Statistical Lifetime of Hydro Generators and Failure Analysis

C. Sumereder
Graz University of Technology.
Institute of High Voltage Engineering and System Management
Inffeldgasse 18, 8010 Graz, Austria

ABSTRACT

One of the most important questions for manufacturers and users of electric power equipment is the failure probability and the expected lifetime of the produced and installed equipment. This question cannot be answered easily because there are many different parameters that influence lifetime behavior. If a breakdown occurs, it has to be determined whether the machine can made operational again within the technical and economical framework or if it has to be completely or partially replaced. The technical decision concerning repair or replacement often results in electric diagnostic measurements, in which economic decisions determined by corporate policy play a large role. In this paper, the characteristics of typical insulation systems for hydro generators will be discussed and a failure statistics of each system will be calculated. The resulting lifetimes for these systems will then be evaluated with Weibull distributions.

Index Terms — **Dielectric Breakdown, Failure Analysis, Hydroelectric Generators, Risk Analysis, Statistics.**

1 INTRODUCTION

THE aim of this paper is to give a view of the procedure of failure statistics and lifetime analysis. The most important factor for reliable statistics is the quality of the data source and the interpretation of the given data. For this reason, it was not possible to trust failure statistics found on internet or in publications published by machine producers and users or conference papers, wherein an expensive literature review and a questionnaire the lifetime of 15 utilities of more than 400 generators were investigated [1]. Within this review the insulation systems of hydro generators are categorized into three groups and two production technologies. The collected dates were analyzed with two parametric Weibull distributions, each insulation system separately.

2 HISTORICAL DEVELOPMENT

The commonly-used electric insulation systems of hydro generators have greatly changed in the last 100 years. In the basic form of machine insulation systems that has been utilized for many years, mica placed on woven fiber glass fabric as carrier material is fixed with a binder. In the beginning of generator production, asphalt mica systems were used with low rate electric field strength. Later the asphalt systems were replaced by natural resins as shellac. The ratio of electric field strength rose over the years and along with construction experience. Today the current, state-of-the-art insulation systems are made from an epoxy resin [2]. Figure 1 should give an impression of the development of the construction and progress in dimension insulation for HV rotating machines.

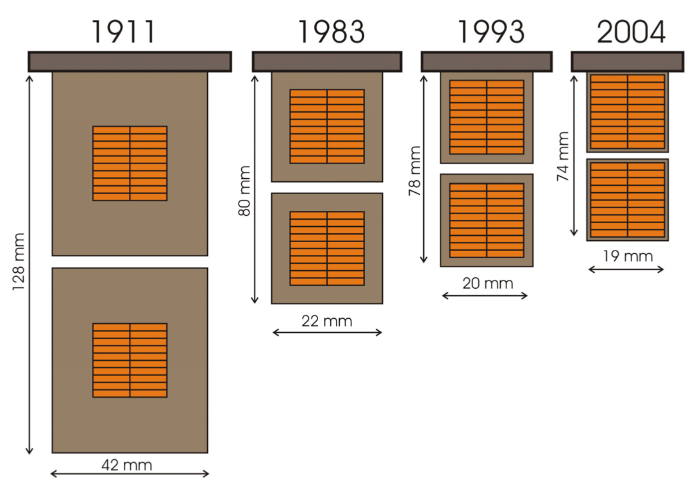


Figure 1. Development of dimensioning HV insulation systems for rotating machines since the beginning [2].

As seen in Figure 1, it is clear that early constructions were oversized and the various kinds of stress did not lead to aging as with systems with less material reserve. Later on in the analysis of the different insulation systems, we will see that

Manuscript received on 13 March 2007, in final form 10 December 2007.

the characteristic of asphalt insulations has a very long lifetime. On the one hand, reducing the groundwall thickness of the electric load is becoming more important; however, on the other hand, other aging factors like mechanical (vibration) and thermal stress now have more influence. The connections between different aging parameters are very complex; the focus in this paper is not related to the differentiation of aging mechanisms, because in failure statistics the cause of breakdown is irrelevant.

In reaction to the reduction of groundwall thickness the rated electric field strength made a permanent increase from 0.75 kV/mm for asphalt systems 100 years ago up to 3.5 kV/mm for the modern resin systems that are built today [2]. In Figure 2 the historical developments of the last century are shown. In the more recent years, a push for technological development can be observed and the demand for higher utilization factors requires a more and more of a move in the direction of the construction limit; hence, a sharp bend in the curve can be observed.

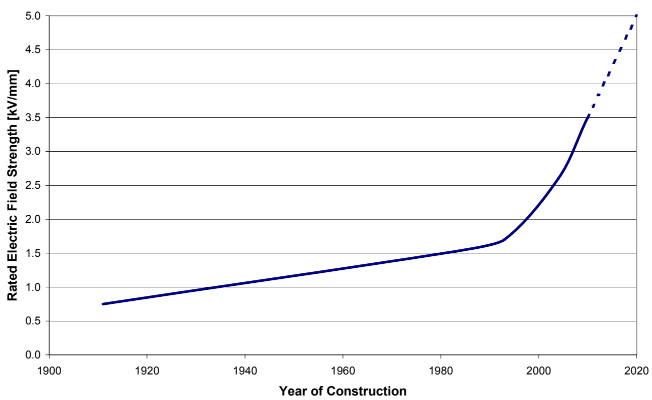


Figure 2. Development of rated electric field strength for HV insulation systems for rotating machines since the beginning.

