriate maintenance strategy. Besides, this strategy of course significantly derogates supply reliability, which may cause additional economic consequences for the network operator. It is suitable if the regarded equipment is non-critical and consequences of the failure aren't serious. In distribution networks this method is widely used for MV-XLPE cables, where no preventive maintenance measures are available, and usually at the low-voltage level.

So, preventive maintenance is required in order to prevent failures and significant damage or even destruction of equipment. The easiest way, and the strategy most widely used today, is the so-called Time Based Maintenance. There are fixed time intervals for inspections and for certain maintenance works. These time intervals are either given by the manufacturers of the equipment or they are based on the experience of the network operator. However, it seems that the time intervals chosen in the past were far on the safe side, as there are many inspections revealing no problems at all. So, the time intervals obviously could be extended – the question is from which point on the occurrence of failures will increase significantly. This method is often appropriate for those instances where an abrasive, erosive or corrosive wear out takes place and/or material properties change due to fatigue etc. This strategy was widely used in maintenance of HV- and MV-grids in the past. Depending on the length of the intervals it combines an acceptable availability with comparably high maintenance costs.

In order to be able to determine the condition of the equipment, additional information on the current condition of the component is required. This current condition is described by certain indices, and in the concept of Condition Based Maintenance, maintenance activity is triggered by the estimated condition reaching certain thresholds. Of course, the determination of the component condition is not trivial, and several methods are described in the following chapters. Condition based maintenance leads to high availability with moderate maintenance costs and is mainly in use within EHV and HV-grids [2]. Nowadays a lot of utilities try to adopt this approach also for the medium voltage level.

In practice, the limitation of both financial and logistical means requires the additional definition of priorities. And especially in competitive markets, the effectiveness of any activity is watched with special interest. These aspects relate to the importance of the network components. Of course, the importance should be defined as objective as possible. As supply reliability in distribution is a technical key characteristic and as it can be calculated and quantified by a set of well-defined indices [3] the usage of probabilistic reliability calculation as presented in chapter 5, it is a favorable solution to relate the importance to supply reliability. In EHV-grids, focus in importance evaluation is on system integrity, scheduling of power stations and the prevention of bottlenecks in transmission capacity. So, the Reliability Centered Maintenance does not only consider the condition of the system components, but also takes into account the impact on the performance of the system [2,4,5].

RCM is not only evaluating the priorities for maintenance actions but is also a powerful tool for the ranking of replacement and refurbishment activities, because bad equipment conditions lead immediately to the question whether it is more economical to do further maintenance or replace the equipment. This analysis can be done for the single equipment as well as for complete substations in transmission where a combination of the conditions of the different parts (concrete and steel, primary and secondary equipment) is regarded [6,7].
If the economical consequences (penalties, kWh not supplied, change of merit order) of different actions are taken also into consideration the RCM approach is extended to the so called Risk Based Maintenance.

3 DETERMINATION OF COMPONENT CONDITION

There are several basic possibilities on how to acquire information on the actual condition of network components. These possibilities differ significantly in the amount and type of information that is delivered, and of course in the effort required to gather the information. It is common to all methods that it is not possible to measure an index directly expressing the remaining time to failure. So, the derived statement on the component condition is subject to certain approximations and statistical aspects, which imply a certain risk.

The best method from the technical point of view is the on-line monitoring of condition-related indices of the components, e.g. coil temperatures or parameters describing the oil quality of transformers, or the SF_6-pressure in a gas-insulated circuit breaker. The evident drawback of this method is that it requires a very high effort, both relating to financial aspects as well as relating to the handling of the gathered information. Due to their high costs most of the power or generator transformers are equipped with monitoring systems. Nowadays also more and more new substations (mainly GIS) are equipped with condition monitoring devices based on modern digital technologies like sensors and actuators in the drives.

Another possibility is to perform off-line measurements delivering statements on condition-related aspects, e.g. partial-discharge-measurements on cables in order to determine the quality of the insulation, or special measurements in order to determine the loss of contact material of circuit breaker contact elements. Such measurements also require a high effort, additionally it is required that the components under consideration are taken out of service for the actual measurement. Comprehensive and practical examples on applications for power and generator transformers are given in chapter 6.

As these two methods are comparatively expensive, more or less broad application is practicable only in EHV- or HV-networks. Here, the limited number of components – compared to MV-networks – the high value of an individual component and the possible severe consequences of system failures justify the high effort [8,9].

One way to reduce the effort in condition evaluation is the usage of operational stresses, like e.g. voltages, currents and power flows, as these values are measured on several components throughout the system. In order to link these parameters to maintenance specific aspects, physical models on the impact of operational stresses and ageing are required. For example, the life-time-usage of a transformer can be modeled using the actual power flows, and for a circuit breaker it may be oriented at the sum of the actually switched-off short-circuit currents $I_k^{''}$. Of course, the meaning and the accuracy of these derived maintenance-related indices strongly depend on the physical models available. At present, such models typically are very rough, if available at all. One reason for this weakness is, that the models strongly depend on the construction details of the various types of equipment.

