

The Reliability Effects of Transient-Induced Degradation on the Performance of Large Power Transformers

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Abstract: Increased knowledge of the effects of severe operational transients on component reliability, in combination with currently used mechanistic component degradation models, could augment the predictive capability of reliability modeling. A new component reliability model has been developed that considers the effects of both types of degradation. An application of the new model was sought in order to provide insight into both the sources and consequences of severe component transients and how these considerations can be formulated into a new framework for component aging management supporting component reliability programs.

The large power transformer was selected for demonstration of this new reliability model. This component was selected as it is a component that has failed prematurely, has experienced strong transients during its operational lifetime, data are available about the important effects that the occurrence of strong transients have had on this component, and the transients experienced have resulted in effects that are not readily repairable (i.e., requiring component replacement). In this work, a strategy is proposed for the development of a physics-of-failure model of large power transformers that could be implemented in order to make more realistic performance predictions, supporting improved long-term plant asset management.

Keywords: transient-induced degradation, reliability, physics-of-failure, transformers

1. INTRODUCTION

Traditional component reliability models consider exclusively the effects of age-related degradation in their estimation of the component failure frequency. These reliability models could be further improved by also incorporating the effects that transient-induced (or event-induced) degradation has on the characteristic failure frequency of the component. This more realistic representation of the failure frequency that incorporates plant-specific operating experience could provide for improved asset management capabilities, as more accurate predictions could be made concerning the remaining useful life of components.

These improved reliability predictions provide strategic value specifically for those components that are characterized by a high capital cost, a long lead-time for replacement, or whose failure would result in an unplanned plant shutdown. The large power transformer is characterized by these component qualities, as it is a component that has failed prematurely, has experienced stressful transients during its operational lifetime, information is available about its important effects resulting from the occurrence of stressful transients, and the transients experienced have resulted in component effects that are not readily repairable (i.e., requiring component replacement). Therefore, it was selected as a component eligible for application of the new reliability model.

In this work, a strategy for the development of a physics-of-failure model for the large power transformer is proposed in order to be able to apply the transient-induced degradation reliability model. The application of this method demonstrates the importance of the availability of component-specific operational data pertaining to transient-induced degradation.

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2. DESCRIPTION OF RELIABILITY MODEL

The reliability model [1] developed for application to this work is a probabilistic model that accounts for three types of failures: random failures, a random failure following a transient and a failure due to the occurrence of the transient itself. The general model provides the probability of failure for the component lifetime from the beginning of life to the time of planned shutdown (t_s) and is shown in Eqn. 1.

$$P(\text{fail}) = \int_0^{t_s} \lambda e^{-\lambda t} dt + \int_0^{t_s} \lambda' dt \int_0^t \lambda_T P(\Delta\lambda_R | T) e^{-\lambda t_T} e^{-\lambda'(t-t_T)} dt_T \quad (1)$$

In Eqn. 1, the first term represents the failure probability distribution representing the occurrence of random failures and the second term represents the failure probability distribution of the failures resulting from the occurrence of the transient. (See nomenclature section for variable definitions.) The failure frequency is defined as the summation of contributions from both the random and transient-induced failures, as shown in Eqn. 2.

$$\lambda = \lambda_R + \lambda_T \cdot P(\text{failure} | T) \quad (2)$$

In Eqn. 2, the total failure frequency (λ) is expressed as the sum of the random failure contribution (λ_R) and the transient-related contribution where λ_T is the frequency of the damaging transient, and $P(\text{failure}|T)$ is the probability that failure occurs due to the occurrence of the transient. In this way, the total failure frequency can be dependent upon the occurrence of many different degradation-inducing transients, which are characterized by various frequencies and failure probabilities.

The occurrence of the transient(s) results in the creation of a new failure frequency defining the operation of the component, as shown in Eqn. 3.

$$\lambda' = \lambda_R + \Delta\lambda_R \quad (3)$$

Here, λ' represents the new failure frequency characterizing the latter failure probability distribution of Eqn. 1, where the $\Delta\lambda_R$ represents the step-change increase in failure frequency due to the occurrence of the degradation-inducing transient.

3. COLLECTION OF PLANT-SPECIFIC DATA

3.1. Fault Evaluation

Because the successful application of the reliability model that we seek to apply in this work requires the use of a component-specific event history, it was necessary to identify a utility partner who would be willing to share their transformer operating history data. In choosing a partner, we looked for a utility that had experienced unanticipated transformer events at a nuclear power plant. The record of these events allows for the development of a relationship between classes of transients and resulting increases in expected failure frequencies. While general relationships between types of transients and increases in failure frequencies can be derived, the prediction of future transformer reliability is dependent upon an accurate record of its event-history, as the effects of degradation resulting from these degradation-inducing transients are cumulative.

