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Failures of Electrical Machines - Review

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***Abstract*—In general, there are many types of electrical rotating machines and transformers within various classes of power range and duty cycles. These machines are operated under either industrial or civil conditions. It is a matter of fact that every machine can eventually fail and both damage and losses can occur. Therefore it is necessary to evaluate failure rates and their distribution over certain types of electrical machines and their subsystems. This paper presents an analysis based on the publicly available data, summarizes and compares results obtained from the studies which have been carried out in the past years. In this paper, important machines' subsystems in terms of failure rate are identified. The failure rate is presented in examples. The cause and location of the faults are discussed. Furthermore, this paper suggests general possible procedures for failure elimination or mitigation of the risks. Outcomes of this paper may be important in the field of maintenance, diagnostics and testing, project management and asset management.**

***Keywords*—Transformers, Generators, Electric motors, Failures, Maintenance**

I. INTRODUCTION

Both the transformers and the rotating electrical machines are widely used in many fields of industry and civil applications and many of them are critical in terms of their location in the network or the function itself. Hence those machines might be crucial for the function of the whole particular technology. It is highly beneficial to have a knowledge of electrical machines' failures in order to take the risks into account and reevaluate the service plan, maintenance strategy or even design of those machines. Although many studies have been published on the failures of various types of electrical machines, this paper claims to present an overview of outcomes of several studies oriented on the failures of each main type of electrical machines in order to make an overview of failures' origins with importance given to broken components or subsystems of the machine type and failure rates. Subsequently it is needed to use procedures within field of asset management and set appropriate maintenance strategy in relation to the importance and level of risk linked to the certain asset. Asset is a general term for an electrical machine for this paper's purposes.

II. ELECTRICAL MACHINES' FAILURES

In following sections the failures of electrical machines will be categorized by faulty components along with specific information about each type of electrical machine.

A. Transformers

A study [1] has been carried out in the location of South America, Brazil in particular, and it was focused on power transformers within the electrical network. Those transformers were filled with mineral insulating oil. The faultiest components of such transformers were: windings (34 %), bushings (14 %) and tap changers (20 %) - both switched with or without load (approximately the same portion of 10 % failures of each type of tap changer). Results of study [1] are shown in Fig. 1.

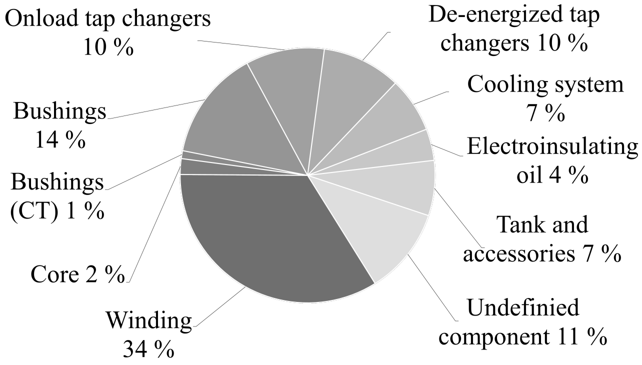

Fig. 1. Failures of transformers' parts.

These outcomes are in accordance with the interim report [2]. This report contains data about substation transformers and step up transformers. However, a slight difference between these two types of transformers can be observed. Step up transformers had proportionally less failures at tap changers, but there is a higher portion of failures related to lead exits. Authors also stated that in general there is a significant decrease of failures on the tap changers compared to the study [3]. Overall failure rates according to [2] are calculated as 0.43 % for substation transformer and 0.46 % for step up transformers. This interim report mentions that for certain voltage level there are low sample sizes and thus should be taken into account with caution. However, overall failure rate values are corroborative by the reference [4], which determined average failure rate for European substation transformers as 0.5 % per year. Failure rates of transformers are calculated according to Eq. 1, where λ stands for failure rate per year in percentage, m_i is the number of transformers which failed in the i^{th} year and the M_i is the number of transformers

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that has been in service in the i^{th} year. Authors have also stated that various maintenance strategies and repairs were carried out, thus data are not suitable for lifetime modelling based on statistical distribution.