Finally, statistical methods can also provide information on the condition of system components. The basis of this approach is the systematic collection of any data related to component condition, e.g. maintenance or failure reports. The information is categorized and assigned to certain component types [10]. The level of detail in the categorization and in the definition of component types is a compromise between the resulting level of detail of the results on the one side and the availability of data and effort for the data collection on the other side. Also, the quality of results provided by statistical methods improves with the number of incidents taken into consideration, so there should be a certain number of devices in each component type. Due to the high number of components installed in distribution networks, the statistical method is the only solution practicable for a widespread application in these networks.

Regarding single equipments in MV-networks assumptions of the equipment condition can also be derived from inspection and maintenance protocols. Very important is also the operational experience of the utility personnel. There are methods available [2,4] based on only very little information to estimate the condition of accessible equipment in MV networks.

Nationwide fault statistics are mandatory and do exist in a lot of countries to survey the component availability and the reliability of the electrical grid [11]. What could be found is data based on the maintenance practices of the past and very often not detailed enough to analyse the real causes of equipment failures. Chapter 5 explains in detail a comprehensive approach to overcome these weaknesses in a German research project.

4 ASSET SIMULATION

4.1 Basic theory

Asset simulation is an approach to predict the long term monetary consequences of maintenance and renewal strategies for electrical grids [12]. It can me modelled by the use of system dynamics [13,14]. The system dynamics approach has also shown its strength in other fields, where cause and effect can be described well while the availability of data is rather poor [15,16,17]. It is a modelling approach that enables building of a formal representation of a dynamic behaviour of a business system, where the behaviour of the system is a direct result of casual relationships between different elements of the system. The effects of causal relationships are based on assumptions and decision rules, which are then formalized by using mathematical equations. Fundamental to system dynamics is the idea that all dynamic behaviour is a consequence of the structure of the system, where the structure refers to how the elements of the system are put together. Unlike the linear flow of spreadsheet models, system dynamics focuses on interrelationships rather than linear cause and effect and sees change as a process rather than a series of snapshots. It operates with feedback loops. The system is made up of these feedback structures, which reflect the actions of one factor on the other. This allows the user to model highly complex systems with relative ease [1,18].

4.2 Simulation approach

Since the grid is basically a number of ageing assets which are being inspected, maintained, refurbished and renewed, the model has to describe the asset ageing process (Figure 3). Additionally the strategies of doing something to the asset have to be described as a set of rules like "if the asset is >x years old and not renewed, then y will happen” [19,20]. Also the costs and resources needed for these actions have to be calculated. Last but not least, the age distribution and a failure distribution of the assets are needed.

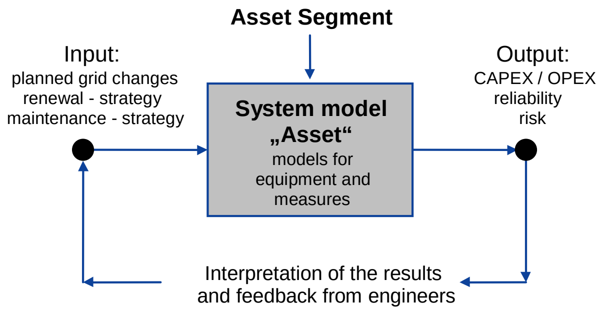

Fig. 3: The link between strategy and costs

4.3 Data and models

The most crucial part of the simulation is the asset model. This model describes the ageing of the assets and the actions which can be done to the assets to prevent them from reliability degradation. A deep discussion on probabilistic and deterministic ageing models can be found in [20]. Figure 4 shows a very simple ageing model which can be used to get first suitable results.

This model describes an asset with three different states: reliable, degenerated and unpredictable. For each of the states different calculations for e.g. strategic maintenance, renewal decisions and failure rates are made. The principle is that, during its life time, an asset will pass through each state and spend a certain amount of time in each state. Work done by maintenance and refurbishment will slow down the rate at which an asset moves from one state to the next. Eventually an asset moves out of the system by being replaced. In each state an asset will have a different level of performance.