The utility partner provided to us a record of the condition reports of the plant events that potentially posed a threat to the integrity of the transformers. There are seven large power transformers at this site, two main transformers and one auxiliary transformer for each of the two units, and one spare transformer. The record extends back to the beginning of operation for each unit, 26 years and 25 years, respectively.

Based upon the knowledge of the fault location, voltage fluctuations and physical inspection findings, the utility staff ranked the severity of the transient's effect on each of the transformers through the use of impact codes, which are defined in Table 1. In the evaluation of the fault, it was assumed that if the fault were a phase-to-ground fault, these events should contribute to relatively little through fault current in the transformers, as the damage would be limited by the neutral grounding resistors in the auxiliary transformer and main generator, and the delta windings of the auxiliary transformer and the generator step-up transformer. The faults that were considered to be more severe were those involving multiple phases, as in a phase-to-phase fault or an exciter fault. [2]

Table 1: Impact Codes

<i>Code</i>	<i>Severity</i>
0	None
1	Low
2	Low/Medium
3	Medium
4	Medium/High
5	High

The occurrence of voltage transients was also considered in the development of the impact code for each event, but their occurrence was not given as much weight as the contribution of the fault to the severity. This lesser importance derives from the likelihood that voltage transients have a more immediate effect on the transformer, rather than the through-faults, which have a cumulative effect on the transformer internal components by loosening the windings and the clamping. Also, the transformers are protected from internal damage by arrestors on their bushings. In general, since voltage transients are more severe closer to the fault, if the fault is not close to the transformer it is less of a concern. Additionally, the transient's dispersed effects are difficult to evaluate. [3]

Lastly, in the evaluation of the fault severity, if the sudden pressure relays on the transformer actuate during a fault, it is an indication that there is a cause for concern for the integrity of the transformer internals. In the management of these events, the utility performed an analysis on the transformer oil in order to see if degradation occurred based upon the test findings.

3.2. Fault Evaluation Data

During the lifetimes of the seven transformers present at the two-unit site, 17 transient events occurred that affected the transformers. The lifetime-sums of the impact codes characterizing the events affecting each transformer are shown in Table 2. Due to the different nature of each transient event, not every transient affected all transformers. Examining the lifetime sum of the individual event impact codes reveals the variability of the impact of the events over the fleet of transformers, ranging from only 2 to 26.

Table 2: Lifetime Impact Codes from Plant Data Set

Transformer Name	MT1A	MT1B	UAT1	MT2A	MT2B	UAT2	Spare
Lifetime Impact Code Sum	2	20	11	20	26	20	13

3.3 Classification of Internal and External Transformer Events

In comparing the undesirable quality of transformer-related transient events, a contrast can be drawn between events that are internal and those that are external to the transformer. Here, we define internal events as those that occur as a direct result of the malfunctioning of components internal to the transformer. External events are defined as those that could affect the future performance of the transformer by inducing degradation to the transformer, but were initiated by another component affecting the plant electrical equipment, thereby affecting the transformer. In contrasting these two classes of events, the internal transformer events are the more severe of the two event classes from the perspective of both the asset management and reliability of the transformer. Internal events are worse from this perspective because the transformer itself is the source of the problem requiring plant shutdown, versus other equipment that do not represent single point vulnerabilities for plant power generation. Furthermore, they occur presumably as a result of the existence of a degraded material state within the transformer, indicating the potential for reduced confidence in future transformer performance.

The premise behind the application of the reliability model described in Section 2 is that the occurrence of external events can influence both the frequency and the severity of the occurrence of events internal to the transformer. Therefore, as the number of events, both internal and external, increases during the lifetime of the transformer, degradation will be expected to accumulate over time. While the utility's definition of the impact codes for each transient event is not based upon a scientific physics-of-failure basis, the qualitative-engineering judgment employed is based upon the premise that the more severe the event, the more degradation induced. Also, it is plausible that a more degraded transformer will experience future events more severely than its less degraded counterpart. These two inferences from the impact code classification suggest that as the total number of events experienced by a transformer increases, the severity of the events, as indicated by the sum of the impact codes, will increase as well.

