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Reliability Assessment of Alternator Winding Using Mathematical Modelling

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Abstract- The Aim of present work is to asses the reliability of alternator winding which being the most fundamental element of Alternator. A mathematical model for time based assessment of reliability is developed. The model has been tested on the alternator winding and results summarized. Also due to continuous duty of alternator the alternator winding is left to undergo sustained increase in temperature which in turn is responsible for degradation in quality of insulation. When the degradation of insulation at a particular time falls below a threshold level the alternator winding is considered to lose reliability and it no more remains serviceable.

Keywords- Reliability, Alternator winding, Degradation, Insulation, Temperature.

Introduction

Alternator winding is the most fundamental constructional element of alternator. It is marked as the place or body where the e.m.f. is induced in the alternator due to relative motion between the stator winding (conductor) and flux. Alternator winding is fixed in stator by following winding rules while the flux is created by the field winding wound on magnetic poles mounted on rotor. The filed winding is given D.C. supply with the help of an exciter. Also the relative motion between rotor flux and stator winding is achieved by making rotor to rotate with the help of turbine impeller run by a steam power plant.

It is important to point out here that the generation of power could be ensured if and only if the alternator winding has no short circuit i.e. no faulty condition.

Here comes the question of reliability of alternator winding. Since the alternators have to maintain generation over months and years without any rest, the windings of alternator come across high temperature. The insulation of winding undergo deterioration and it loses its dielectric strength and ultimately with time it leads to breakdown of insulation or loss of reliability or end of life of alternator winding. The purpose of present work is to assess the reliability of alternator winding on time to time basis and to determine the moment or the length of time when the winding is no more useful. Such a moment will mark the loss of reliability of alternator winding or the end of useful life of stator winding. In the present work a mathematical model has been proposed for assessment of reliability of stator winding of an alternator on the bases of usage and lapse of time.

The authors of [1] noted that the shortcomings or flaws of the earlier systems were the need for a significant quantity of data, lengthy computations, intricate modeling, and low accuracy. As a result, the authors set out to create a goal that would have a reliable estimation of assessment. In order to solve these flaws, the authors suggested a novel method for dependability study of power systems based on artificial neural networks (ANN). It has been demonstrated that by strengthening the ANN's training patterns, the reliability estimate accuracy has been increased. The acquired findings line up with IEEE reliability test systems, confirming the validity of the presented technique.In order to explain various brittle fracture modes, [2] developed a much better version of a brittle fracture model based on the production of nitric acid in service via corona discharges, ozone, and moisture. Only the most crucial elements of the brittle fracture process and the background data have been covered in the study. The failures are linked to SCC of the insulator GRP composites, and the paper brittle fracture model states that there are primarily two types of brittle fracture failures that can happen in service. The chemical compositions of the glass-reinforced polymer rods have been optimized in this article as a means of preventing brittle fracture or failure in service.A report describing an improved test system (RTS-96) with a number of changes for use in bulk power system reliability evaluation studies is provided in [3]. No user should feel pressured to adopt all of these improvements because they were designed to be 'optional' upgrades. It is expected that one will be more suited than the others for a given application, and it is up to the user to make a choice. Authors supplied one, two, and three area systems for analytical purposes. The test system was created by revising and modernizing the original IEEE RTS (also known as RTS-79) to account for advancements in assessment techniques.In [4] it was mentioned that because diagnostic testing and condition monitoring (DTCM) on pro-rated OIP bushings based on terminal measurements is frequently inconclusive and occasionally leads to dangerous conclusions, authors advocated controlled accelerated ageing experimental designs. The essential thermal concepts of power transformers, operational philosophies, and thermal protection strategies were covered in [5]. To do this, the microprocessor relay's 49 thermal functions relied on observed or estimated top-oil temperatures and an estimated hottest-spot winding temperature. This relay also forecasted the hottest location winding temps for the upcoming minutes or hours. Nameplate information, measurements of current, ambient temperature, and top-oil temperature are all needed for the relay algorithm. The nameplate data specifications, the real-time current, and the outside temperature can all be used by the relay to approximate the top-oil temperature if it is not accessible.[6] sought to present the hot-spot and top-oil temperature models since these temperatures grow above ambient temperature models and thermal models when subjected to linear and non-linear loads. Authors developed a MATLAB simulink IEEE and thermal dynamic model via MATLAB to calculate the oil and hot spot temperatures of power transformers with more accuracy. The hot spot, top oil, and loss life of power transformers under harmonics load were determined after the models were applied to 25 MVA, 66/11 kV ONAF cooling transformer units under various loadsThe relationship between space charge and the aging processes of polymeric insulation was highlighted by researchers in [7]. The aging of polymeric insulation under dc and ac pressures is illustrated in the paper with regard to the role played by space charge. Under the implicit presumption of a geometrical field distribution in the insulation, the aforementioned (and other related phenomenological) models take rate constants that rely on electrical field into account.According to [8], the winding insulation of a power transformer is what determines its dependability, and the winding insulation is constructed of cellulose insulation that has been soaked with insulating oil. To evaluate this writer Consider a 47-MVA transformer that has a tap changer of around 8 steps at the neutral end of the HV winding and a 120/26.4 kV, wye/delta connection. Each step modifies the primary's rated voltage by 2.25 kV, or 1.875% of the rated voltage when the primary is in the neutral state. The secondary side (26.4 kV) tap changer on these transformers is designed to control voltage, so fluctuations in voltage and current may be seen. The results show that the aging of winding insulation is exponentially related to temperature.

