Prediction of Stator Winding Remaining Life From Diagnostic Measurements

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Abstract- Diagnostic tests such as insulation resistance, polarization index, dissipation factor, capacitance and partial discharge can be useful to diagnose the condition of the stator winding insulation, and identify many problems that could lead to insulation failure. Many years of experience, however, has shown these quantities by themselves cannot predict the remaining life of a winding. However, asset managers would prefer an estimate of the remaining stator winding insulation life. Knowing the remaining life allows asset managers to obtain the maximum use from the existing winding, while avoiding in-service failures and permitting the planning of the optimal time to rewind. Over the years, various machine repair organizations in Japan, Europe and India have claimed the ability to determine the remaining life. This paper examines the literature and practical experience using these remaining life estimation tools. It is concluded that there is no evidence that the available tools provide an accurate estimate of the remaining life. A protocol is suggested for evaluating the validity of any new method to estimate remaining life.

I. MOTIVATION FOR WINDING INSULATION LIFE PREDICTION

Plant managers and asset managers are not interested in diagnostic test results. Instead, they want to know when a motor or generator stator winding will fail. Since about 50% of machine failures are caused by winding insulation failure [1,2], it is obvious that they want to know the remaining (or residual) life of the windings. The reasons for wanting to get a good estimate of the remaining life are:

- To maximize the capital investment they have in the existing winding – i.e. to make it last as long as possible.
- To avoid in-service failure, with the consequent unexpected loss of production and the possibility of far more damage and repair costs than if the winding was repaired or replaced prior to an in-service failure.
- To budget (plan) for repairs or rewinds with at least a year or so forewarning, so that the cost and time for the repair can be anticipated and minimized.

There are a number of off-line and on-line diagnostic tests for winding insulation that have been widely used for many decades [3,4]. These include insulation resistance, polarization index, capacitance, dissipation factor and partial discharge (on-line and off-line). As discussed in relevant standards (IEEE 43, 286, 1434 and IEC 60034-27-1), it is well known that no individual test is a good predictor of remaining life. Instead the change in the test results over time, or the magnitude of the test result, can indicate that an insulation problem is developing.

The difficulty in predicting remaining life has several causes:

- There are in fact >20 different winding insulation failure processes [1]. It is not realistic to assume that one single test is equally sensitive to all these different failure mechanisms, any more than a single blood test can find all diseases.
- Some failure processes are slow (e.g. endwinding discharge which can take decades to reduce the insulation strength) whereas others are relatively fast (e.g. vibration sparking or slot discharge). Yet all these mechanism can produce the same high PD or high tip-up values.
- Although insulation does age, and presumably dielectric tests will reflect this aging, the actual moment of failure depends not only on the reduced mechanical and electrical strength of the winding, but also on the stresses applied. Often the actual time of failure is associated with a voltage or current transient (from voltage surges or power system faults) that exceeds the strength of the winding in its deteriorated condition. If the winding had not seen the transient, the winding may have survived for many years more. Without knowledge of the transient environment, reasonable estimates of remaining life will be very imprecise.
- Some common failure processes, such as endwinding vibration that leads to insulation cracking or abrasion, will not change any known dielectric property, except breakdown strength.

Nevertheless, plant/asset managers continue to encourage objective methods that can predict the remaining life for the reasons stated above. Thus machine manufacturers and/or their service organizations have developed several methods
that they claim can predict remaining life. This paper reviews
the three main methods that have been proposed and which
have been commercially available over the years. In
particular, their theoretical foundation is discussed, and
evidence as to their effectiveness is presented. All three
methods are based on using several different dielectric
measurements that are combined together to give an overall
assessment of remaining life. Remarkably, all have been
supported by a tremendous amount of dielectric theory. First, a
rapid review is made of the various individual diagnostic tests.
A few are relatively new.

II. DIELECTRIC DIAGNOSTIC TESTS

There are several diagnostic test methods that have been in
common use for decades and that are well documented in
standards as well as books and papers [1, 3-5]. These include:

- Insulation resistance and polarization index tests, described in IEEE 43. These are low voltage DC
tests that seem to be particularly sensitive to absorbed
moisture or surface contamination.
- The DC stepped stress or ramp test to measure
leakage current vs. applied DC voltage which is also
sensitive to surface contamination, moisture and
possibly insulation delamination. See IEEE 95 or [6].
- Dissipation factor tip-up (and the closely allied
capacitance tip-up) as described in IEEE 286. In
these two tests, the increase in dissipation factor with
applied AC voltage or increase/decrease in
capacitance as the voltage increases is a good
indicator of widespread insulation delamination,
although on complete windings, the presence of the
silicon carbide stress relief coating can cause
spurious changes, reducing sensitivity.
- Off-line or on-line partial discharge (PD) tests to
directly measure PD occurring within insulation
delamination, or surface PD caused by looseness in
the slot, etc. These tests are described in IEEE 1434
and IEC 60034-27.