From the economical point of view the cost relation between reduction of groundwall thickness and machine utilization is of high interest. For an estimation of the cost performance the average costs for electrical equipment components of hydro power stations published in [3] were taken.

In Figure 3 the costs for the electric equipment in % per kVA of the installed power in hydro power stations in MVA were given. The curve follows a non linear coherency, higher specific costs for smaller power stations. On the further considerations the slot dimensions were keep constant as it is usual for the uprating of machines. With a 15 % reduction of the groundwall thickness the cross-section of the copper can be increased for 16 % and therefore the efficiency can be enhanced for 4 % [2].

For smaller machines with a rated power of 200 MVA the costs for electric components can be decreased for 2.4 % and for bigger machines of 600 MVA rated power a benefit of 1.4 % can be estimated.

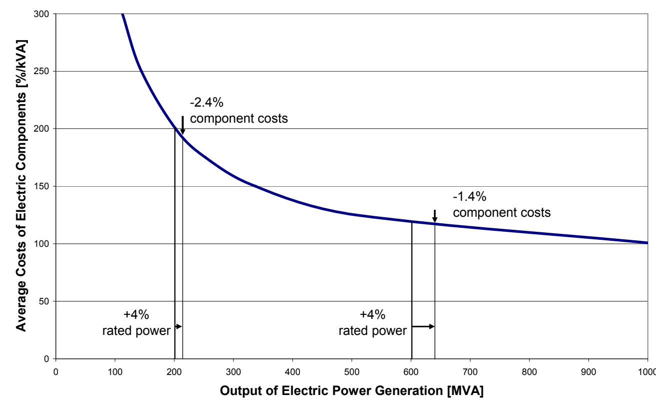


Figure 3. Average electric components cost curve for hydro power plants according to [3].

Beside the economic aspect of capital investment and increase of energy sales by improvement of efficiency or uprating of machines the reliability and estimated lifetime gets more and more important in the liberalized electricity market. To evaluate the consequences of the groundwall reduction and higher machine utilization on the lifetime and reliability a view to generator statistics should indicate the trend of development.

3 INVESTIGATED HYDRO GENERATORS

The basis for the data for the hydro generators was gained from utilities in Austria, which have been in operation for more than 100 years at river and storage power stations, some of them with the option of a pump mode. The older generators were constructed with natural insulation materials and the newer with the composite of synthetic insulation materials described above.

Figure 4 gives an overview of the distribution of the processed insulating systems. The natural materials with asphalt or shellac with cotton or glass fiber carrier build each a group of 10 %, and the newer systems with synthetic resin and glass fiber carrier have the biggest proportion with 70 %. Additionally, miscellaneous systems were recorded and displayed in this figure.

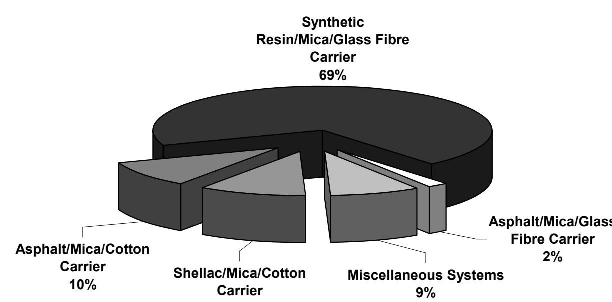


Figure 4. Types of insulation systems at the investigated hydro generators.

In Figure 5, a cumulative bar graph of the different hydro-generator types is shown. The older machines were constructed with natural materials and, since the 1940s, the synthetic materials have been dominant. The three oldest machines were set into operation in 1905 and are still in operation. For several machines, the stator winding has already been replaced, because of a breakdown or due to strategic investments.

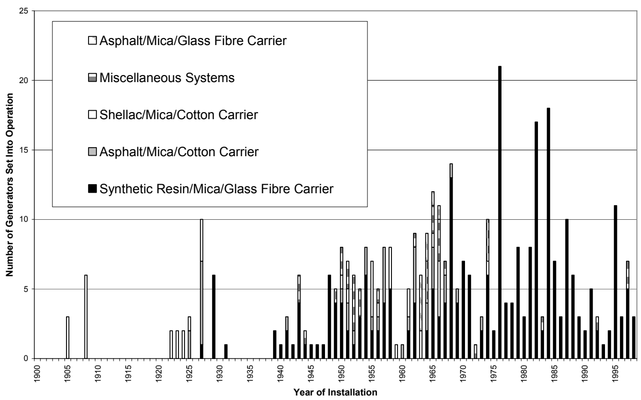


Figure 5. Population of different insulation systems for hydro generators.

By observing the installed rate of power per year, it can be seen that large investments in hydro power were made between the 1960s and 1980s, see Figure 6. Where the peaks of over 500 MVA per year occur, there were large numbers of river power stations (white) on the Danube River and pump storage power stations (black) in the Alps. Typically, a large river power station has 6 generators with a total rated power of 200 MVA and a large pump storage power station has 4 generators with a total rated power of 880 MVA.

