CONDITION EVALUATION OF ROTATING ELECTRICAL MACHINES IN PRACTICE

C. Rupp, M. Marketz and C. Sumereder

Abstract: Taking a look at the structure of the hydro power plants of the Austrian utilities many of the electrical machines are reaching a critical age. A failure or a break down can cause high financial consequences. For this reason a concept for the condition evaluation of the insulation system of hydro generators was developed. The focus of this procedure was to collect operational data, machine data and results of technical diagnosis measurements in order to form an objective analysis.

1 Introduction

For the optimization of the maintenance expenditure for cost-intensive electrical machines the strategy of condition based maintenance (CBM) is of considerable importance. Different procedures of the technical diagnostics are used for accurate condition evaluation of the active components of the machines. Hereby, the insulation system of the stator winding represents a particularly critical generator component as demonstrated by international surveys and breakdown statistics. [1]

Failures at hydro generators are mainly attributed through mechanical root causes (36%) and through damage of the isolation system (50%) as shown in Fig. 1. Through periodic revisions by the experienced revision team the failure due to mechanical root causes are minimized and in most cases avoided. At these periodic revision activities the insulation system is mostly not observed.

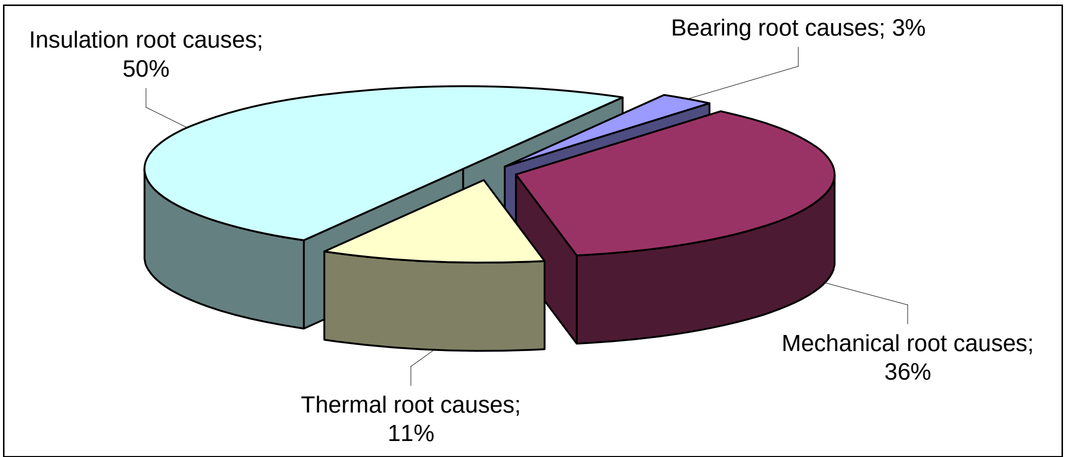

Fig. 1: Statistic distribution of the failure root causes [1]

This paper highlights possibilities for continuing condition evaluation of the machinery and represents a guide for the decision in continuing operation, in renewal respectively about investment within the focus on the insulation system of rotating high voltage machines.

Apart from the diagnostic measurements the technical characteristic data (e.g. year of manufacture, insulation system, soldering technique) and the constantly logged data (e.g. starts, operation hours, reconditioning measures) supply valuable information for a condition evaluation and risk assessment of the machinery.

A three-step concept was applied for the condition evaluation of the machinery [2], [3]. The goal of this three-step approach is to identify machines with worse condition and high risk of default.

(1) Load of the Stator Winding

A first insight into possible risk ranges was generated from the comparison of operation hours and starting processes of the stator windings. Therefore the "equivalent operation hours" were calculated.

(2) Technical Diagnostics

Different measuring and testing methods were applied to the machines in the past. Observing the tendency of the measured values (trending) the aging of the insulation can be pursued. Due to transverse comparisons of the measurement results of the comparable machines certain sequences regarding their technical condition were made. The "worst" machine in each case can be determined. The interpretations in the test reports play an important role in the evaluation of the technical condition.

(3) Qualitative Characteristics

The qualitative characteristics (technology of the insulation system, soldering technique, degree of pollution, movement traces, estimates of the personnel, etc.) were quantified in a suitable form, weighed and included in the condition evaluation.

2 Overview of the machinery

Total 16 machines were investigated; they were labelled from M1 to M16. The apparent power of the investigated machinery ranges from 8 up to 55 MVA (Fig. 2).