More recently, several other dielectric tests have been
discussed. Some have been widely applied to dielectric
assessment in liquid filled transformers and/or power cables.
The polarization/depolarization current (PDC) measurement is
an off-line DC test where a significant DC voltage (from a few
thousand volts to rated voltage) is applied to the winding,
usually for about 1000s, and then the winding is grounded.
The charging and discharging current is then measured [7, 8].
The polarization and depolarization currents should be low. If
they are high, or they diverge from each other, then insulation
problems are developing. One author claims that the earlier in
time the two currents diverge from one another, then the closer
the winding is to failure [7]. The test is apparently sensitive to
contamination (as is to be expected), as well as surface
insulation damage caused by coil vibration in the slot.

A variation on the PDC test is the recovery voltage
measurement (RVM) [8-10]. RVM is now widely used to
assess the deterioration in oil paper insulated transformers,
where it has been found useful to detect thermal aging and
moisture content. In this test a voltage is applied for say 1000
s, then it is discharged to ground for a period of time, and then
the winding is disconnected from ground. The voltage then
climbs to a peak voltage and then declines after a period of
time. The peak voltage and the time to the peak voltage have
been found to be significant indicators of aging in transformer
insulation. It seems there has not been enough work to see if
these factors are significant for machine insulation [9,10].

Another dielectric test is done in the very low frequency range
(rather than with DC voltage). It is called dielectric
spectroscopy [9,10]. An instrument applies a very low
frequency AC to the winding, in the range of 0.1 mHz to a few
Hertz, and the dielectric loss is measured. In some sense this
is the frequency domain equivalent of the PDC or DC ramp
test. Dielectric spectroscopy has been found to be useful in
identifying power cables with water treeing.

More field experience is needed to see if any of these new
tests provide additional information or are easier, cheaper or
more reliable in finding the problems than the traditional
IR/PI, tip-up and/or PD tests. However, experience with the
PDC test, at least, is encouraging.

III. METHODS PROPOSED TO ESTIMATE
REMAINING LIFE

It seems to be widely recognized that no single dielectric test
can be used to estimate remaining life. However, several
researchers have investigated whether combinations of
dielectric tests can be used to estimate the remaining life of
stator winding insulation. The following reviews three of
these "combined test assessments" that have been proposed
and employed commercially.

A. Residual Breakdown Voltage

Different Japanese researchers proposed an indirect way to
estimate remaining life in the 1980s by first calculating the
"residual" breakdown voltage from classical diagnostic tests
including IR/PI, capacitance and dissipation factor tip-up and
PD magnitude [11-13]. The idea was that if one could
estimate the AC breakdown voltage of a winding from non-
destructive diagnostic tests, then one could determine how
close this estimated voltage is to the normal operating voltage
(with perhaps some margin for normal voltage transients), and
thus indirectly determine the remaining life. The key finding
in these studies was that a combination of insulation
resistance, polarization index, capacitance tip-up, dissipation
factor tip-up and/or off-line PD peak magnitude could predict
the residual breakdown voltage, and several experimental
studies supported this contention. Regression equations were
developed which would predict the residual breakdown voltage on windings from the diagnostic tests. Most of the supporting investigations were based on laboratory accelerated aging tests and/or using coils that were removed from the stator prior to diagnostic and breakdown voltage tests.

In the mid 1980s EPRI sponsored an extensive independent investigation to evaluate the validity of the residual life estimation method [5]. Four stators, one from a motor, one from a hydrogenerator and 2 from turbogenerators, were subjected to a range of diagnostic tests suggested by the researchers [11-13], and then coils/bars or parallels were tested to destruction with either 60 Hz AC, DC or impulse (1.2 microsecond risetime). All the testing occurred with the windings still in the stator. None of the stators were near their end of life, as judged by expert visual examinations, but they had seen one to three decades of operation. The results were disappointing. Figure 1 shows the scatter plot of the diagnostic quantity “K”, which is claimed to predict the residual AC breakdown voltage, and the measured breakdown voltage on a number of bars tested within the stator. There appears to be no correlation between K and AC breakdown voltage. Other predictive equations based on diagnostic tests showed equally poor correlation [5]. We are unaware of more recent research that indicates that the residual breakdown voltage approach is viable. Thus, we can only conclude that this approach may work in the laboratory, but not on real stators.