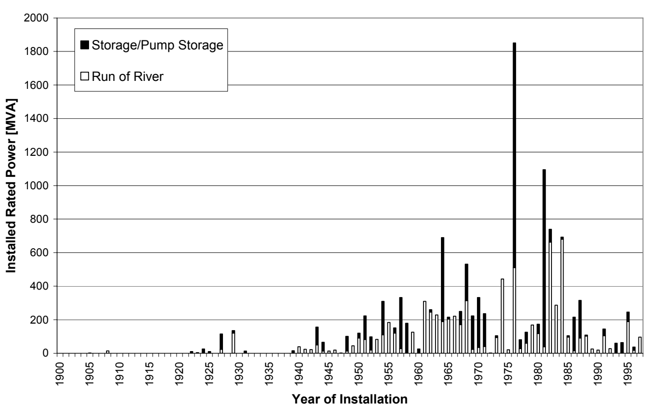


Figure 6. Installed rated power by type of power plant and year

By the end of the 1980, investments were reduced dramatically due to economic measures enforced by the EU directive for the liberalization of the electricity market and additional political reasons.

The extension of hydro power plants was reduced to the necessary minimum for the next 10 years. It has only been since 2003, that some projects have been running and the planning of new power stations has started.

4 INSULATION SYSTEMS AND PRODUCTION TECHNOLOGIES

The main component in the electric insulation is the mica, which is a natural material. Different kinds of mica (muskovite and phlopogite) were processed (calzinated or non calzinated) into mica paper. Mica paper is very mechanically unstable and, for this reason, it is fixed onto a carrier. In the beginning, this carrier was made of cotton braid, today it is composed of woven glass fibers.

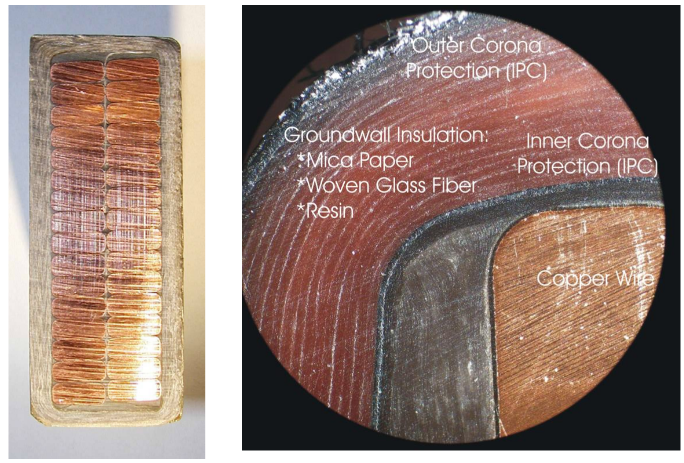


Figure 7. Cross section of conventional generator bar and microscopic view of the structure.

A cross section of a generator bar is illustrated in Figure 7 on the left side. By cutting this generator bar in thin layers of maximum 1mm thickness, the detailed structure can be observed under a microscope for transmitted light (right side). The thin slices were cut with a precision low speed saw with a diamond wafering blade.

Other details under microscope are illustrated in Figure 8. In the picture on the right, the woven glass fiber structure over the mica and resin can be seen. Figure 8 left shows a detailed view of the layers of mica paper on the glass fiber carrier, which is embedded in resin.

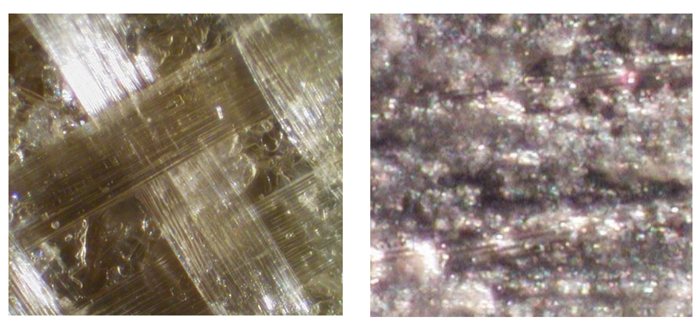


Figure 8. Woven glass fiber (left) and layers of mica paper/glass fiber carrier embedded in resin (right)

Because of the dependence of the bonding agent, two different types of production technologies were developed. The first was the technology for tapes with a high percentage (30 % and more) of resin: Resin Rich-RR. The second technology was invented in the 1960s and developed for resin with poor tapes (lower than 20 %): Vacuum Pressure Impregnation-VPI. The aim of the VPI technology was to produce insulation systems without voids, where partial discharge occur and accelerate electrical aging. Within the production technologies there is a distinction between individual and global coil systems, depending on whether it is just single generator bars or if a whole coil is produced.

Newer insulation systems have an Inner Corona Protection (IPC). The aim of the IPC is the prevention of inner partial discharges. A layer with high specific conductivity is located on the inner side of the groundwall insulation. This layer is connected to the copper conductor to get the same electric potential on this layer.