The literature survey unveils that a large amount of work has been done over the transformer winding and now investigations are needed to be address over alternator winding.

Motivated by previous works it is aimed in the present work to develop a novel mathematical model for the reliability assessment of alternator winding. A mathematical modelling is presented and an benchmark example has been discussed in detail to address the aforementioned issue.

The remaining part of paper is organized in following manner. Section II reports the mathematical modelling. Section III provides an illustrative example of the proposed approach. Finally the paper is concluded in section IV followed by relevant references.

Section II

Mathematical model for Reliability Assessment

Assessment of Dielectric Strength of Winding Insulation

The highest continuous electric field strength that a material can tolerate without degrading or losing its insulating qualities is referred to as the dielectric strength (also known as voltage breakdown).

Furan content in oil and degree of polymerization are used to gauge the insulation quality or dielectric strength of winding insulation.

Release of Furan

It is the deterioration caused by the erosion of insulating material. The growth of heat as a result of insulating resistance and leakage current is what causes this deterioration. The insulation material degrades, erodes, and releases furan material because heat has evil effect on insulation body. The rate of erosion grows with time and loading as this process lasts for years.It also depends on the Alternator's degree of loading. . 5-Hydroxymethyl, 2-Furfural, 2-Furfuryl Alcohol, 2-Furfural, 2-Acetyl Furan, 5-Methyl, and 2-Furfural are all components of furan . The total of all the aforementioned components is referred to as the furan. The total furan release should not exceed 3200ppb (parts per billion); anything beyond this level denotes deterioration of the solid insulation. The dielectric properties of the winding insulating material are affected due to accumulation of heat respectively.

Rate of release of furan content:

$$F(t) = \lambda P_{\text{Leakage Loss}} t^2 \sqrt{e^{\left[\frac{B \times C}{(\theta_W + 273)n}\right]}}$$

Where

$F(t) = \text{Furan release at time t}$

$\lambda = \text{Degree of loading}$

$P_{\text{Leakage Loss}} = \text{Leakage loss at different loading}$

$t = \text{time in years}$

$B = \text{insulation Quality Factor}$

$C \text{ and } n = \text{Empirical Constants (Depends upon oil circulation)}$

$\theta_W = \text{Winding Temperature}$

Degree of polymerization (DP)

A sheet of cellulose-based material is utilized as the solid insulation to protect the conductors of the alternator's windings. The polymeric and fibrous structure of cellulose affects its mechanical strength. The DP value refers to the count of monomer units that remain present in the polymer chain. This DP value is used to assess the cellulose material's quality. A diagnostic tool to ascertain the state of the solid substance is the DP value. The DP value of a new insulation winding of alternator is predicted to be 800. The DP value of winding insulation may be theoretically approximated based on the release of furan from winding insulation.

$$DP(t) = DP_{\text{initial}} \sqrt{e^{(-F(t) \times K)}}$$

Where

$DP(t)$ = Degree of Polymerizationat time t

$DP_{Initial}$ = Initial value of DP

K = Thermal conductivity coefficient

Dielectric Strength of Winding Insulation

The dielectric strength of insulation fluctuates depending on the degree of polymerization, and as the DP value falls, so does the insulation's dielectric strength. Mathematically speaking, the following describes how the dielectric strength of winding insulation degrades over time based on the DP value:

$$DS_{WI}(t) = DP(t) \times \sigma \times \sqrt[3]{(1 - d \times t)}$$

Where

$DS_{WI}(t)$ = Dielectric Strength of Winding Insulation at time t

σ = Surface Tension Coefficient

d = Direct Stress coefficient

Assessment of Reliability of Alternator Winding

The dielectric strength of the winding insulation, may be used to assess the alternator's dependability. This value can be calculated using the averaging theory described by

$$DS_{Net}(t) = DS_{WI}(t)$$

Therefore

Reliability(%)= (K_5-K_6/(DS_Net (t)))×100

Where

K_5=DS_(Net Initial)/(DS_(Net Initial)-DS_(Net Threshold))