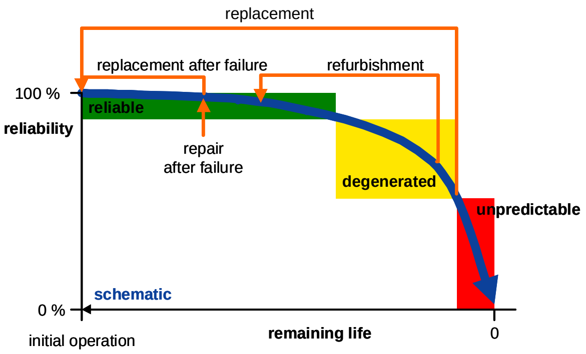

Fig. 4: Simple ageing model for asset simulation

Such models are being implemented in dynamic system simulation methods. Tools implementing such methods are available in the market (e.g. Powersim, Anylogic, iThink, SD-Library). A common visualization of the model in those tools is shown in Fig. 5. The states an equipment is in like reliable, degenerated und unpredictable are modelled either as conveyers or stocks (conveyers preserve a first in first out order, stocks don't). The transfers between these conveyers or stocks are modelled as flows which are controlled by the valves (eg. ageing, replacement after failure,…). As shown in the example conveyers know two different kinds of outflows. One of them represents the time an asset needs to go through the conveyer (used for ageing). The other one represents a leakage which occurs independent from the asset age (used e.g. to model replacement after failure or refurbishment during the degenerated state).

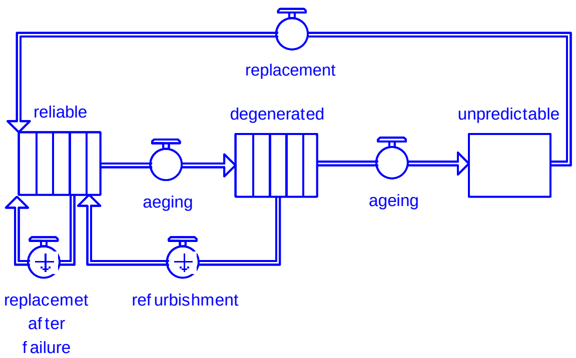

Fig. 5: Simple ageing model for asset simulation

In the example an asset starts its life at the beginning of the "reliable" conveyer pass through the state degenerated and will end up in the stock of unpredictable assets. The outflows of the conveyers and stocks are parameterised by use of statistical data for asset life time and failure statistics.

4.4 *Uncertainties due to the stochastic process*

Since the "flows" in the model which represent the ageing process are parameterised by use of statistical data the approach is suitable for modelling the system behaviour but inaccurate with respect to individual equipments. Also only those effects are parameterised with highly accurate figures which rely on incidents or actions which happen quite often. Parameters for incidents which are very rare will be of poor quality and results of simulations have to be verified to see if they are more or less independent from those parameters or not. In practise this theoretical problem should not influence the quality of the results much since the actual processes are dominated by the more frequent procedures.

4.5 *Inaccuracies due to model and data deficiencies*

Obviously the approach can only be as good as the underlying models are. The task here is to find a balance between theoretical model accuracy and data availability to parameterise the model. Especially the knowledge of the state where the assets are in the asset chain of the model might not be available, if no maintenance strategies which rely on the knowledge of the condition of the assets are currently used in the utility. Using the age of the assets instead might lead to the problem, that the asset age databases only provide the time when there were financial investments but not the information what exactly was replaced. Additionally e.g. failure rates have to be provided for all the states within the asset model. So here it is also necessary to verify if an additional state which might be necessary to explain a special effect can really be parameterised with the available data. But since the decisions for e.g. renewal are being taken in the utilities in the processes today, for a start it is definitely good enough to find out how those decisions are taken today and then to model them exactly like that. Doing this the model will reproduce the decisions like they would be taken in practice and that is what asset simulation is all about.

4.6 *Sensitivity analysis*

For scenario analysis and assessment detailed and sensitive data regarding the current asset portfolio are necessary. In addition to asset data specific information regarding expenditures, quality of supply, risk etc. have to be provided. The availability of such data has already been discussed in chapter 3. Gaps regarding data availability and quality have to be systematically identified and closed by specific measures. Sensitivity analysis on those specific parameters by use of the model can help to identify where improved data quality has a great impact on the results and so efforts can be focused on important data.

Provided the ageing models and the model parameters are accurate enough, the results can be used to compare different asset management strategies. For example, the analysis of different scenarios for asset investment planning provides a transparent and reproducible basis for the quality of a strategy and the costs resulting from it. It also gives insight in the way the long term costs of a network can be influenced by strategic investments in the grid. The approach also has the capability to identify and explore the risks associated with different strategies and how these risks can be minimized.

5 ASSET MANAGEMENT IN DISTRIBUTION NETWORKS

5.1 Introduction

As discussed in chapter 3, the high number of components in distribution networks gives advantages to statistical asset management approaches. Not the individual components, but component classes are considered in the corresponding methods. The level of detail in the definition of component classes depends on different aspects, a major aspect being the availability of suitable data.

Different statistical approaches vary in their level of complexity and the focus of the analysis. The range is from practice-proven methods aiming at preventing the deterioration of components beyond certain levels to comprehensive approaches considering failure and ageing models of the components, which are currently developed by many different institutions worldwide. The following sections give short examples on asset management processes currently in operation or under development, respectively, in Germany.