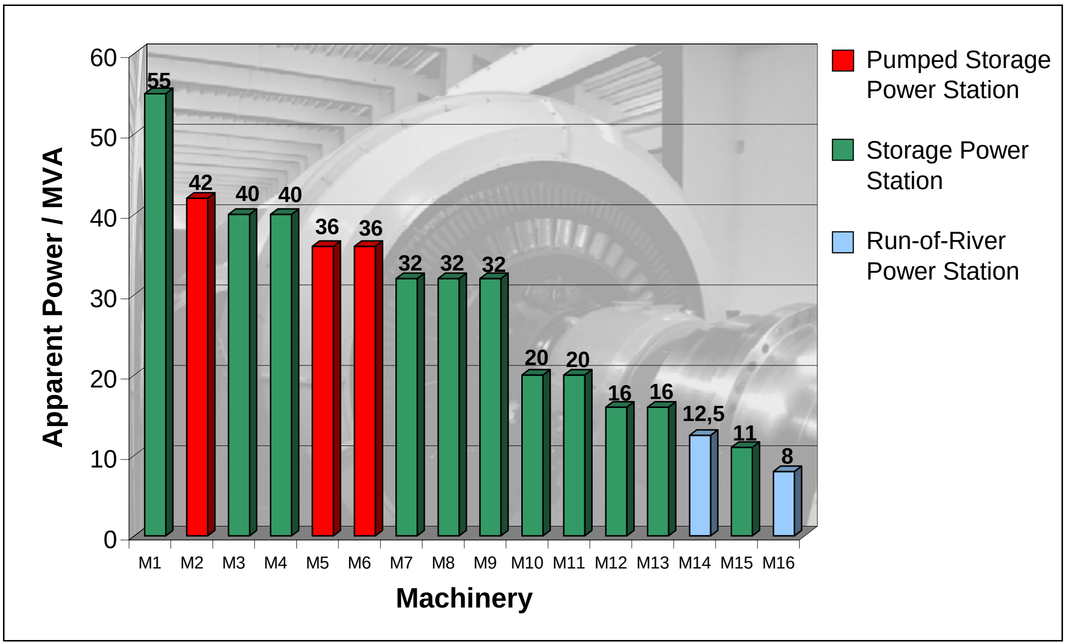

Fig. 2: Range of apparent power (8 to 55 MVA)

Three different operation modes must be distinguished – the pumped storage, the storage and the run-of-river mode (Fig. 2).

In addition the machinery is implemented with two different voltage levels. Machines at high power range are carried out with 10.5 kV most machines at low power range have a rated voltage of 6.3 kV.

The kind of used insulation system plays an important role in the interpretation of the technical diagnostics [4], [5] (e.g. partial discharge measurement). A distinction of the different systems was made in type of insulation technology, insulation material and production technology.

3 Process of the condition evaluation

As described in the introduction the condition evaluation consists of three stages where each step was determined by objective criterions.

3.1 Load of the Stator Winding

The mode of operation of the machines (continuous or intermittent operation) has a crucial influence on the aging of the insulation. Through the comparison of operation hours and starting processes of the stator windings the machines can be organized into ranges of different high loads. The number of operational hours and starting processes of the stator winding from the start-up to the present are shown and compared in the following figures (Fig. 3 and Fig. 4).