Assuming the wide range of insulation and production technologies, the following important insulation systems can be distinguished:

--muskovite / phlopogite - calzinated /uncalzinated

--Asphalt / Natural Resin / Epoxy Resin

--Resin Rich (RR) / Vacuum Pressure Impregnation (VPI)

--Inner Corona Protection / no IPC

This is the division according to which the statistical investigations were done.

5 BREAKDOWN MECHANISM IN STATOR WINDINGS

The most important question in lifetime statistics is: at which point of the lifetime does the breakdown occur? In hydro generator stator windings, aging and failure mechanisms find the beginning in the change of the material due to stress. This stress can be described as impact from thermal, electrical, mechanical or chemical energy. In [4] the term "aging" is defined as the action of electrical, thermal, mechanical or environmental nature on an electrical insulation system, which may cause property changes. In stator windings, normally a combination of electrical, thermal and mechanical (vibrations) stress is utilized for artificial aging tests. For the simulation and mathematical description of the aging mechanism, the Inverse Power Law is applied for electrical and mechanical aging and the Arrhenius Law for thermal aging. Several publications about aging tests at accelerated conditions in laboratory and standards with raised test levels have been published, but do they conform to the reality?

The idea behind the tests is based on a model that is supposed to agree with the aging mechanism exactly and this is the weak point in all of the tests: the results can only be as good as the model or test arrangement. Of course, there are some satisfactory and well-proven standards and test arrangements that can be used to compare similar constructions and to determine the best one, but to do a lifetime assessment for complex devices, such as generators, the results of these tests can only be taken within a specific confidence interval.

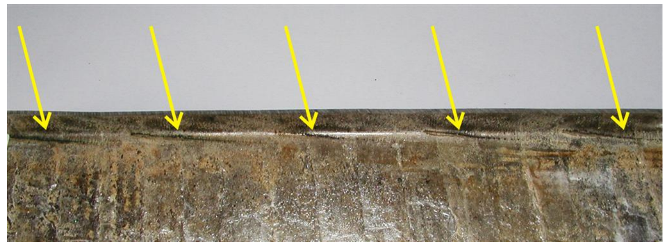
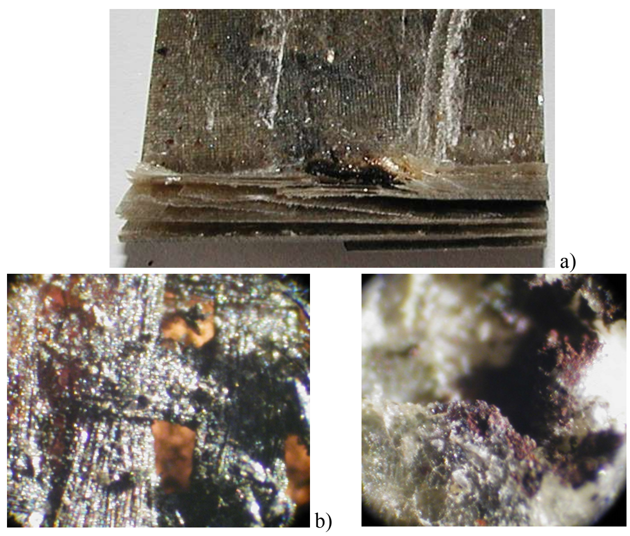


Figure 9. Multiple weak points in the goundwall insulation.

Any kind of overload and a change in the chemical and/or physical structure of the material can lead to the failure mechanism. When the impact energy on an insulation system is high enough, the damaging mechanism is present on the weakest points. In the special case of a generator winding, experience has shown that there is always more than one weak point in the insulation system, due to the very heterogeneous structure, see Figure 9. With the stress duration, the failure mechanism steadily reduced the insulation strength. Finally, it becomes enough if one the weak points does not keep the load and causes a breakdown. In Figure 10, one example of a typical breakdown is shown, the position of the breakdown channel was located at the point of the highest electric field strength, the energy of the dielectric breakdown caused carbonization in the insulation components.



a)

b)

c)

Figure 10. Breakdown of groundwall insulation: a) discharge channel and delamination at bar edges, b) carbonization of glass fiber carrier and c) resin.

Depending on the condition of the winding and the strategy of the machine operator, a stator winding with a breakdown can be repaired. Normally, the utilities have some spare bars to replace the damaged part, for just such an occurence. If the general condition of the winding is very bad, a repair is not economically viable and the further operation of the machine would not be safe. In this case, the winding is normally replaced. Often, such a winding replacement is used to maintain the whole machine and to raise the rated power by using thinner groundwall thickness and more copper conductors.

6 FAILURE CAUSES AT GENERATORS

In an international survey [5] the causes of hydro generator failures was observed and analyzed over several years. More than 20 utilities in 5 countries over the world collected the failures and breakdowns of 1.200 generators. In total, 69 incidents within 10 years up to 2002 were recorded. The main causes of failures can be categorized in the following order: breakdown of the insulation system; mechanical defects and thermal problems; and, lastly, failures due to bearings, see Figure 11.

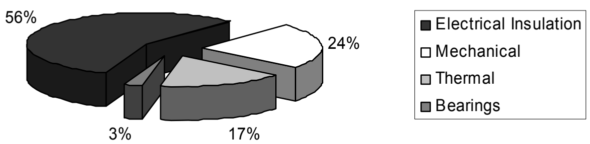


Figure 11. Root causes of hydro generator failures.