It seems that this method is still used today by some of the machine manufacturers.

B. Modified PD Test

Also in the 1980s, a test method called “TestACEC”, was proposed [14, 15]. ACEC was a Belgian rotating machine manufacturer. Instead of using the conventional diagnostic tests described above, Goffaux proposed a new technique that involved the measurement of “V_{BF}”, as well as the more conventional peak PD magnitude (Qm). The method allowed the direct prediction of the remaining life of the stator winding insulation. The details of the method are proprietary, but it involved the measurement of PD at a lower than typical detection frequency. Goffaux suggested that the remaining life is better estimated by determining what happens to the charge after a partial discharge (rather than measuring the PD itself), and in particular if any mobile ions that result from the PD can accumulate to further degrade the insulation. The measurement used a modified Schering bridge, where the 50/60 Hz AC voltage was gradually increased to rated voltage. Although not published, it seems the Qm and V_{BF} were measured in the few tens of kiloHertz range. A number of case studies were published that indicated that the new method correctly predicted remaining life (that is, failure occurred at the predicted time) [14, 15].

Again, EPRI sponsored an independent evaluation of this method [16]. In this case, since proprietary equipment was needed, the tests were done by the test developer. The testing was done on several 80 MVA hydrogenerators owned by Ontario Hydro. The condition of the generator stator winding insulation was well known (and ranged from excellent to poor) by the utility based on on-line and off-line conventional diagnostic tests, and most importantly, by expert visual examination. The researcher was unaware of the winding condition, prior to his assessment. The new method predicted that a few of the generators were at risk of imminent failure. This was in contrast to the utility assessment. The new method predicted that a few of the generators were at risk of imminent failure. This was in contrast to the utility assessment. In fact the machines predicted to fail operated for at least a decade longer, and were rewound only because the units were being uprated. Thus, it seems that independent (blind) evaluation did not validate the method. Apparently this method is no longer in commercial use.

C. Combined Dielectric Test and Life Method

Pinto has published several papers on the dielectric behavior of stator winding insulation over its life [17-19] and combined it with a model of how life is consumed to predict the remaining winding life in an approach called “LEAP”. Pinto was one of the first to suggest that DC polarization/depolarization current measurements may provide more information on the state of the stator insulation [17]. He also suggested that measuring the change in the dissipation factor and capacitance during the AC cycle could provide useful information that delamination was present [18], much as Simons and Dakin had done previously [20,21]. In his approach, Pinto also uses conventional IR/PI, off-line PD and tip-up tests. None of the papers indicate how one moves from the dielectric measurements
to remaining life, and certainly none of the methods described above indicate that diagnostic tests alone can predict remaining life.

However, in a few case studies published in marketing literature, it seems that the new method assumes that each stator winding has an assumed design life (200,000 or 400,000 hours, roughly corresponding to 20 or 40 years), and the “life” is consumed linearly with hours of operation, with the addition of 20 hours for every machine turn-on. Presumably the AC and DC diagnostic tests amend this simple linear model for the consumption and yields a prediction of the remaining life (design life minus modified consumed life). The assumption that life is consumed linearly at a steady rate seems oversimplified. In addition, it is almost certain that machine manufacturers did not design the winding for a precise life such as 20 or 40 years, since apparently, even identical insulation samples will produce a 10 to 1 variation in life under thermal, electrical and mechanical accelerated aging tests [1]. If the method is predicated on an accurate design life, then the method seems flawed.

Unlike with the other prediction methods described above, to date there apparently is no independent verification by a third party on the validity of this new method. To validate the method, the test organization would need to disclose the method in its entirety to a third party to enable replication, or apply the method to several stator windings. The machines would then need to be operated to failure to determine the accuracy of the estimates.

IV. CONCLUSION

Asset managers desire accurate methods to predict the remaining life of equipment, and rotating machine stator windings in particular. Over the years at least three methods have been proposed which claimed to predict the remaining life, and thus enable asset managers to determine when repairs or replacement is required. In independent evaluation, two of these methods were not validated. Until independent evaluation is done on the most recent method to predict remaining life, there seems to be little scientific reason to expect this new method will be any more accurate.

The goal of remaining life estimation is a valid one. Based on the data above, it does not seem likely that diagnostic tests on their own can accomplish the task. Perhaps at best a probabilistic approach would be achievable.

REFERENCES