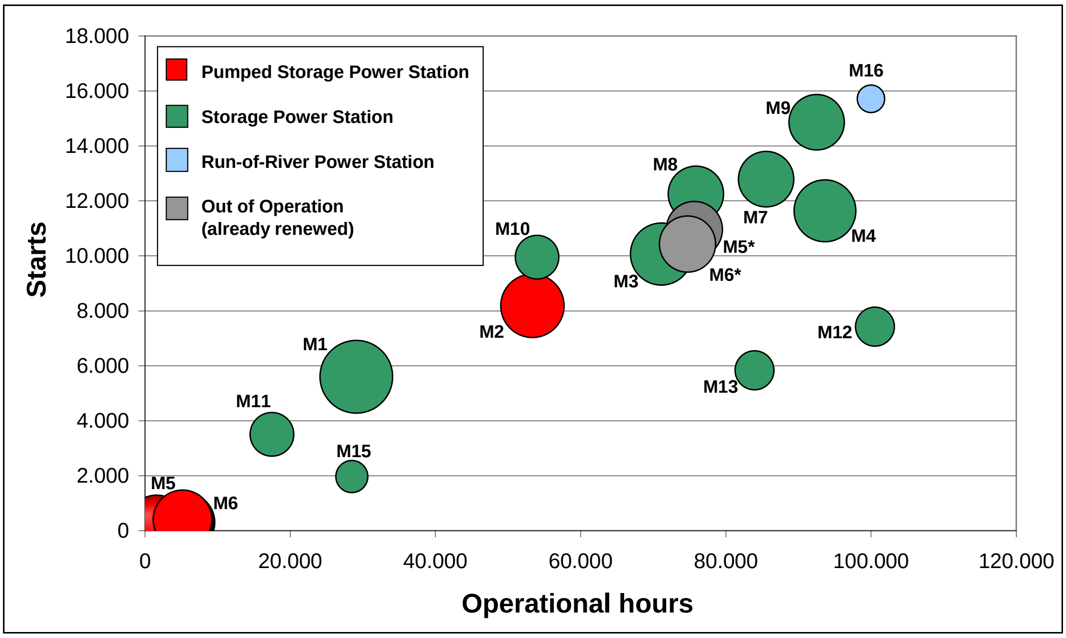

Fig. 3: Operation hours and starting processes of the stator winding

Each bubble in Fig. 3 refers to a stator winding of a generator. The size of the bubble is proportional to the apparent power and the color represents the operation mode of the different machines. Through the position of each bubble in Fig. 3 each machine can be allocated to a certain range of load.

For example machine M9 with over 90.000 operation hours and over 14.000 starting processes will be in a range of high load and machine M5 with 1.600 operation hours and 200 starting processes in a range of low load.

For the purpose of clarity the run-of-river power stations with more than 120.000 hours of operation and only a few starting processes are not mapped in Fig. 3. Machine M16 runs in intermittent operation, thereby it forms an exception. The stator windings M5* and M6* were renewed in the years 2003 and 2004.

Another possibility to compare machines with different number of operation hours and starting processes is to calculate the “equivalent operation hours”: [6]

$$T_E = T_O + n_S \cdot T_S \qquad \{1\}$$

T_E Equivalent operation hours
T_O Period of operation, operation hours
T_S Period of operation for special load through the starting process ($T_S = 10$)
n_S Number of starts, which can be taken into account

The weighed number of starts (weighing factor 10) is added thereby to the operation hours. The received characteristic number serves a means to compare the load of stator windings at different modes of operation (see Fig. 4). Grey marked bars refer to a stator winding already renewed.