5.2 Statistical Fault Analysis

A practice-proven statistical asset management method is the so-called "surveyed" break-down strategy [21]. It consists of a comprehensive fault and damage analysis which is realised by the use of a fault and damage database in conjunction with SCADA, ERP-software and a geographical information system (GIS). Figure 6 schematically shows the surveillance of disconnectors.

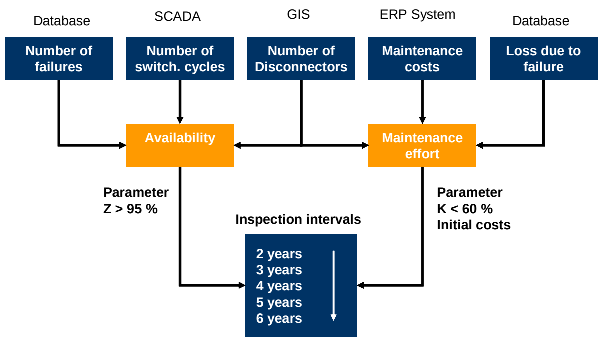

Fig 6: Surveyed break down strategy

In this example the number of failures of all disconnectors is compared with the number of switching cycles and the number of all disconnectors. Thus, the availability for a given time period in the near past can be calculated. It is compared against threshold "Z", in this example it should be better than e.g. 95 % - which is the probability for a successful disconnector operation.

Furthermore, the maintenance effort is calculated and compared with a second parameter "K" which in this example should be below 60% of the initial maintenance costs (based on time-based overhaul).

If one of the limits is exceeded, a trigger informs the asset manager about a worsening of the equipment condition. The detailed fault and maintenance histories enable the asset manager now to detect if the failures are caused by material or other problems or are due to a lack of maintenance. This can lead to a variation of the maintenance strategy as well as to selective maintenance actions for an individual equipment type.

5.3 Comprehensive statistical asset management approach

A comprehensive asset management approach of course has to consider the life cycle costs of the equipment and of the system in total. But it should also consider the quality of supply that is delivered by the system, as the dependency between costs and quality is obvious and of high relevance in recent discussions. In the end, asset management has to support the delicate balancing of costs versus quality according to the given requirements and regulations.

The principle of a comprehensive, risk-based asset management approach for distribution networks using a statistical description of the network equipment is shown in the schematic diagram in figure 7 [22].

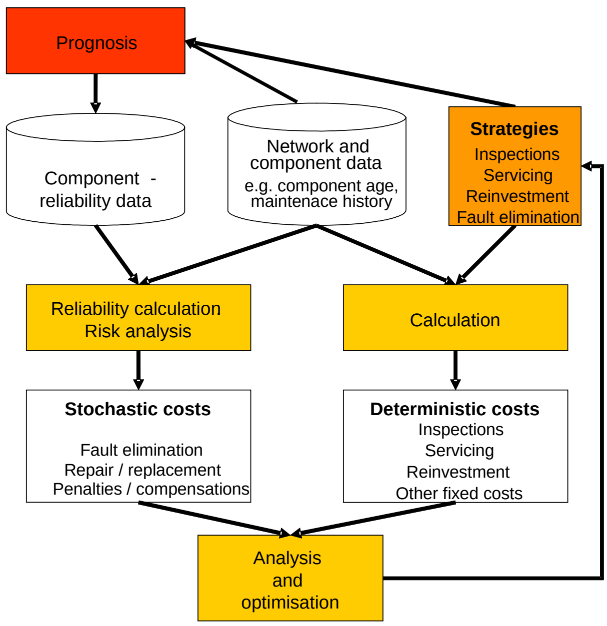

Fig. 7: Principle of a comprehensive asset management approach [22]

An important part of this approach is the calculation of relevant costs – which is typically much easier than the quantification of supply quality. Here, deterministic and stochastic costs are differentiated.

Deterministic costs are determined by the chosen strategies for inspections, servicing, reinvestment and fault elimination. Also these deterministic costs cannot be predicted exactly, but compared to the cost aspects described as stochastic costs, the uncertainties are on a far lower level. Other fixed costs, e.g. capital costs, are included in this group, too.

Stochastic costs are depending on the occurrences of damage and disturbance events on the components in the network – which are governed by chance. Thus, these costs – including costs for fault clearance, costs for repair or replacement of damaged equipment, and costs for penalties or compensations (if applicable) – can only be calculated stochastically. Typically, these costs are subject to distributions with large dispersions.

While the assessment of deterministic costs is a straightforward task based on the chosen strategies for maintenance, reinvestment and fault elimination, the stochastic costs are based on the results of a probabilistic reliability calculation of the network. This calculation requires – next to usual network and component data – a description of the failure occurrences of the components. This description is given by so-called component reliability data.

