Condition Assessment of Electric Machines

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Abstract — The rules of the electric energy market in Europe changed in the last years due to the liberalization tendency. Local supply monopoles disappeared and the structure of the electric utilities changed fundamentally. The companies were split up into areas of energy production, transmission and distribution. Each of these companies has to operate for itself in an economic successful way. For being economic and technical competitive in this surrounding field it appears useful to compare the efficiency of the own resources and to optimize the maintenance, operation and investment strategy. Different new management tools for risk and asset management were developed and applied successful. The condition assessment should ensure a save operation, high availability and low maintenance costs.

Index Terms — Condition Evaluation, Maintenance Strategy, Risk Analysis

I. Introduction

For a reliable operation of an electric power grid the technical condition of the equipment is a very important factor. International statistics have shown that the insulation systems have a high fault liability. The liberalization of the electric energy market accommodates that beside technical aspects also others gain in importance. Economical and juridical subjects have to be considered more increased. For this reason the maintenance strategies changed. For expensive power equipment the time dependant maintenance is replaced by condition based. The condition based maintenance requires diagnostic measurements on the one hand and on the other hand operational and machine dates have to be taken into account. Most monitoring systems concentrate on electrical, mechanical, thermal or chemical quantities. The electrical diagnosis concentrates on the measurement and evaluation of partial discharges, dissipation factor, tip-up test, dielectric strength, insulation resistance, polarization and depolarization current. To evaluate the operational dates the operating hours, the capacity utilization as well as the number of starts for pumping machines has to be taken into account. To assess the machine dates the relevant information were the age, the production technology and the design of the insulation system. For condition assessment all these factors have to be weighed.

The risk of outages can be minimized by evaluating and weighing the relevant information about the condition and planning the inspection, overhauling and repair of the machines. The decision on continue in operation, overhauling the machine or of a replacement often can not be done only with technical assessment. Beside the technical facts others have to be taken into account. It has to be distinguished between the technical, the economical and the juridical risk. The technical risk can be defined by the risk that a component of the machine has a defect or a part is breaking. The economical risk depends on the range of application and which financial expenses have to be calculated in the case of a failure or standstill. And the juridical risk is the risk of liabilities due to public law and private law. Local authority regulations or obligations from contracts can demand restrictions to the machine operation. In the time of a liberalized energy market the economical and juridical risks gain in importance. For this reason these two components have to be considered in the condition assessment of electric machines stronger as any time before. Fig. 1 shows the systematic process to determine the condition and residual life time.