$$\lambda = \frac{\sum_{i=1}^{n} m_i}{\sum_{i=1}^{n} M_i} \cdot 100 \tag{1}$$

Reference [4] also indicates that the most significant failure locations are tap changers, windings and bushings, but it also offers a different perspective in terms of the nature of the failure. As the major ones the dielectric (31.3 % of failures) and mechanical (20.4 %) have been determined. Worth mentioning is also the effect of the failure. In a significant majority, no external effect has been reported (78.7 % of events), but still the fire (9.5 % of external effects reported), explosion (3.32 %) or leakage (5.7 %) may occur.

III. GENERATORS

Since the turbo and hydro generators are such complex technical devices which are commonly designed for long lifespan and specific requirements [5], there is a problem to find a significant number of similarly oriented studies on the failure origin, faulted component and failure rates. However, for turbo generators the reference [6] presents a percentage of failures related to subsystems of turbo generators. As it is shown in Fig. 2, the distribution of the failures across these subsystems is quite uniform, but still the stator contains the most failures [6].

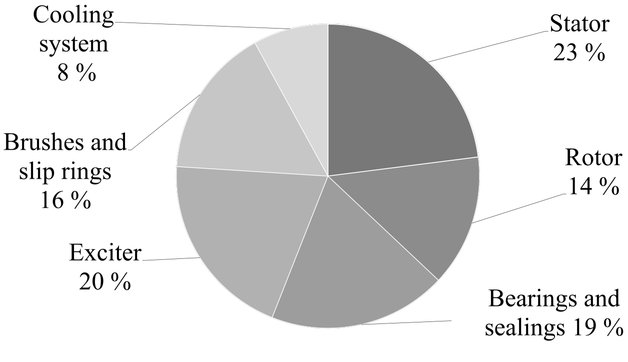

Fig. 2. Failures of turbo generators.

The Allianz insurance company's data has been revealed in report [5] and it states that the majority of failure causes are related to the design and materials and operation of the generator itself, the aging with other causes is the minority here. Report [5] also presents results of the North America Electric Reliability Corporation (NERC) analysis. There are three main components that fail the most: stator winding, rotor winding and rotating parts. In the report, there is also stated that appx. 100 failure modes can be distinguished for turbo generators and most of them are related to the stator winding, core, connections and the rotor. This is in accordance with the publication described in reference [7] by Samodorov. It describes 112 specific turbo generator failures and again most of them are associated with the stator winding and rotor.

Study [8] refers to results of the International Council on Large Electric Systems (CIGRE) report [9] which assesses the failures of hydro generators and the mostly failed component has been investigated further. The insulation system has been identified as the faultiest component and it turned out that the most reported cause of its breakdown was natural aging of insulation. Other significant causes based on were winding contamination and internal partial discharges [9]. Whole chart with percentage portions is shown in Fig. 3.

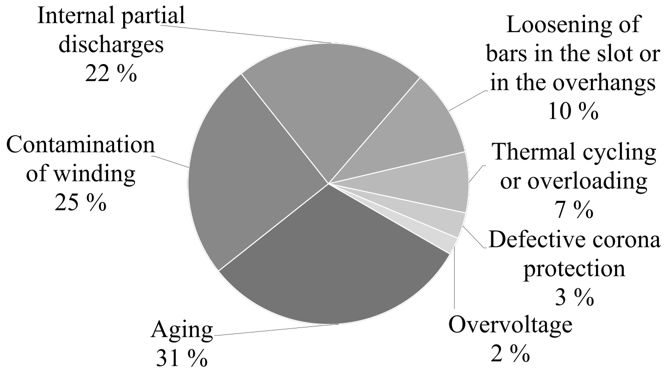

Fig. 3. Hydro generators' failure causes.