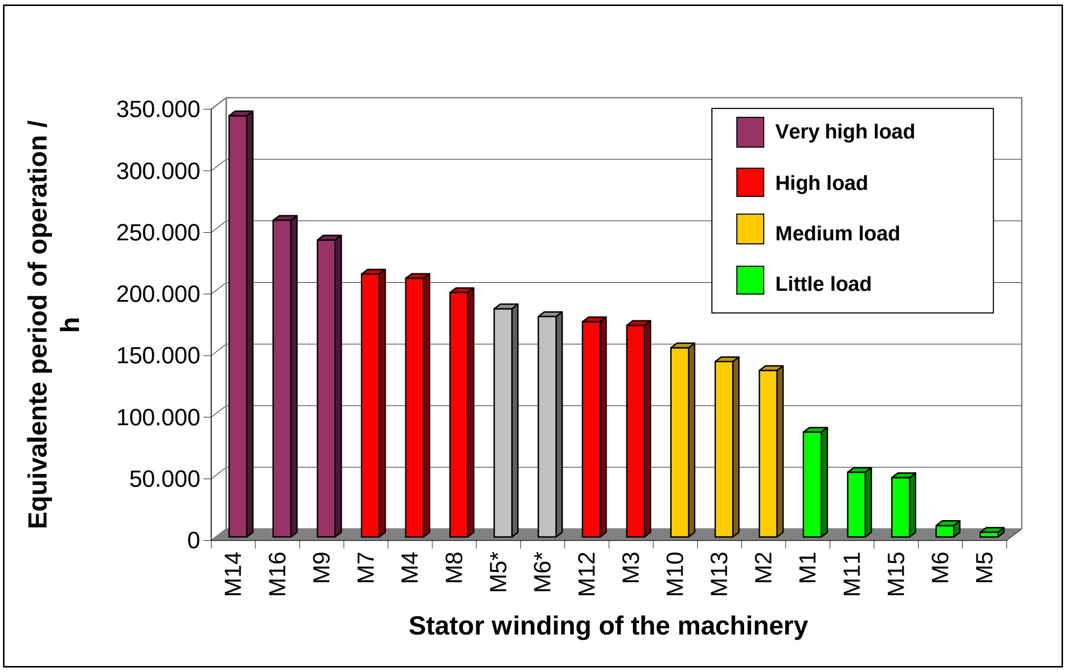

Fig. 4: Equivalent operation hours of the stator windings of the machinery

A direct correlation between the load of the stator winding and the risk of default is not given. The allocation of the machinery into ranges of differently high load supplies a first estimation of possible risk ranges (Fig. 3 and Fig. 4). The two presented different variants for the evaluation of the load of the machines supply an almost identical result.

Rating and Quantification: The machine with the highest number of equivalent operation hours gets the worst condition number of load (5). The remaining machines are standardized accordingly. A number of 1 (little load) to 5 (very high load) will be allocated to each machine. The result is shown in descending order in Fig. 5.

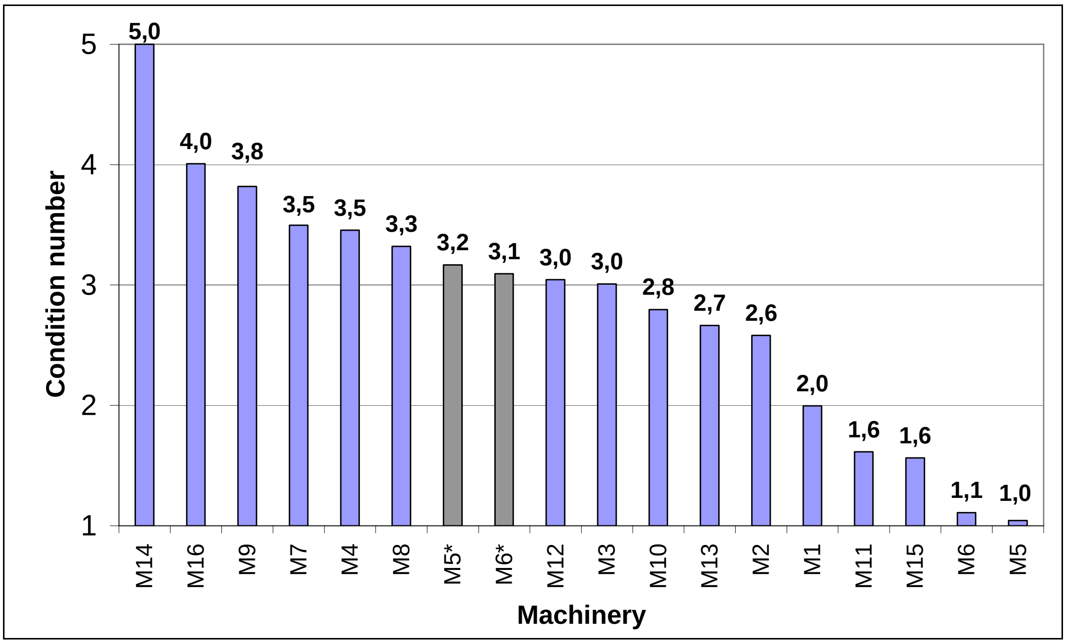

Fig. 5: Condition evaluation (load)

3.2 Technical Diagnostics

The accomplished measurements and tests of the machines supply different statements about their condition. [7]

Trend tracking for the condition evaluation of the insulation system measuring data of the PDC-analysis, the dissipation factor measurement, and the partial discharge measurement are consulted. By the changes and deterioration of the measurement values the process of aging of the insulation is assessable.

From other procedures of the technical diagnostics (voltage tests, hub of the slot keys, lamination stack pressing, etc.) a trend cannot be derived. These procedures supply a yes/no result concerning required revision activities.