K_6=DS_(Net Threshold)×K_5

Section III

Illustrative Example

Testing and validation of Mathematical model

As we observed that the reliability of Alternator depends upon the dielectric strength of its winding insulation. The rate of decrease in dielectric strength is mainly due to the formation of furan content and degree of polymerization. By reducing the load on Alternator the rate of furan content formation and degree of polymerization can be controlled. Here we are determining the time duration till which alternator winding insulation does not fail or reliability of winding remain faithfully dependable as fare as the generation of voltage is concerned.

Case Study

Consider the following issue: Estimation of Alternator Reliability Affected by Dielectric Strength of Winding Insulation with Aging Time 't'.

Benchmark Problem: Evaluate the dependability of a 400MVA power alternator that is being utilized to supply 400kV transmission line. This alternator has an ageing time of t, full load leakage losses of 1.6 MW, and 550oC winding temperature. Also check the dependability of alternator winding under full load or 100% loading condition. Select different statistics, according to the Indian Electricity Rules of 1956.

Solution: It is important to note that alternator dependability decreases over time (t). This is because, a decrease in the degree of polymerization cause the dielectric strength of winding insulation of alternator to decrease with time. This leads to (i) Estimation of dielectric strength of winding insulation

Rate of release of furan:

$$F(t) = \lambda P_{\text{Leakage Loss}} t^2 \sqrt{e^{\left[\frac{B\times C}{(\theta_W+273)n}\right]}}$$

Where

$$F(t)_{\text{Threshold}} = 3200 \text{ ppb}$$

$$\text{for } 100\% \text{ loading } \lambda = 1, P_{\text{Leakage Loss}} = 1.6 \text{ MW}$$

$t = \text{time in years}$

$B = 1500, C = 0.0417, n = 0.59$

$$\theta_W = 55^0\text{C}$$

Degree of polymerization (DP) at time 't' based on furan content is given by

$$DP = DP_{initial}\sqrt{e^{(-F(t)\times K)}}$$

Where

$DP_{Initial} = 800$

$DP_{Threshold} = 300$

$K = 1.78 \times 10^{-4}$

Dielectric strength of winding insulation:

$$DS_{WI}(t) = DP(t) \times \sigma \times \sqrt[3]{(1 - d \times t)}$$

Where

$\sigma = 0.05625\ N/m$

$d = 0.000172$

$DS_{WI\ Initial} = 45\ kV/mm$

$DS_{WI\ threshold} = 35\ kV/mm$

The overall reliability of Alternator is affected by dielectric strength of winding insulation. It is given by

$$DS_{Net}(t) = DS_{WI}(t)$$

$$Reliability_{Alternator}(\%) = \left(K_5 - \frac{K_6}{DS_{Net}(t)}\right) \times 100$$

Where

$K_5 = 4$ and $K_6 = 120$

$DS_{Net\ Initial} = 40\ kV/mm$

$DS_{NetThreshold} = 30\ kV/mm$

For Full Load or 100% Loading

The table 1 shows the assessment of dielectric strength and reliability of Alternator with 100% loading at the end of every year.

Table 1

Alternator reliability affected by the dielectric strength of winding insulation with 100% loading

Years (t)	Furan	DP	DS_{WI}	DS_{Net}	Reliability (%)
0	0	800.00	45.00	40.00	100.00
1	2	799.87	44.99	39.99	99.95
2	8	799.46	44.96	39.97	99.81
3	17	798.80	44.92	39.94	99.57
4	30	797.86	44.87	39.90	99.22
5	47	796.66	44.80	39.84	98.76
6	68	795.19	44.71	39.76	98.17
7	92	793.47	44.61	39.66	97.46
8	120	791.48	44.50	39.55	96.62
9	152	789.23	44.37	39.43	95.63
10	188	786.72	44.23	39.28	94.50
Continued…					
32	1926	673.99	37.84	31.48	18.75
33	2048	666.70	37.43	30.94	12.21
34	2174	659.26	37.01	30.40	5.32
35	2304	651.69	36.58	29.85	-1.95

The manner in which dielectric strength of winding insulation and reliability at 100% or full loading with ageing is graphically shown in Fig.1.