The failures of the electric insulation system were investigated more in detail and the results were illustrated in the diagram of Figure 12.

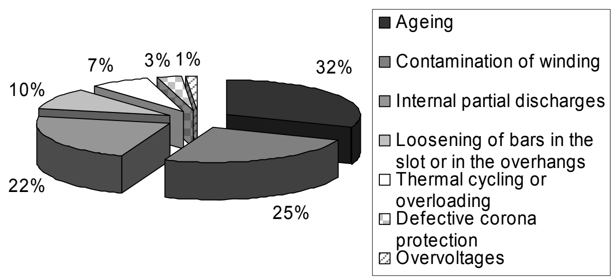


Figure 12. Failure causes at electrical insulation system.

The most frequent failures are caused by aging effects and contamination of winding by dust and humidity. Electrical failure mechanisms were caused by internal partial discharges at the corona protection of the voltage grading and by voltages that were too high. Due to vibrations it's possible that bars can loosen in their position or in the overhang (slot wedges).

The statistics that were taken into account confirm the observed and reported effects to winding insulation systems as described in Chapter 5. The electrical insulation system (stator winding) plays the most important role in the overall construction of a generator. Most defects occur in the electric system and are caused due to aging and electrical, thermal and mechanical load.

7 STATISTICAL LIFETIME OF GENERATORS

The evaluation and statistical analysis was done by the means of two parametric Weibull distributions. It is possible that other distributions were a better fit, but the Weibull distribution is the most suitable statistical distribution in high voltage engineering. The systematic procedure in preparing for this statistical analysis called for the collection the lifetime of the stator winding of approximately 400 generators. The dates correspond to the type of insulation system. Both the materials used and the different production technologies were investigated. In terms of the generators, 73 % were impregnated with a resin system, 11 % with shellac and 9 % with asphalt and the others were unknown. Within the production technology, 43 % were of VPI, 37 % of Resin Rich and the others unknown.

The results of the Weibull evaluation are illustrated in Figure 13. One dot in the diagram represents a breakdown respective of a replacement of the whole stator winding. The insulation systems that were investigated show a characteristic lifetime of 27 years for resin impregnated insulation systems, 45 years for shellac impregnated and 55 years for asphalt systems. The resin systems have early breakdowns earliest (4 under 10 years), the first outage of an asphalt system was at 39 years. The Weibull exponent of the resin and the shellac systems were very similar with 2.0 and 1.8 the asphalt has an exponent of 3.4, which means that there was a much smaller deviation of the failure events and/or there were no early failures.

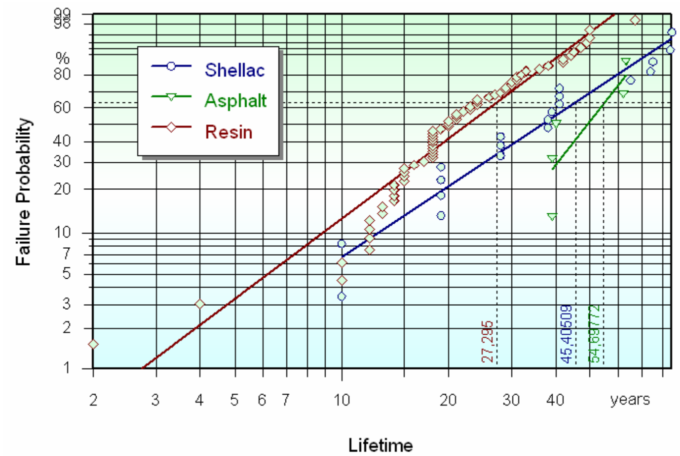


Figure 13. Statistical lifetime of hydro generators by insulation system.

The significant difference between the insulation systems is not surprising. The reason can be found in the different rated electric field strength of these systems. The older systems utilizing asphalt as insulating material had the most spacious dimensions, as mentioned above. The electric and thermal loads to the generator bars were dramatically lower than in the newer resin systems. The half characteristic lifetime of asphalt and resin systems correlates to the rated electric field strength, or, in other words: a higher load decreases the lifetime.

In the second viewing, the lifetime with respect to production technology was analyzed. As before, one dot represents a breakdown or replacement of a stator winding. The RR technology shows a characteristic lifetime of 41 years compared to the VPI generators with 29 years. The Weibull exponent of both systems is very similar with 1.7 and 1.8, the calculated curves are shown in Figure 14.

When comparing Figure 13 with Figure 14 it needs to be pointed out that the VPI curve of Figure 14 is quite similar with the resin curve of Figure 13. It also should be mentioned that almost all VPI generators were impregnated with resin. For this reason, the resin impregnated systems were analyzed in more detail.