This relationship between the event severity and the number of lifetime events experienced by each of the seven transformers is depicted in Figure 1. Not only does the severity tend to increase as the number of the lifetime events increases, it also does not increase proportionally to the number of events. If a comparison is made between UAT1 at 9 events and an impact code of 11 and MT2B at 12 events and an impact code of 26, it can be seen that the severity does increase with the number of events, but as the number of events increases, the associated impact code increases more significantly. This trend suggests that the transformers are experiencing the transient events more severely as they become more degraded with the occurrence of each new event.

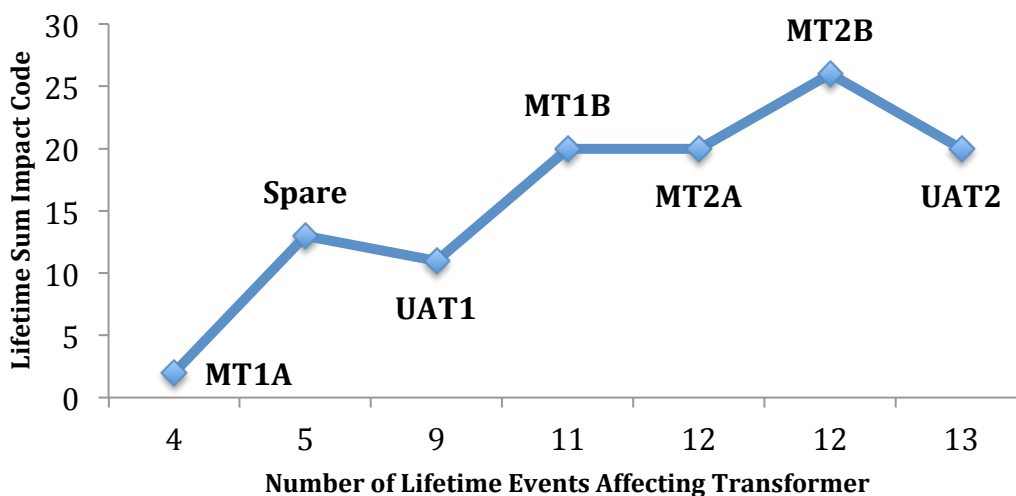


Figure 1 Comparison of the Lifetime Severity and Number of Events Experienced by Each Transformer

Examining the relationship between the number of both the external and internal events that have occurred during a transformers life also suggest that it is plausible that the number of external events influences the likelihood of the occurrence of internal events. Table 3 contains the number of internal and external events that each transformer experienced during its lifetime.

If the number of external events that a transformer experiences induces degradation on the transformer, we should expect that the number of internal events that the transformer experiences would increase with increasing occurrence of external events. In Figure 2, the relationship between the number of internal events and external events for each transformer is depicted.

Table 3: Numbers of Lifetime Events for Each Transformer

Transformer Name	<i>MT1A</i>	<i>MT1B</i>	<i>UAT1</i>	<i>MT2A</i>	<i>MT2B</i>	<i>UAT2</i>	<i>Spare</i>
Internal Events	0	1	1	2	1	2	0
External Events	4	10	8	10	11	11	5
Total Lifetime Events	4	11	9	12	12	13	5