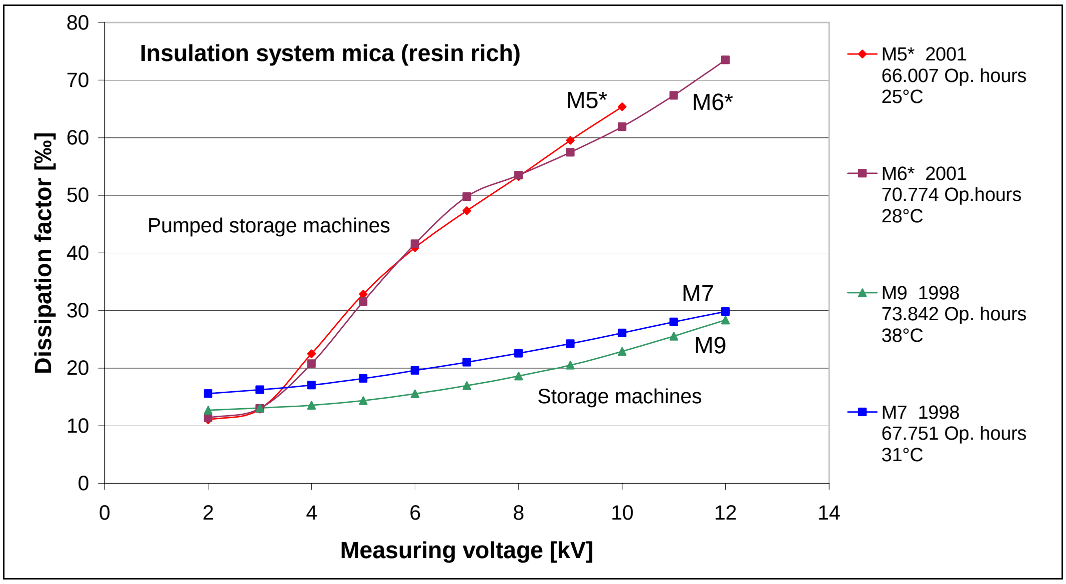

Fig. 6: Comparison of the dissipation factor of machines with the same insulation system

The most recent results of measurements were confronted at comparable machines and the “worst” machine regarding the differently measured parameters was determined (Fig. 6). The stator windings of M5* and M6* (already renewed) exhibit clearly higher and thus worse values of the dissipation factor measurements.

Results of the measurements of the technical diagnostics and the estimation and recommendation in the test reports by the test personnel were quantified according to Table 1:

Condition	
1	**New condition;** partly increased characteristic values due to incomplete hardening of the insulation; risk-free operation is expected
2	**Good condition;** no and/or marginal signs of electrical aging; risk-free operation is expected
3	**Satisfactory condition;** Aging is clearly ascertainable; e.g. deviations between line and neutral point generator bars (partial discharge measurement) or high rises at the dissipation factor values; medium risk of default is expected
4	**Little satisfactory condition;** strong signs of electrical aging; e.g.: high partition discharge activity; increased risk of default is expected
5	**Bad condition**; high risk of default is expected

Table 1: Evaluation table

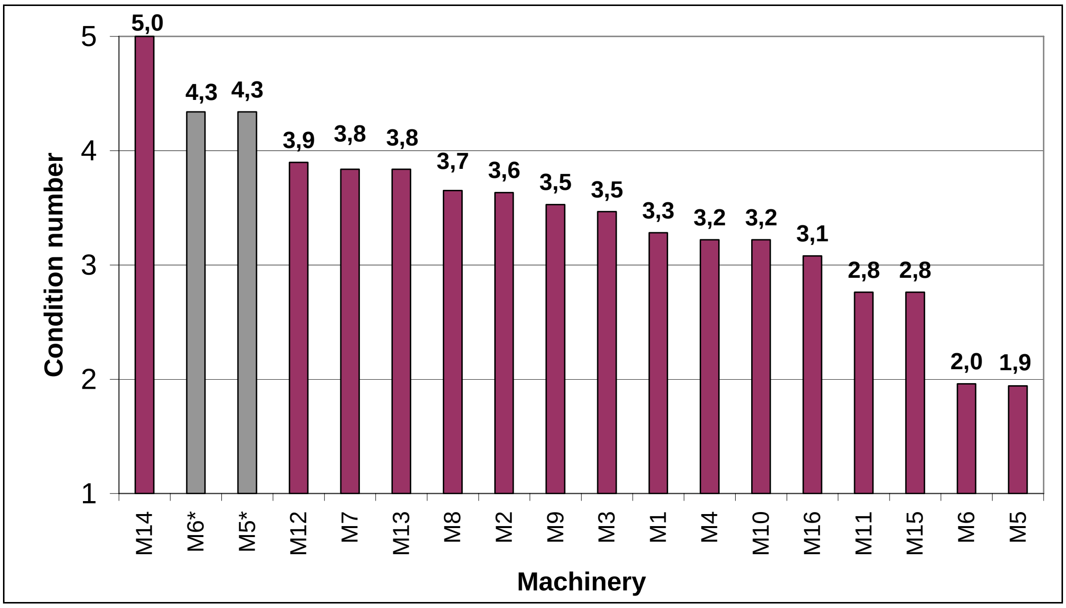

Fig. 7: Condition evaluation (technical diagnostics)

Rating and Quantification: In determining the technical condition the taken individual measurements affect the condition number of the technical diagnostics in varying degrees. The dissipation factor and partial discharge results as well as the development of aging have a special significance. The result is a condition number for the technical condition of the machines generated through diagnostic investigations (Fig. 7).