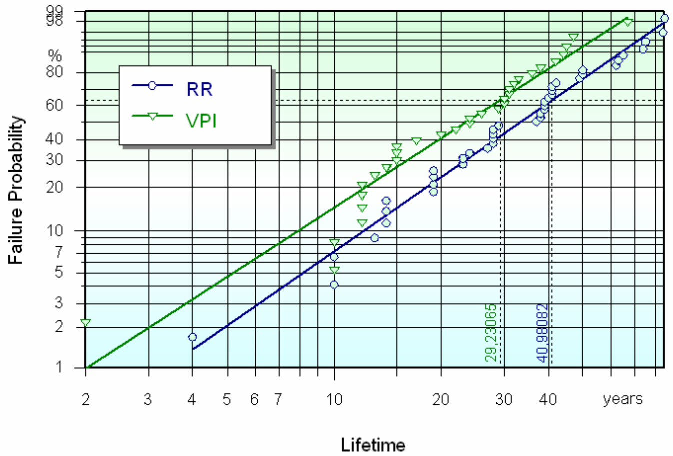


Figure 14. Statistical lifetime of hydro generators by production technology.

Figure 15 shows the statistical lifetime of resin impregnated windings divided into RR and VPI technology. A significant difference cannot be seen; RR has a characteristic lifetime of 31 years and the VPI of 29.5 years, the Weibull exponent is 1.6 at both.

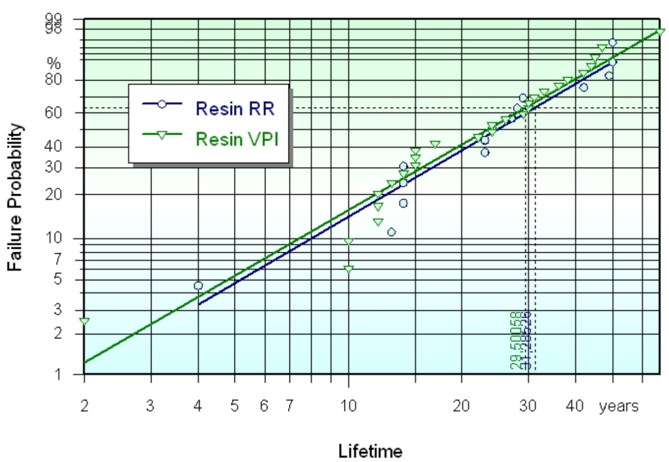


Figure 15. Statistical lifetime of resin impregnated stator windings by production technology.

Table 1 gives an overview of the results from the statistical investigations. The insulation materials and production technologies were compared.

Table 1. Results of Statistical Investigations.

material/technology	Characteristic Lifetime η / years	Weibull Exponent β
asphalt	54.7	3.4
shellac	45,4	1.8
resin	27,3	2.0
Resin Rich (RR)	29,2	1.8
Vacuum Pressure Impregnation (VPI)	40,9	1.7

8 STATISTICAL RELIABILITY AND FAILURE RATE

With the characteristic values of Weibull distributions for the stator windings additional statistical functions can be calculated [6]. Through the characteristic lifetime and the Weibull exponent the failure probability F(t) is given, see equation (1).

$$F(t) = \int_0^t f(t).dt = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{1}$$

with: η … characteristic Lifetime
β … Weibull Exponent

The first deviation in time in equation (1) results in the density function f(t), which is given by gradient of the failure probability. The reliability R(t) is a very important quantity for maintenance strategy and renewal program of the utility, which is defined in equation (2).

$$R(t) = 1 - F(t) \tag{2}$$

Dividing the density function through the reliability, the failure rate λ(t) results in equation (3). The failure rate gives the number of failures at the present time by the total number of failures.

$$\lambda(t) = \frac{f(t)}{1-F(t)} = \frac{f(t)}{e^{-\left(\frac{t}{\eta}\right)^{\beta}}} \tag{3}$$

The curves of Figure 16 and Figure 17 were calculated with the results of the Weibull analysis and equations (1) through (3). In Figure 16, the failure probability, reliability and failure rate of different material systems and production technologies are shown.

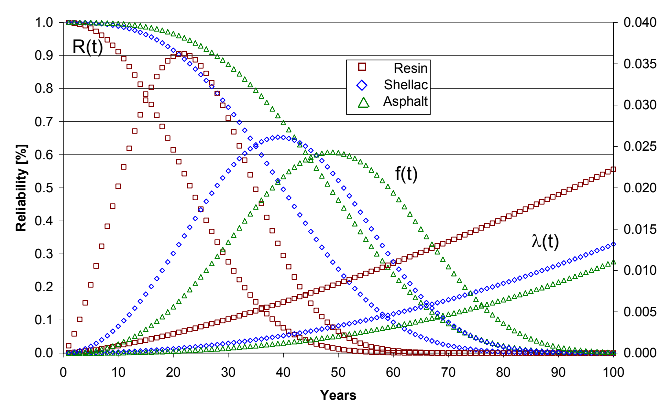


Figure 16. Reliability, failure density and failure rate of different insulation materials.

In Figure 16 the statistical characteristics for resin, shellac and asphalt insulation systems are displayed and, in Figure 17, the statistical characteristics for resin rich and VPI produced generator bars are shown.