The calculation methods required for this asset management approach are all readily available today – including probabilistic reliability calculations [23]. However, certain aspects of this approach typically cause problems in practical application:

- Meaningful statistics about the distribution of the costs caused by damages of network components, e.g. repair costs, are not available. Up to now, only rough estimated values can be assumed.
- Component reliability data can be determined for networks in their current state by suitable statistics. But changes in the asset management strategies – e.g. reduced maintenance, reduced reinvestment leading to increased component age, or staff reductions increasing the duration for fault elimination – of course will have effects on component reliability. As the parameters of these asset management strategies are to be optimized in this process, such effects have to be considered appropriately by models for the prognosis of component reliabilitiy.

The level of detail of the implemented models for the prognosis of the component reliability is a key characteristic of the different methods following this basic approach. Especially concerning XLPE cables affected by water tree problems, sophisticated models and suitable input data were developed already (e.g. [7,24]).

However, for the prognosis of component reliability in dependency of these parameters – which is a crucial step for asset management methods – typically only very rudimental models and scarce data are available.

As an example, one research project trying to contribute to this field is presented in the next section.

5.4 Research project on asset management in distribution systems

This knowledge gap in the modelling of component reliability in dependency of characteristic influence factors has been the motivation to initiate a research project carried out by more than 20 network operators, academic institutions and service providers in Germany. The project is sponsored by the German Federation of Industrial Cooperative Research Associations "Otto von Guericke" (Arbeitsgemeinschaft industrieller Forschungsvereinigungen AiF) with funds of the Ministry of Economics and Labour (Bundesministerium für Wirtschaft und Arbeit BMWA) as well as by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG).

The main goal of this project is to collect information on component damages and outages in a specially designed statistic. This database then allows not only the determination of component reliability indices, but in particular the analysis of the influences of component age and maintenance history. These results allow the definition and – even more important for practical application – also the parameterization of suitable models to predict component reliability depending on the chosen asset management strategies.

Additionally, also the costs that are caused by damage occurrences on components are not available in systematic statistics up to now. The specially designed statistic in this research project also includes information on such costs, so that damage costs and their statistical dispersion can be delivered.

As an example, figure 8 shows the age related outage rate for low-oil-content circuit breakers in medium voltage substations. Note that this diagram is based on a preliminary data set, as the data collection was not completed yet. In the diagram, a very clear dependency of the outage rate on the component age can be seen.

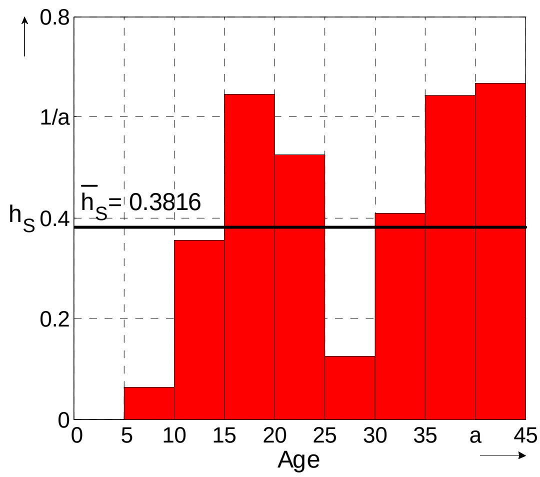

Fig. 8: Medium voltage stations, low-oil-content Circuit Breaker, outage rate f_O depending on component age

6 ASSET MANAGEMENT IN TRANSMISSION SYSTEMS – EXAMPLE: TRANSFORMER LIFE MANAGEMENT

6.1 Objectives of life management processes

As explained in the precedent chapter distribution asset management can be approached from a statistical or stochastical point of view. In transmission grids, where the single equipment is much more expensive, an individual observation is required.

In the following life management for transformers will be discussed as an example. In principle, similar models can be developed also for other equipment types. E.g. for HV circuit breakers, several failure modes for subsystems of the circuit breaker were evaluated in a research project [25].

A reasonable asset management of transformers has to include life management ensuring long-term utilisation and exploitation of the assets. Regarding the high reinvestment costs, the long manufacturing time and the capacities of the transformer manufacturers a long-term planning is necessary.

The objective of the life management process is the optimal utilisation of the remaining life time regarding a definite reliability and a constant distribution of costs for reinvestment and maintenance.

6.2 Ageing behaviour of transformers

When discussing the ageing behaviour of transformers, it is useful to subdivide the transformer in its main components. In this contribution only the ageing behaviour of the active part, the components bushings and the tap changer will be described. Presuming a good maintenance the ageing of the other components like vessel, cooling system, etc. can be neglected, because the ageing of these parts is not dominant or they can be exchanged or repaired in the substation if necessary.