A. Electric motors

These machines operate within a wide range of applications including the critical ones. Therefore the assessment of their faults might be beneficial for maintenance strategy, chosen diagnostic signals and the upkeep itself. The well known Electric Power Research Institute (EPRI) study [10] was originally introduced back in 1983 (4 785 machines surveyed) and in 1986 (additional 1 527 machines) the updated version was published. It contains a solid amount of data about machines from 65 sites in different geographic locations, made by various manufactures and failures were assessed for 6 312 motors. Range of applications includes fans, pumps and drives for various purposes in power plants. Types of machines surveyed were induction motors (both squirrel cage and wound rotor) and synchronous motors. Failures distributed over the most general main motor parts according to [10] are shown in Fig. 4. The following specific components failed most frequently: ground insulation (17.9 % of all failed machines reported) followed by sleeve bearings (11.4 %) and ball bearings (5.5 %) [10].

Bearings related failures are for instance associated with failure of various types of bearing (sleeve, thrust, ball bearings), leakages, seals or oil systems. Stator related failures are especially ground insulation failure, turns insulation, bracing, wedges, frame or cable and connections. Rotor failure are represented mainly by cage, shaft, core and balance weights. Study [10] states in reference to IEEE survey's data in [11] that

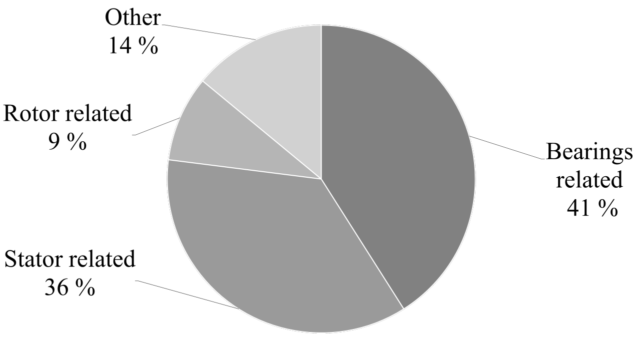

Fig. 4. Failures of electric motors' main parts.

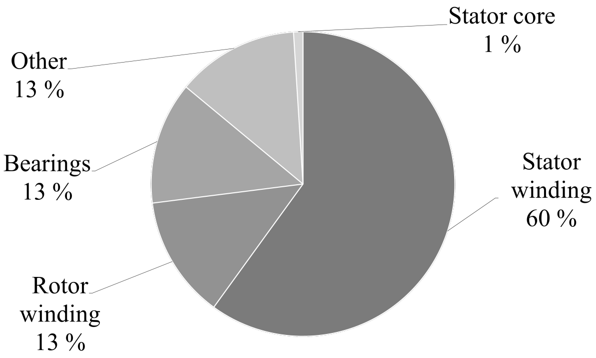

Fig. 5. Failures of synchronous motors' main parts.

the distribution of failures across the main construction parts is generally the same. The accordance in main component failure distribution from [10] is confirmed in the discussion section in [11]. Study [10] also highlights that overall failure rate differs. The overall failure rate in EPRI study [10] has been determined as 3.12 % per year and the study also points out that the IEEE study [11] reported 7.08 %. IEEE survey [11] uses a metric for expression of sample size as well. Failures per unit years $FPUY$ can be calculated directly using Eq. 2. It is quite similar to the failure rate λ defined in Eq. 1, however the denominator is already known by defining the sample size in unit years.

$$FPUY = \frac{\text{Number of Failures}}{\text{Sample Size in Unit Years}} \tag{2}$$

Further studies on the issue have been conducted. Methodology used in study [11] was also applied in references [12] and [13] which were more focused on high voltage induction motors in the oil and petrochemical industry, gas terminals and oil refineries. Overall failure rates could be calculated as total number of failures divided by total sample size in unit years resulting in value 6.38 % based on data from reference [12], but it should be noted that failure rates also depend on many parameters such as power, voltage level, maintenance intervals, age of the machine etc.

It should be pointed out that motors operated in outdoor environment had significantly higher failure rate according to both surveys [12] and [13].

Synchronous motors' failures are discussed in the introduction section of [14] and the distribution of faulty component was presented. As it is shown, for high voltage motors the majority of failures is reported for the stator winding (60 %) followed by rotor winding and bearings (13 % each). Chart is shown in Fig. 5.