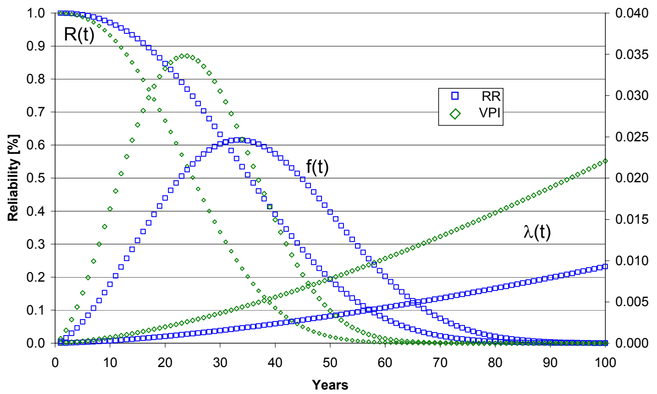


Figure 17. Reliability, failure density and failure rate of different production technologies.

The most reliable impregnation material is the asphalt and the most reliable technology the resin rich technology. The slowest growing failure rate can be observed at shellac and RR systems. The highest failure density occurs in resin impregnated and VPI bars.

Another statistic parameter of interest is the failure rate λ(t), which is heavily dependent on the Weibull parameter β. When we do a variation of β over time, the characteristics of the failure cause can be observed. Three areas can be distinguished: at the beginning, there were early failures with decreasing mortality present, later on a constant and low failure rate is normal and at least the failure rate is increasing due to end of life wear outs [7]. This behavior is shown within the so called bathtub curve, which is shown in Figure 18. According to the described states in the lifetime of power equipment the three areas can mathematically be described using the Weibull parameter β. For aging investigations, only the last area with a β > 1 is of interest.

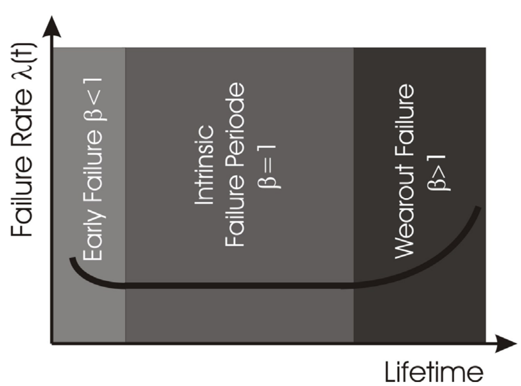


Figure 18. Bathtub curve of aging equipment.

In the described insulation systems and production technologies only failure rates with a β > 1 were given. This means that there were no early failures present. The lowest β could be observed in resin and shellac systems, the production technologies were almost similar. The highest β had the asphalt system with 3.4, that means that this system has the lowest failure rate over the whole lifetime period (compare the λ(t) functions in Figure 16 and Figure 17).

9 OPERATIONAL RISK OF STATOR WINDINGS

According to the calculated statistical parameters of stator windings a reliability characteristic curve was derived. With this Weibull distribution an estimation of the evaluation for the generator reliability, the operational risk and the risk of a breakdown can be found. For example, the analysis of the reliability and the failure probability of the curves were assessed into different areas, as it is shown in Figure 19. The white area on the left side means that the winding is in a good condition and the risk of a failure is low. The grey area on the right side means that the condition of the winding shows some type of aging symptom and the failure risk is high.

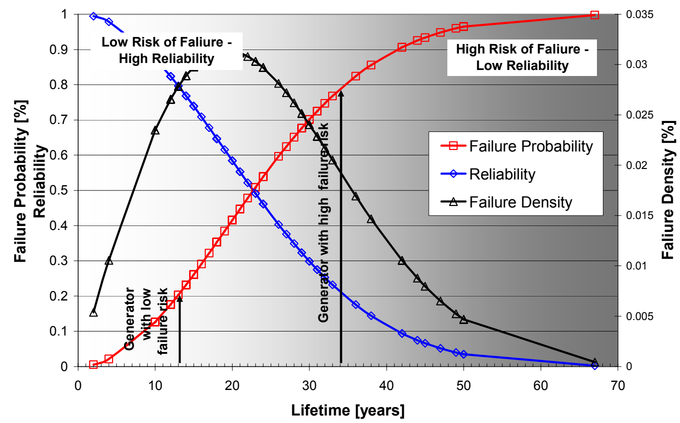


Figure 19. Classification of stator winding reliability and operational risk of resin impregnated stator windings.

Often from this classification of the reliability and failure probability, a technical risk is assessed [8]. Within a risk matrix the condition is divided into states as good, used or bad and the importance of the generator into low, normal or high as shown in Figure 20. The resulting risk matrix can be used for strategic considerations of maintenance, investments or replacement of the machinery.

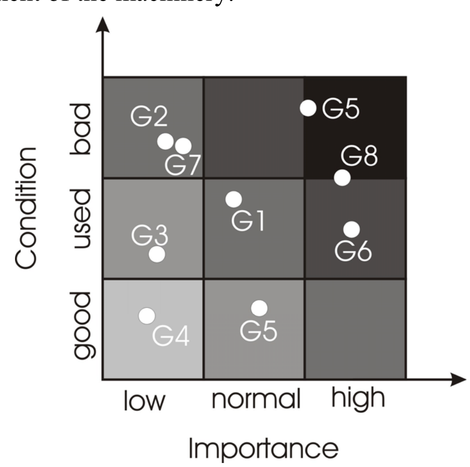


Figure 20. Risk matrix and risk assessment.