6.2.1 Active part

The ageing of the active part mainly depends on the loading of the transformer. The thermal stress reduces the mechanical strength of the cellulose insulation, a weak cellulose insulation can cause an internal fault due to transient current stress. The strength of the cellulose insulation can be determined with DP measurement (degree of de-polymerisation). A new cellulose insulation has DP > 1000, cellulose insulation with insufficient mechanical strength has DP < 200. Unfortunately DP measurement can only be performed during a workshop investigation or when the transformer is scrapped. The design of the insulation system, the cooling method and the specification (power) of the cooling system affect the ageing gradient. The distribution of measured DP values in figure 9 demonstrates that the technical life time of generator transformers (GSU) is limited to 25 years whereas transmission transformers can reach a technical life time up to 50 years.

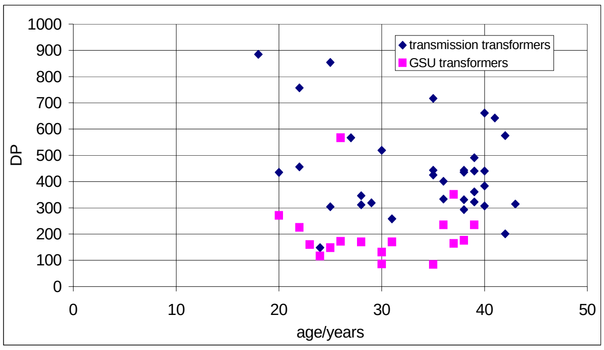

Fig. 9: Ageing behaviour of cellulose insulation of power transformers

The technical life time of insulating oil is influenced by the loading condition of the transformer and the ageing stability. Using high quality mineral oil with extended ageing stability the technical life time of the insulating oil is similar to technical lifetime of the active part.

6.2.2 Condenser bushings

The condition of condenser bushings can be determined by measurement of capacitance and dissipation factor tan δ. An evaluation of the measurement results shows that ageing is only observed at resin bonded paper bushings (Fig. 10). The ageing of these bushings is caused by cracking of the resin bonded paper and inhomogeneous impregnation with insulating oil. The technical life time has a great scatter and should not exceed more than 30 years.

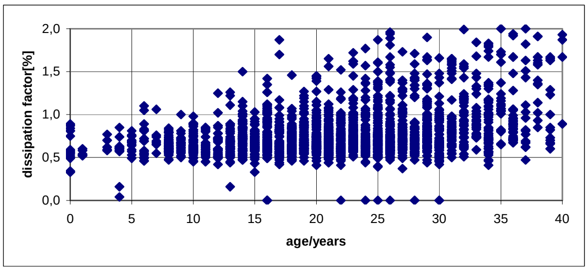

Fig. 10: Ageing behaviour of resin bonded paper bushings

6.2.3 On load tap changer

The ageing of the on load tap changer (OLTC) depends on the number of switching operations and the cumulated switching current. Expecting a good maintenance the technical life time of an OLTC is nearly unlimited, because the condition of OLTC is determined during a diverter switch inspection and wearing parts such as switching contacts and insulating oil are exchanged if necessary. However there is a risk of oil cooking if the tap selector contacts are not silver-plated.

6.3 Diagnosis strategy

A reasonable life management has to be supported by a stepwise diagnosis strategy (Fig. 11). There are some routine tests for condition assessment of the active part, the insulating oil, the bushings and the tap changer. In case of an indication or for extended condition assessment several additional diagnosis methods are used. During repair in a workshop or when the transformer is scrapped a visual inspection is done and paper samples from the windings are taken to perform DP measurements.

component	diagnosis method	online	offline	off site	remark
active part	oil ageing	x			routine
	DGA	x			routine
	resistance measurement		x		after indication (DGA)
	PD measurement		x		after indication (DGA)
	imdepance measurement		x		after short circuit
	FRA		x		after short circuit
	PDC measurement		x		condition assessment
	furfurol measurement	x			condition assessment
	DP measurement			x	condition assessment
bushing	capacitance / tan δ measurement		x		routine
	DGA		x		condition assessment
	PD measurement			x	condition assessment
tap changer	diverter switch inspection		x		routine
	torque measurement		x		condition assessment

Fig. 11:Stepwise diagnosis strategy

The dissolved gas analysis (DGA) is the most important diagnosis method to assess the condition of the active part of a transformer. For an optimal interpretation of DGA the consideration of gas development rate and the comparison of the measured gas values with normal values is necessary [26]. By an additional expert system the DGA is transformed into a three stage warning level (normal, first warning, urgent warning). The expert system also provides a condition based oil sampling.

The measurement of furanic components in the insulating oil is used to get information about the degradation of the cellulose insulation [27]. The interpretation of measurement results depends on oil treatment and cooling method.

The capacitance and tan δ measurement of bushings and the diverter switch inspection are fundamental to ensure the integrity of bushings and tap changer. A failure of a bushing can cause a collateral damage, the breakdown of the diverter switch can destroy the regulating winding of the transformer.