An evaluation of a bad technical condition results for generator M14. The decision towards a renewal of the windings M5* and M6* is confirmed by the result shown in Fig. 7.

3.3 Qualitative Characteristics

Qualitative characteristics affect the evaluation of the condition likewise. The following factors were considered in the qualitative characteristic number:

- Modes of operation (pumped storage, storage, run-of-river)
- Age of the generator and the stator winding
- Insulation system - an evaluation is made on the basis of different material properties, dielectric properties and the design of the systems with or without inner potential grading
- Soldering technique
- Degree of pollution
- Movement traces of the winding and loose slot keys

Great importance is attached to the age of the stator winding, the movement traces and the loosening of the slot keys. The modes of the machine and the insulation system have medium importance for the qualitative condition. Fig. 8 shows the comparison between the evaluated qualitative characteristics of the machines.

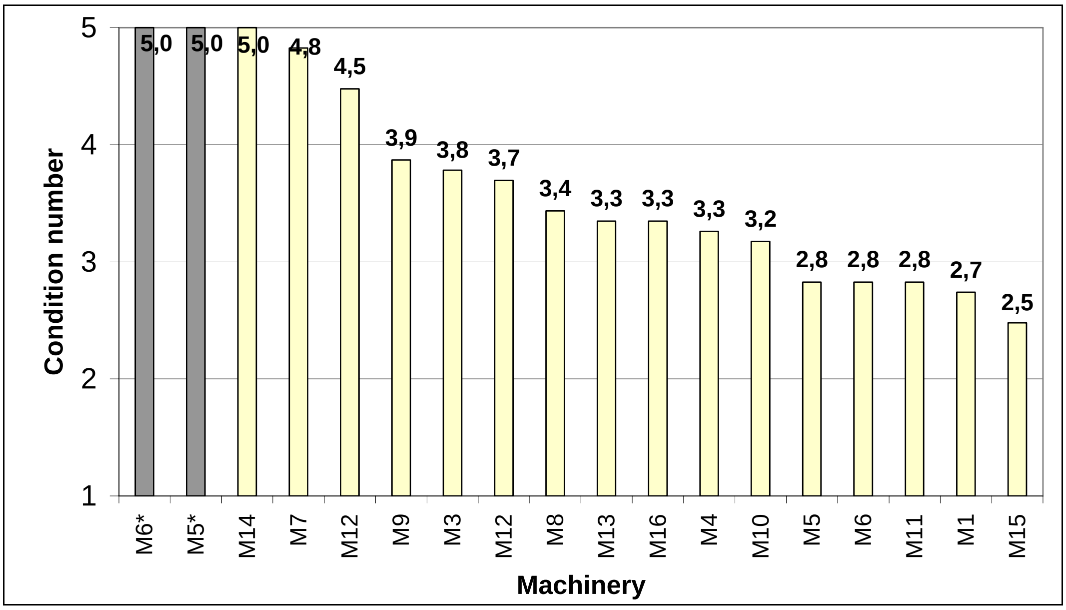

Fig. 8: Condition evaluation (qualitative characteristics)

4 General condition evaluation and risk assessment

For the total condition evaluation the operational dates, results from technical diagnostics and the qualitative characteristics have to be weighed. A distribution of importance according to Fig. 9 was established for this investigation.