The generators of high risk were inside dark grey or medium grey fields and were pre-selected for overhaul or renewal. The soft grey and bright grey fields indicate that the condition is satisfactory and no urgent call for action is present. Additional considerations about other kinds of risk (economical, environmental, contractual…) can be helpful over a list of priorities or the tools of risk management can be applied.

10 RISK MANAGEMENT

Since the liberalization of the electricity market, most utilities appoint management tools like asset or risk management [9]. Risk management is classically divided into four steps as shown in Figure 21:

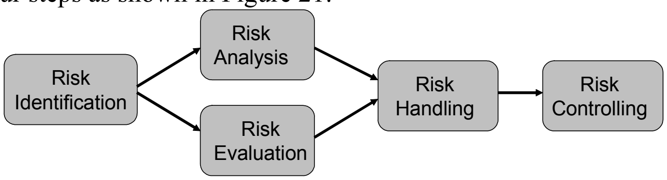


Figure 21. Risk management

With the knowledge of statistical functions shown above, the basis for the technical risk management is given. The first step “identification of the risk” can exemplarily be done with the risk matrix in Figure 19. For the next steps in risk management, the different kinds of risk have to be considered. Risk can be divided into following aspects:

-- technical risk
-- economical risk
-- judicial risk (laws, contracts)
-- management, financial and trading risks
-- ecological and environmental risk
-- other risks

Depending on the politics and philosophy of the machine operator, further decisions relating to the analysis, evaluation and handling of the risk could also occur.

11 CONCLUSION

In a historical overview of the insulation materials and production technology, it could be pointed out that the rated electrical field strength has steadily increased with the development of new materials and technologies in the last ten years.

With the reduction of groundwall thickness the machine size can be reduced or at the same core and slot dimensions, the cross-section of the copper conductor can be enlarged, which results in a higher utilization respectively efficiency. The correlation to the cost performance showed that the economic relevance of machine uprating is more efficient at smaller machines than at bigger units.

When taking a look at the causes of failures it could be pointed out that aging of the insulation system is a multi-stress phenomenon, which is a very complex procedure. In most cases, aging processes were present at several points in the insulation system. Other statistics have shown that the electric insulation system is the most frequent point for a breakdown.

Within this paper, it was shown that it is very important and useful to collect the operational data of the machines because they deliver the necessary information for lifetime statistics. The statistical evaluation of lifetime data showed that the older insulation constructions have the highest characteristic lifetime of the generators investigated. One reason is the more conservative dimensioning of these generator windings with lower rated electrical field strength compared to the newer constructions. From the standpoint of production technology, there were not as many major differences found. The reason can be seen in the very similar construction of both technologies.

For the statistical lifetime, the reliability, density function and failure rate were calculated. As expected the highest reliability has the asphalt system followed by shellac and resin impregnated stator windings. Resuming the results of this statistical analysis, it should be pointed out that machines with high oversized winding dimensions show the highest expected lifetime and best reliability on the dates of investigation. The evidential import of the economic profit for higher machine utilization has to be qualified by the results of lifetime statistics.

The investigated statistical functions deliver the basis for further strategic decisions about the operation philosophy of the machine operator. Management tools, such as risk management, can be applied successfully, to assist in making the correct decision about maintenance, overhaul or replacement.

REFERENCES

[1] H. Koch, Fire Prevention of Generators, Diploma Thesis, TU Graz, Austria, 1998.
[2] P. Marek, New Carrier for High voltage Insulation Materials”, Doctoral Thesis, TU Graz, Austria, 2006.
[3] W.-D. Blecken, “Applying new technologies in the upgrading or uprating of generators”, Intern. J. Hydropower & Dams, Issue 5, UK, 1997. (www.hydropower-dams.com).
[4] IEC 60505 Third Edition 2004-10, “Evaluation and Qualification of Electrical Insulation System (EIS)”.
[5] Hydrogenerator Failures – Results of the Survey, CIGRE Study Committee SC11, EG11.02, 2002.
[6] W.J. DeCoursey, Statistics and Probability for Engineering Applications, Elsevier Science (USA) Newnes, ISBN: 0-7506-7618-3, 2003.
[7] L. A. Dissado, J. C. Fothergill, S. V. Wolfe and R. M. Hill, “Weibull Statistics in Dielectric Breakdown Theoretical Basis, Applications and Implications”, IEEE Trans. Electr. Insul., Vol. 19, pp. 227- 233, 1984.
[8] CIGRE WG D1.17 “Fundamental Aspects of Data Quality for HV Asset Condition Assessment”, Electra No. 228, 2006.
[9] D. Dörner, P. Horvat and H. Kagermann, Praxis des Risikomanagements, Schäffer-Poeschl Verlag Stuttgart, Germany, ISBN 3-7910-1452-8, 2003.

Christof Sumereder was born in Linz, Austria on 6 May 1969. He received his doctorate in technical science (Ph.D.) from Graz University of Technology in 2003 with honours and he is presently an Assistant Professor at the Institute of High Voltage Engineering and System Management. He has worked on new technologies for insulation materials as well as cryogenic systems. Currently his field of special interest is the onsite diagnostics of hydro generators as well as maintenance and reliability engineering and life time investigations on insulation systems. He is a member of ÖVE and CIGRE.