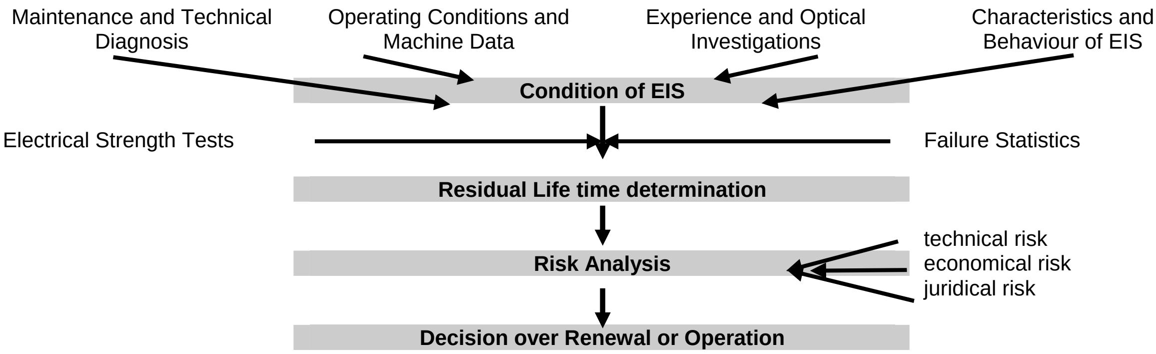

Fig. 1: Assessment of Condition and Residual Life Time

II. AGEING OF ELECTRICAL SYSTEMS

Taking a look to failure statistics the insulation system takes a very high percentage. The condition and reliability of electric insulation systems is marked by ageing mechanism. The common expression ageing is defined as the irreversible changes of the properties of an electric insulation system (EIS) due to action by one or more factors of influence [1]. Ageing stresses may cause either intrinsic or extrinsic ageing. Electric insulation systems are mostly predominated by extrinsic ageing because, in practice, they include some imperfections and contaminations. The ageing stresses can be divided into the so called TEAM stresses: Thermal, Electrical, Ambient (environmental) and Mechanical causes, which have an effect on the EIS. In dependence of the strength and their interaction the EIS is subjected to the ageing mechanism. These ageing mechanisms involve a decrease of the condition. A temporarily reduction of the condition is called degradation and a permanent deterioration.

In dependence of the type of stress different ageing models were developed. For electrical ageing physical effects of partial discharges, tracking, treeing electrolysis, dielectric losses or space charges are the cause of deterioration. For these processes one empirical relationship was found. The inverse power law is often used for the relation between electrical stress and life time. The life time is dependant on the electric field strength as a linear decreasing function in a double logarithmic scale. In a double linear scale it can be expressed as a potential function.

$$L \approx E^{-nt} \qquad (1)$$

L	… life time
E	… electrical field strength
t	… time
n	… exponent of the electrical life time

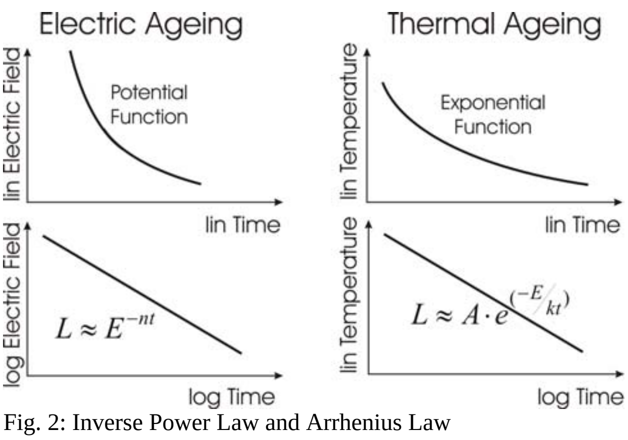

Fig. 2: Inverse Power Law and Arrhenius Law

Thermal ageing involves the progress of chemical and physical changes as a consequence of chemical degradation reaction, polymerization, depolymerization, diffusions or similar and thermomechanical effects caused by forces due to thermal expansions or contractions. The thermal ageing was described very early by Arrhenius as a chemical reaction. It can be interpreted that chemical processes in nature proceed in same percentages per constant time intervals.

$$L \approx A \cdot e^{(-E/kt)} \qquad (2)$$

L	… life time
A	… constant
E	… electrical field strength
k	… Boltzmann factor
t	… absolute temperature [K]

The other ageing mechanisms were also described with mathematical models but they will not be discussed now. In the figure 2 the electrical and thermal ageing models are illustrated in different scales. The inverse power law is a potential and the Arrhenius law an exponential function. For the application on life time models the single ageing models have to be completed with a threshold value. The reason can be found in a simple explanation. E.g. partial discharges disappear at the inception voltage; no electric ageing would occur under this level, the mathematical formulation of the inverse power law is limited to this threshold. Every mathematical description of the ageing behaviour does not meet the real behaviour exactly, a deviation of the life time values has to be taken into account in form of a tolerance band.

III. RESIDUAL LIFE TIME ESTIMATION

For the estimation of the residual life time the maximum expected life time has to be found out. The expected life time is a function of the operating conditions. In dependence of the average load level it can get shorter for higher load conditions. E.g. Montsinger found out that the average life time of a paper oil insulation system decreases for the half if the operating load occurs a temperature of 8 degrees over maximum level (8 K Formula). The so called technical life time mostly is defined by statistic methods with a database of empirical values of the bathtub curve. It is an average value of the fall out time of similar devices. The residual life time can be defined as the difference between the expected life time and the actual age. Figure 3 shows the connection of load and residual life time.