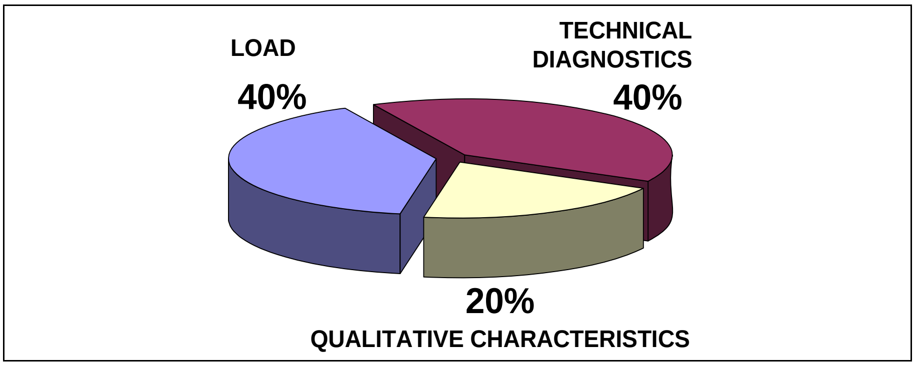

Fig. 9: Proportion of each factor

The equivalent hours of operation (load) strongly affect the total result (40 %), because beside the age also the dynamic operating loads are considered. The measurable diagnostic parameters were likewise highly evaluated (40 %), as an objective observation of the trend development was possible and an evaluation of the insulation quality. And finally the qualitative characteristics were considered with the lowest percentage (20 %). Fig. 10 shows the results of the general condition evaluation.

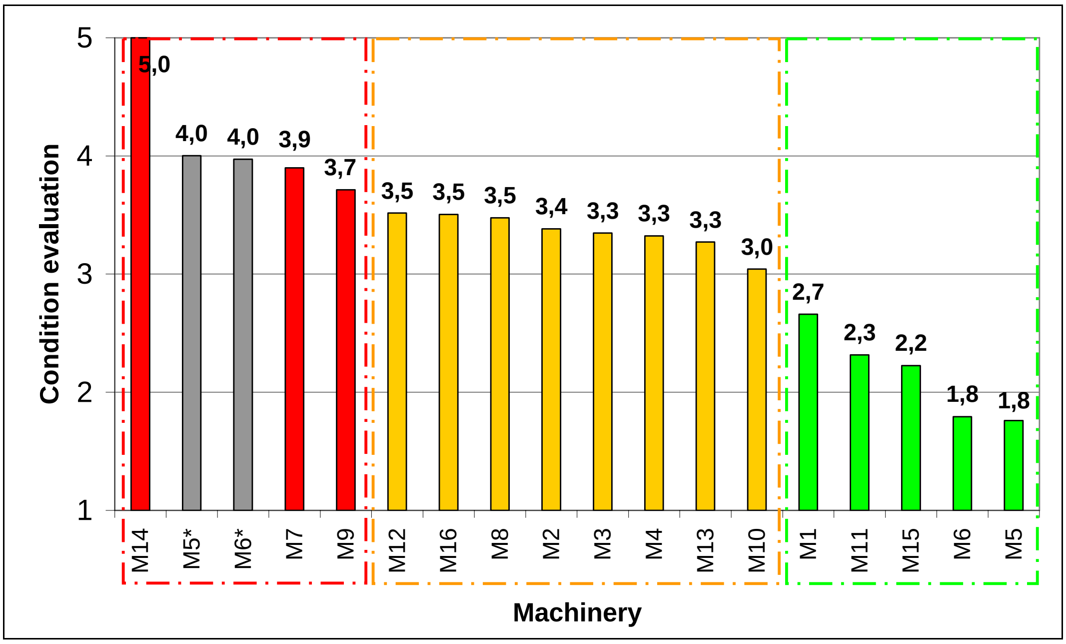

Fig. 10: Result of the condition evaluation and risk assessment

The machines can be assigned to an appropriate range due to their condition number. To estimate the risk of default three category groups were determined.

Machines in the red area have a high risk of default. The yellow area is defined as medium risk area and the green one comprises machines with low risk of default.

In the high voltage technology mostly the Weibull distribution is used for reliability investigations. The condition gets worse and the reliability decreases with higher load and working time of the insulation system - in reverse the risk of default rises. Fig. 11 shows the combination between condition number and risk of default. The risk ranges were defined according to Fig. 11.