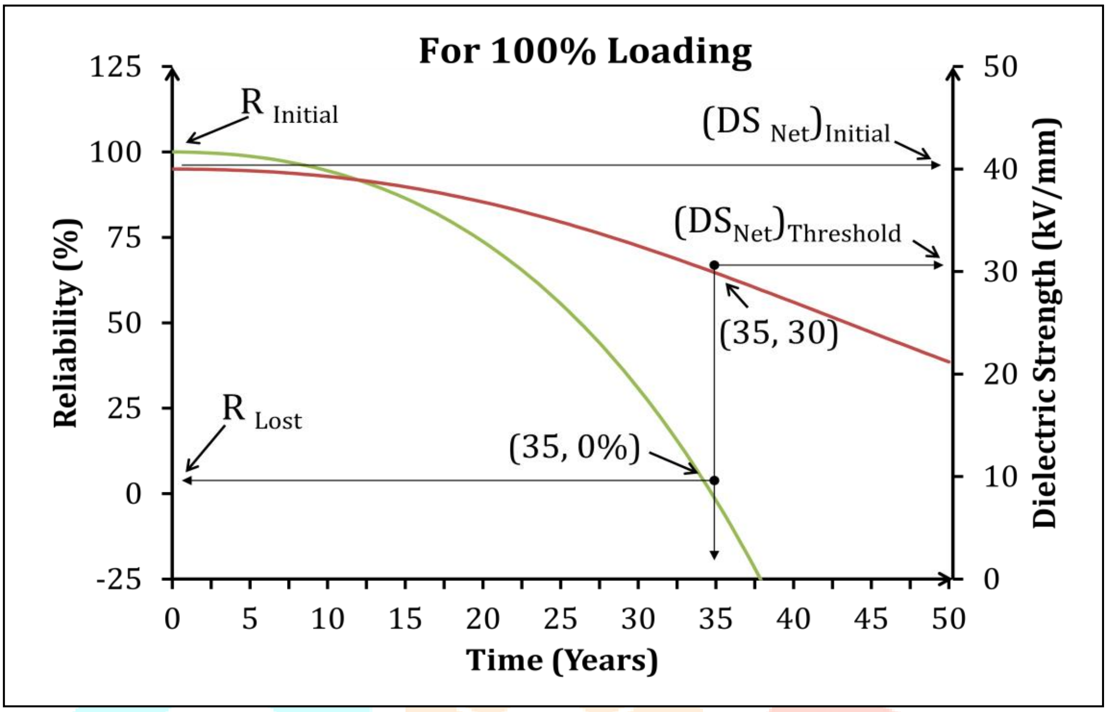

Fig. 1 Assessment of Reliability of Alternator for 100% or Full Load Loading

It is clear from "the calculation and graphical analysis that the reliability of Alternator winding at 100% i.e. full load loading is affected by decay in dielectric strength of winding insulation" .Also it takes 35 years for the overall dielectric strength of an Alternator to completely reach to its threshold value, i.e. 30 kV/mm. After 35 years the alternator winding loses its dependability or reliability.

Section IV

Conclusion

The alternators work continuously over months and years without rest to feed power to consumer in an uninterrupted manner. As such the winding of the alternator suffer sustained increase in temperature. This in turn causes degradation in quality of insulation. With the presage of time the insulation fails to act as insulation and leads to short circuit in stator winding and finally failure of winding is inevitable. This stage is marked by loss of reliability of alternator winding. The alternator thus fails to generate electricity thereafter.

In the present work efforts are made to develop mathematical model for assessment of reliability of alternator winding when it is affected by infusion of heat in winding due to regular increase in temperature across the insulation of alternator winding. Next the proposed mathematical model has been tested through an illustrative example. The model provides the assessment of reliability as a function of time. It therefore supports to evaluate the time to failure of insulation and the moment when the reliability of alternator winding would be lost.

Such an out come is of great value to alarm the maintenance engineer to remain ready with the stepney of new alternator to replace the running one. This also spares the engineer from keeping in reserve of so costly alternator even when not needed.

Future Direction: Reliability assessment can also be extended to reliability of field system. Later the combined effect of failure of field and alternator winding could be studied in assessing the reliability of alternator as a whole.

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