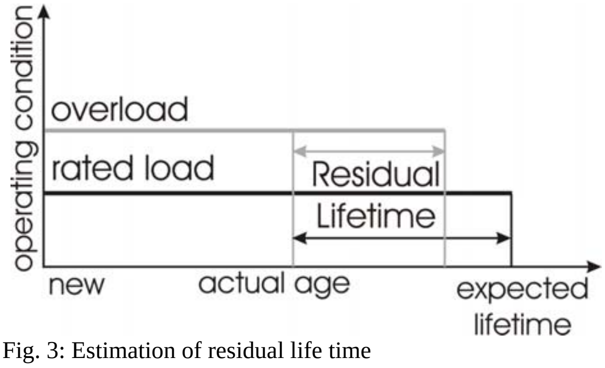

Fig. 3: Estimation of residual life time

The expected life time of the electric power equipment often has been discussed. The utilization duration of different components was collected from literature and statistics, an average of the expected life time is presented in the following table 1.

Table 1: Expected Life Time of Power Equipment

Component	**Life time years**	**Reference**
Overhead Lines		
Insulators	50-60	[2]
Conductor	50-70	[2]
Muff of Foundation	40-60	[2]
Coating of Pylon	15-25	[2]
Fittings	50-60	[2]
Spacer	20-30	[2]
Surge Arrester	35-40	[2]
Cables, paper-oil	30-60	[2]
Cable, PE insulated	10-30	[2]
Cable, XLPE insulated	30-40	[2]
Transformers	30-45	[3]
Generators	20-40	[3]

The determination of the residual life time respectively electric strength is often done in laboratory with voltage endurance tests. At such tests a higher load level is applied to accelerate the ageing mechanism. It is recommendable to do voltage endurance tests with a greater sample number to gain an expressiveness result. Statistical methods have to be applied to evaluate the test results and to calculate life time curves.

For electrical strength tests normally a two parametric Weibull distribution is applied. The statistical evaluation with this distribution shows the parameters characteristic life and shape factor. The characteristic life describes the calculated 63% quantile and the shape factor the gradient of the Weibull line. With these information forecasts of breakdowns can be done and adequate measures to prevent failures or long periods of standstill can be bend forward. Mostly failure statistics were used for the development of reliability models.

IV. MAINTENANCE

The maintenance strategy plays an important role on efficiency and dominates the life cycle costs. Doing maintenance aged or failure liable components were replaced and the condition of the network components increases. In figure 4 the schematic course of the condition is illustrated. During life time of network components the power equipment is exposed different kinds of load: electrical, thermal, mechanical of environmental. Stress causes a degradation of the condition (blue line in fig. 4) and accelerates the aging process. When the critical condition level (red line in fig. 4) is reached maintenance measures should be set to increase the condition and to allow a save and reliable operation with low risk of failures.

Maintenance can be interpreted as a kind of life time extension. In dependence of the way how maintenance is done different maintenance strategies can be distinguished. Often measures were done periodically (time based - TBM), dependant on the status (condition based - CBM) or failure oriented (incident based - IBM), also many other maintenance strategies were known.