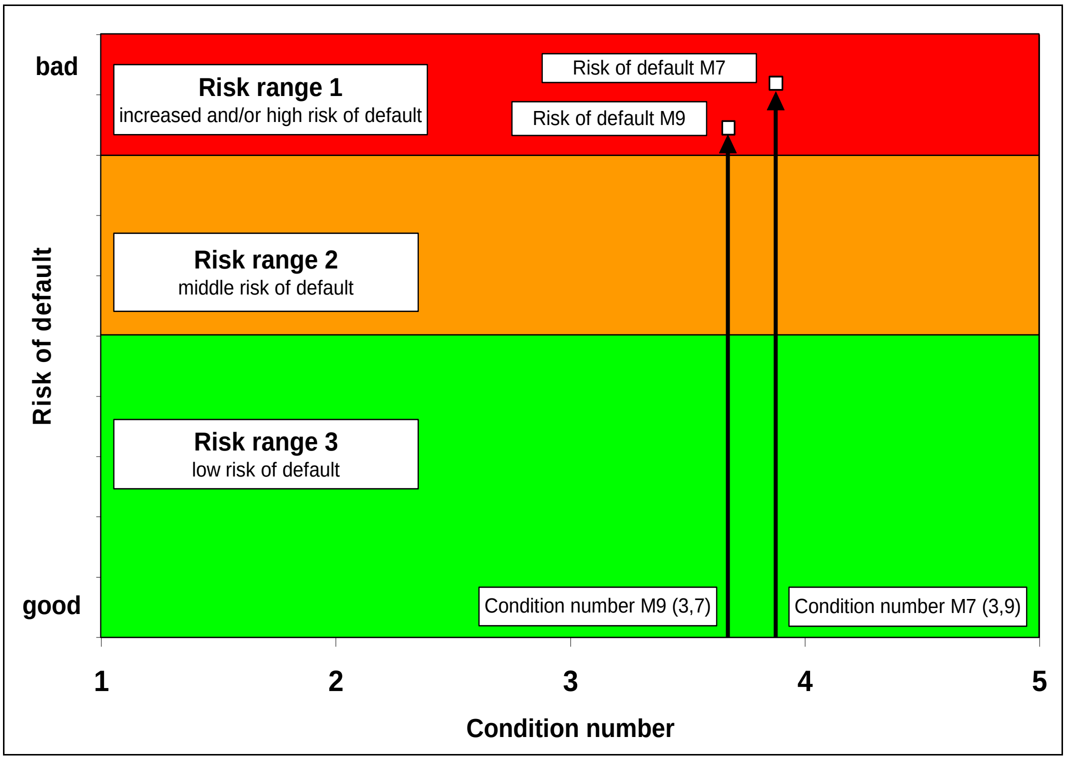

Fig. 11: Definition of risk ranges

Exemplary the allocation into risk ranges for two machines (M7 and M9) is represented. The machines M7 (condition number of 3.9) and M9 (condition number of 3.7) fall into risk range 1.

5 Conclusions

The result of the investigations is exclusively directed towards the condition of the insulation system with consideration of several factors such as load, technical diagnostics and qualitative characteristics. The aim was to make a kind of benchmark of all investigated machines. This should result in making the right decisions about further operations, maintenance activities or replacement measures.

The overall condition evaluation and assessment contribute considerably to the estimation of future maintenance expenditure and the need for replacement investments. Hence, it is the starting point for strategic and economic considerations and risk analysis. For a renewal investment or the introduction of a revision the economic significance of the operational funds has to be considered too.

[1] Hydrogenerator failures - results of the survey, Study committee SC11, EG11.02, CIGRE 2002

[2] Rupp, C.: Condition evaluation of rotating electric machines; diploma thesis, Graz University of Technology, 2005

[3] Muhr M., Sumereder C., Rupp C.: Zustandsbewertung rotierender elektrischer Maschinen; commissioned study not published, Graz University of Technology, 2006

[4] Stone G., Warren V.: Differences in Stator Winding Partial Discharge Activity Between Manufacturers; Iris Power Engineering, ISH, Beijing, 2005

[5] Egger H.: Strategien zur Überwachung der Hochspannungsisolierung von Betriebsmitteln der elektrischen Energietechnik; Habilitation, Graz University of Technology, 2002

[6] ELIN: Revisionsempfehlung für horizontale / vertikale Synchronmaschinen mit Trag- und Führungslager; 1983

[7] Stone G. C., Boulter E. A., Culbert I., Dhirani H.: Electrical Insulation for Rotating Machines – Design, Evaluation, Aging, Testing and Repair; IEEE Press, 2004

Authors

DI. Christian RUPP
Kärntner-Elektrizitäts-Aktiengesellschaft (KELAG), Austria
E-mail: christian.rupp@kelag.at

DI. Dr. Michael MARKETZ
Kärntner-Elektrizitäts-Aktiengesellschaft (KELAG), Austria
E-mail: michael.marketz@kelag.at

DI. Dr. Christof SUMEREDER
Graz University of Technology
Institute of High Voltage Engineering and System Management, Austria
E-mail : sumereder@hspt.tu-graz.ac.at