Visual inspection and analysis of paper samples are the only tools to get a feed-back of the true condition of the transformer compared to the results of condition assessment gained by the different diagnosis methods. The analysis of the paper samples shows that most of the scrapped generator transformers had a cellulose insulation with insufficient mechanical strength. The visual inspection confirms that the failures of some transformers are caused by insufficient mechanical strength of the cellulose insulation. The typical breakdown mechanism starts with an interturn fault in the low voltage winding near the location of the hotspot. The interturn fault causes a fault current that deforms the low voltage winding. From the deformed winding arcing causes tripping of the Buchholz relay.

6.4 Life time extension methods

Life time extension procedures without any condition assessment cannot technically be justified. In case of an indication a refurbishment in the substation may be arranged as a first step in order to avoid cost for transportation and to minimise the outage time. The following procedures are established:

- Oil treatment / oil exchange
- Replacement of bushings
- Exchange of tap changer contacts
- Drying of active part

On-site refurbishment procedures need an exact inspection. The fault has to be identified and located. Furthermore the fault location must be accessible. At least the success of the refurbishment procedure has to be proved [28]. Before carrying out refurbishment procedures chances and risks have to be judged. In case of any doubt a workshop refurbishment or repair has to be preferred.

6.5 Strategic actions

A continuous assessment and evaluation of transformer condition is the most important action for life management. A special assessment scheme and ranking tool based on condition and importance can be implemented. By means of the ranking tool forecasts of the replacement of transformers can be done [29].

Another strategic aspect is the availability of a sufficient amount of spare transformers and bushings. Spare transformers and bushings minimise the consequences of a failure and can reduce the outage time considerably. Especially spare generator transformers are very valuable. However the optimal use of spare transformers and bushings requires a wide standardisation. Moreover, condition based diagnostic and maintenance can minimise the risk of a sudden failure of a transformer.

In case of failure, detected during refurbishment procedures or when a transformer is scrapped, a consequent inspection is necessary. The inspection of a transformer is very valuable to collect experience and can show hidden weak points of a transformer design and construction. Furthermore, it is the only method to verify the empirical assumptions of the condition assessment scheme.

At least, a main issue of transformer life management is to elaborate a renovation strategy and corresponding programs for replacement as far as necessary. Furthermore, the final demand analysis has to include the future demand of transformers due to further network development as well as possible unused transformers which have become available due to reconstruction measures.

7 OUTLOOK

The actual challenge of asset managers is very often not on the methodical side but lies on the IT side to support asset management decisions. Commercial data can be found in ERP systems, but very often it is just subdivided in a few groups, e.g. voltage levels and not related to the single equipment or substation. Also internal costs for operation and maintenance are collected and are not related to the equipments in the system. Geographical data can be found in GIS system, whereas maintenance related data and reports are often stored in separate technical data bases. There are additional tools for the evaluation of maintenance strategies, network calculation, on-line condition data analysis, etc. There is definitely a need for integrated IT systems and decision tools and a lot of utilities are working on their IT landscape mostly in combination with work management systems to execute the task of the asset management.

Besides the IT support a second challenge is the need for better knowledge on equipment deterioration and the corresponding models, especially in distribution systems. Ideally, these models should provide estimates on equipment failure probabilities based on input data of equipment age, operational stresses and maintenance activities in the past. These models are needed urgently in order to make the results of asset simulation approaches reliable. The shown German research project is an example for a first step in this direction, however extensive further research is necessary.

Very often asset mangers face the question of budgets in correlation with supply quality. To answer this and to get a better feeling about reserves in the networks new tools like asset simulation and RCM for the prioritisation of measures and the definition of budgets are an important step. This is mandatory in the utilities to get the needed resources and budgets for the networks in a competitive environment.

8 REFERENCES

[1] Wenzler, Ivo: Development of an asset management strategy for a network utility company: Lessons from a dynamic business simulation approach; SIMULATION & GAMING, Vol. 36 No. 1, March 2005 75-90

[2] Vetter, F., Mühle, J. "Das anlagenbezogene Risikomanagement in der Instandhaltungsplanung der E.DIS AG", EVU Betriebspraxis 10/2002, page 24 ff.