IV. FAILURE PREVENTION AND RISK MITIGATION

As the risk of failure of key electrical machines might be significant, the more concerned should the asset owner be. Establishing the asset management system is recommended. This system has its processes, hierarchy, related standards and beside the technical side it requires company's management involved. The PAS 55:2008 standard for physical assets should be mentioned. The more general standard ISO 55 000:2014 has been introduced afterwards and it describes asset management mainly for tangible assets, but it can be also applied for intangible assets. As it is stated in the standard, the aim is to establish balance between costs, risk and performance. Moreover, this standard introduces evaluation of assets in terms of financial costs as well as environmental and social costs, risks and quality of services and performance which are related to the certain asset.

Maintenance interval may affect the failure rate significantly as it is shown in [12], [13]: 12 month or less (1.24 % and 4.03 %) and 24 months or more (8.81 % and 14.29 %). Maintenance in levels of safety checks, limited inspections and major overhauls are recommended to distinguish, as each maintenance level has different time requirements and capabilities to identify and detect failures [6].

Also several maintenance strategies may be applied. The oldest and the simplest one is the maintenance after failure. This approach is called incident-based maintenance (IBM) or corrective maintenance. This strategy has no special requirements for a monitoring system and therefore there are not any related additional costs. On the other hand, failure is indicated by the faulty state and the machine is no longer operational. This could be satisfactory for relatively cheap machines, which are easy to replace or repair and the failure has no severe consequences. Then, a few more strategies may be distinguished for machines whose failures might have several consequences. The time-based maintenance (TBM) follows the scheduled maintenance plan and is often based on bathtub curve, while the condition-based maintenance (CBM) monitors diagnostic signals in order to evaluate the real condition of the monitored machine. Another possible strategy is risk-based maintenance (RBM) which assesses the hazard through risk analysis and adjusts the priority of assets or their components and subsequent range of maintenance actions and intervals [15]. Aforementioned basic maintenance strategies are depicted in Fig. 6 as the system condition in time. This figure is meant for demonstration purposes only and is based on ideas presented in [16].

For instance, system health indicators might be (i) certain

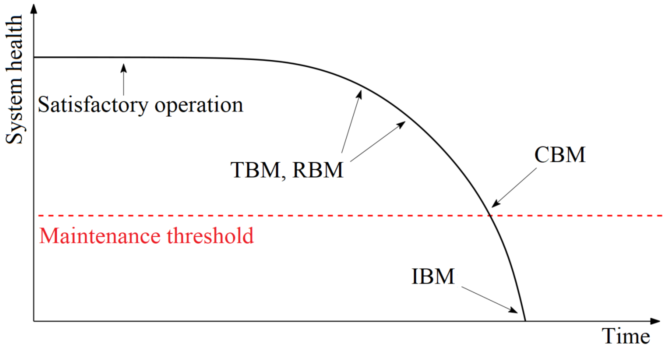

Fig. 6. System health as the function of time with various maintenance strategies.

diagnostic signals (e.g. resistivity, partial discharges etc.), (ii) operational signals such as vibrations, temperature in particular locations, or (iii) remaining useful life. The time dimension is usually expressed in hours or years.

Latest trend in this area is predictive maintenance (PdM) which is extending capabilities of CBM strategy by prediction of the trend of evaluated diagnostic signals. This approach uses methods of artificial intelligence (AI) [17].

CONCLUSION

An evaluation of electrical machines' components, failure rates and specific outcomes of mentioned studies was carried out. These studies focused on power transformers, turbo and hydro generators and electric motors.

It was found out that transformers have lower failure rate than electric motors. Unfortunately, the failure rates of generators have not been compared because no such study dealing with failure rates could be found. This may be due to the specific design and application of these power electrical machines, which generators certainly are. A failure study of transformers filled with alternative electrical insulating liquids such as synthetic esters and natural-based esters should be carried out and thoroughly evaluated.

Assessment of risks and operational conditions should be taken into account and a suitable maintenance range, period and strategy should be chosen. Even though this seems obvious, data has confirmed that shorter maintenance intervals lead to lower failure rates.

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