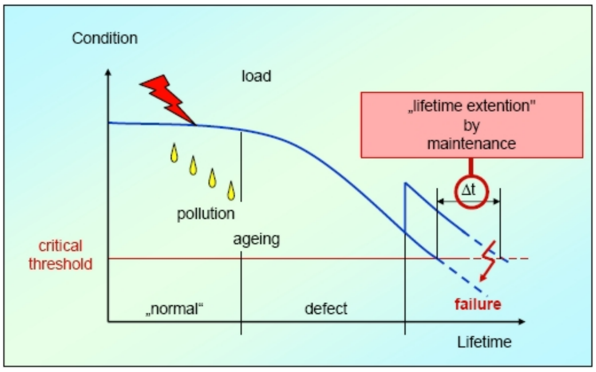

Fig. 4: Condition vs. Maintenance

In former times the TBM or IBM strategy were preferred by the utilities. Due to cost pressure in the liberalized market the strategies changed. CBM gets most effective for expensive power equipment, e.g. CBM is not useful for large distribution networks with medium or low voltage over head lines. The reason can be found in the differences of the cost structure. CBM demands a permanent monitoring of the component condition, which can be done by high personal expense on diagnostic measuring or monitoring methods. For the condition monitoring offline or online diagnostic tools have to be applied. Offline measurement methods afford higher personnel costs and online methods higher costs for monitoring systems. Intelligent online systems include an evaluation algorithm of the monitoring dates. Further the expenses and the scale of diagnostic measurements are responsible for the maintenance costs, modern diagnostic tools can be cost and service intensive.

V. Technical Diagnostics

As already mentioned the technical diagnostics plays an important role in maintenance and life time of power equipment. In dependence of the type of network different diagnostic measurements were done. Technical diagnostics is applied to watch the insulation condition or to locate possible weak spots. The main job is to detect these weak spots and to prevent of failures. The most important electric diagnostic tools were the dissipation factor measurement, partial discharge diagnostics and insulation resistance measurements.

Also other physical parameters were observed, e.g. electrical, mechanical or chemical parameters. The thermal behavior of power equipment often is watched with different kinds of sensors or the recently established thermo vision cameras based on infrared technology. Local hotspots can be detected and maintenance measures can be planned in time. The observation of the thermal behavior is often used to control the utilization of power equipment or to regulate the load flow in an electric network. The importance on the thermal utilization of power equipment and its observation stands out if we take a look back to the ageing mechanism, the higher the thermal load the faster the degradation of the condition goes on according to the law of Arrhenius.

As example of mechanical diagnostics the wedge tightness test for rotating machines should be mentioned. Magnetic forces tend to generate vibrations of the generator bars in the slots of the core with the doubled power frequency as well as twice the frequency of any other strong hamonics in the stator current. If the mechanical dimensions and the mass reach a ratio which favors the vibrations close to the mechanical resonance frequency, then it is likely that the end windings will vibrate no matter how well they are braced. This mechanism leads to groundwall insulation failures due to fatigue cracking or abrasion. One of the purposes of the wedge tightness test is to ensure that the end-windings do not have a natural vibration at single or twice power frequency.

Also an example for chemical analysis should be given: At power transformers the mineral oil has to be measured periodically. The most important chemical analysis methods were humidity (water) content, dissolved gase analysis, furanic compounds, number of particles, oxidation stability and oxidation inhibitor content and halogens. Beside these parameters the electric and dielectric values of breakdown voltage, power factor or permittivity were also measured. From the chemical analyses conclusions to the ageing condition can be derived. A high humidity percentage accelerates the decomposition of the transformer board and the degradation of transformer oil. A reduction of the breakdown voltage possibly is the consequence or the viscosity of the transformer oil results in a worsening of the cooling properties, thermal hot spots can emerge and result in a life time reduction of the transformer.

VI. Risk Analysis

As shown the mechanisms were linked very complex and the relations between single diagnostic parameters have to be evaluated very sophisticated. For a risk analysis the results from technical diagnostics and the life time estimation give the basis information. The reliability of power equipment is defined as one minus failure probability according to [4] and equation 3:

$$R(t) = 1 - F(t) \tag{3}$$

$$\Gamma(t) = F(t) \cdot H(t) \tag{4}$$

Risk in technical mind is defined as the product from failure probability timed by costs of damage according to equation 4. The risk is a time dependant quantity where the ageing structure of the equipment is a dominant factor. Also the resulting damage is a time dependant factor because the financial height of the failure increases with the moment and the duration of the damage.

VII. Conclusion

For the condition assessment of power equipment and electric networks the ageing mechanism and type of loads have to be considered and the results from technical diagnostics were needed to estimate the residual life time. In dependence of the utilization of the equipment the ageing process goes on and causes degradation of the insulation properties. With the right maintenance strategy the technical condition and inspection costs can be optimized and a long life time period will be reached. Using the distribution of the cumulative failure frequency statistical methods can be applied to calculate the reliability, the failure ratio or the risk of a failure.

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