[3] International Electrotechnical Commission, IEC 60050-191 – International Electrotechnical Vocabulary. Chapter 191: “Dependability and Quality of Service”, Geneva, 1990

[4] Schmitt, O., Schneider, A. "Moderne Werkzeuge zum integrierten Asset- und Instandhaltungsmanagement" International ETG- Congress “Energietechnik für die Zukunft”, 23.-24. Oktober 2001, Nürnberg

[5] Hogräfer, J.: "Von der Erfassung zur Entscheidung: Einsatz von Expertensystemen zur Bewertung der Ergebnisse aus der Betriebsmitteldiagnostik", ETG-Fachbericht 87, page 157–160

[6] Breitling, Lina; Allan, Ron; Eriksson, Roland: A reliability-centred asset maintenance method for assessing the impact of maintenance in power distribution systems, IEEE Transactions paper submitted 030511 revised 031210, 040324 and 040629, accepted 040716

[7] Bertling, Lina: Reliability Centred Maintenance For Electric Power Distribution Systems, Doctoral Dissertation, Stockholm 2002

[8] Neumann, C., Sundermann, U., "Assetmanagement im Hochspannungsnetz – Transformatoren und Schaltgeräte", FGH Symposium Versorgungs- & Anlagenqualität, Heidelberg, September/October 2004

[9] McIlroy, C., Cunningham, M., "Transfix - ein neues Online DGA-System zur Transformatorüberwachung", ew 103/26, 2004, page 30-35.

[10] Stötzel, M.; Wellssow, W.H.; Zdrallek, M.: Reliability Calculation of MV-Distribution Networks with Regard to Ageing in XLPE-Insulated Cables. IEE Transactions Generation Transmission Distribution 148 (2001) Number 6, 597-602

[11] Obergünner, M., Schwan, M., Krane, C., Pietsch, K., von Sengbusch, K., Bock, C., Quadflieg, D., "Using the VDN Statistic on Incidents to Derive Component Reliability Data for Probabilistic Reliability Analyses ", Elektrizitätswirtschaft, Juli 2004, Vol. 15

[12] J. Nilges, A. J. Gaul, H. Spitzer, 2004, "Strategische Investitionsplanung - Praxisnahe Wege für eine nachhaltige Bewirtschaftung der Assets", Energiewirtschaftliche Tagesfragen et 54. Jg. Heft 10, 655-656. (German language)

[13] Forrester, J. W.: Industrial Dynamics, Cambridge, MA, 1961

[14] R. Thurlby; C. MacQueen, 1999, "Managing the Asset Time Bomb", Proceedings of the DADSM Conference in Spain.

[15] Vannan, Mani; Glass-Husain, Will: Managing Gas Assets through Simulation and Scenario Planning; International System Dynamics Conference Wellington, New Zealand, 1999

[16] Kenward, Michael: System Dynamics: A ‘simulating’ idea widens Managers Horizons, Financial Times, 7. 1.1998

[17] Lander, Sandra: Strategische Planung von Kreislaufwirtschaftsystemen, Strategic Planning of Recycling Management Systems, Dissertation TU Berlin 2004

[18] Moeller, A.: Continuous Simulation in Material Flow Networks, International Environmental Modelling and Software Society iEMSs 2004 International Conference

[19] Stürmer J., Instandhaltungs- und Erneuerungsstrategien in Verteileilungsnetzen, 2002 Shaker Verlag, Aachen, Germany. (German language)

[20] Endrenyi, J.: IMPACT OF MAINTENANCE STRATEGY ON RELIABILITY, Final report by the IEEE/PES Task Force on Impact of Maintenance Strategy on Reliability of the Reliability, Risk and Probability Applications Subcommittee, July 1999

[21] Giese, H.-P., Hogräfer, J., "Einführung des automatisierten Netzbetriebs bei der enviaM", etz 2002, vol. 23-24, page 14 ff.

[22] Schwan, M.; Weck, K.-H.; Roth, M.: "Assessing the Impact of Maintenance Strategies on Supply Reliability in Asset Management Methods", 40th CIGRE session, paper C1-108, August 2004

[23] Singh, C.; Schwan, M.; Wellssow, W.H.: Reliability in Liberalized Electric Power Markets- From Analysis to Risk Management -Survey Paper. 14th Power System Computation Conference PSCC (2002), Sevilla.

[24] M. Böhme, I. Krage, K.-H. Weck: Instandhaltung von Mittelspannungskabelanlagen. ETG-Fachtagung Verteilungsnetze im liberalisierten Markt (ETG-Fachbericht 82), 2000, p. 157-167

[25] FGH: Zustandsmodell für die Instandhaltungsplanung für einen 123-kV-Leistungsschalter. Technischer Bericht 295, FGH e.V., 2001

[26] Möllmann, A., DePablo, A.: New Guidelines for furans analysis as well as dissolved gas analysis in oil-filled transformers, CIGRE 15/21/33-19,1996.

[27] Möllmann, A., Pahlavanpour, B.: New guidelines for interpretation of dissolved gas analysis in oil-filled transformers, Electra No. 186, October 1999.

[28] C. Neumann, K. Feser, C.-G. Henningsen, H. Pein, H. Röhsler, K.-H. Weck : The German practice of on-site tests and measurements on GIS, transformers and cables at commissioning and in service. CIGRE 33-305, 2002, Paris.

[29] Petterson, L., Fantana, N., Sundermann, U.: Life assessment: Ranking of power transformers using condition based evaluation. A new approach; CIGRE 12-204, 1998, Paris.