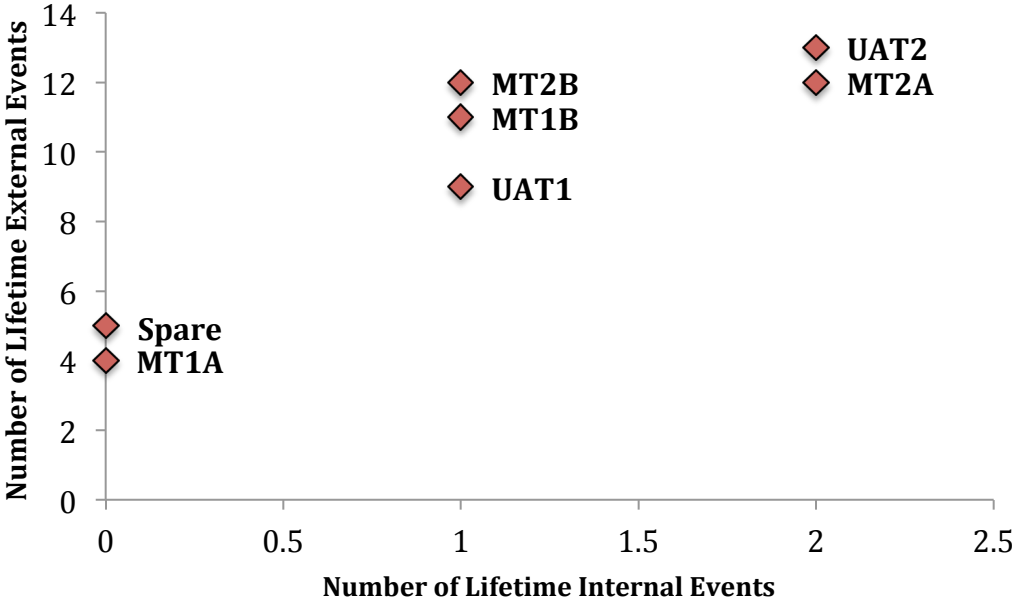


Figure 2 Comparison of Internal and External Events for Transformers Examined

Figure 2 shows that there exists a plausible physical dependency of the number of internal events upon the number of external events. Logically, the level of this dependence will depend upon the influence of the severity of the external events upon the integrity of the transformer, but even disregarding the severity of the events, the trend shown in Figure 2 is suggestive of a correlation between the number of internal and external events experienced by a transformer.

4. STRATEGY FOR DEVELOPING A PHYSICS-OF-FAILURE PREDICTIVE MODEL

While the fault impact codes provided by the utility give a good first indication of the impact of historical transient events upon future transformer reliability, the data give only a relative indication of confidence about future performance, and do not provide a means for making numerical predictions about the future failure frequencies (and reliability) of the transformers. In future work we shall develop the capability for ensuring both a more accurate characterization of the induced degradation and improved reliability predictions that are based upon the results of a physics-of-failure model. The current practice of characterizing transformer-related events with impact codes implicitly makes this assumption of induced degradation, but it does not do so in a scientific manner. The introduction of an increasingly explicit accounting of induced degradation levels will likely provide for improved reliability predictions; however, because of the possibility for many failure mechanisms, our proposed approach will not address all failure mechanisms, but will acknowledge all operational events that have occurred. We anticipate that this approach will help bridge the gap between the implicit and fully explicit approaches of degradation characterization and provide insights into improvements in plant reliability programs supporting long-term operations.

3.2. Fragility Analysis

In structuring an approach for the development of an impact code analysis with improved realism, it is most logical to consider those components and associated degradation modes that would dominate the risk of transformer failure. Ultimately, the usefulness of this new approach will be judged by one simple criterion: how it is able to predict the occurrence of transformer downtime. In considering the application of this model as an asset management tool, utilities are primarily concerned with the occurrence of an unanticipated transformer end-of-life failure event. Because transformers have a long lead-time for fabrication, this class of event has significant economic consequences for the utility. As a secondary concern, utilities are interested in avoiding unplanned shutdowns caused by transformer failures (or degradation) since these also result in lengthy and costly plant shutdowns.

Naturally, the most severe of the two scenarios is that in which the transformer experiences an ultimate failure for which the utility has not planned, as this event has the potential for the most severe economic consequences. Therefore, the goal of the development of our approach is to focus exclusively on the life-limiting failure modes of the transformer in order to enhance the predictive capability of the time at which end-of-life occurs. Here we present the steps for the development of an approach to improve the current standard of using impact codes by implementing a physics-of-failure based approach in order to develop a fragility characterization for the components most significantly contributing to transformer failures.

3.2.1. Component/Degradation Mode Identification

The first step in developing a fragility analysis for the transformer is to identify the most important life-limiting components. Industry data on transformer performance will be used to inform this selection process. After this selection has been made, the predominant modes of degradation contributing to the ultimate failure of these components will be identified.

3.2.2. Development of the Fragility Factor

The development of a fragility factor in order to characterize the level of degradation is key to improving the current methods of assessing transformer degradation. Developing this fragility factor requires a mechanistic understanding of three general factors contributing to a component's level of degradation. These three areas are the contributions of age, shocks (external events) and repairs to degradation.

In the development of this fragility factor we do not seek to develop new physical models, but instead we seek to apply those that already exist in order to provide for a more realistic assessment of transformer performance. Therefore, for each dominant mode of degradation identified for the life-limiting components, the currently existing physical models of degradation will be evaluated for application to the development of the fragility factor.

The successful application of the physical models will be determined by their ability to apply the information relevant to the occurrence of external events and repair-induced failures. Therefore, a key criterion for selecting these physical models will be their ability to be related to event-related data, such as temperatures, voltages etc. Successfully meeting this criterion will ensure that there exists continuity between the physical nature of the external events and the degradation consequently induced.

In order to predict transformer failure better, the development of the fragility factor will require the definition of the failure state. While this definition could be based upon the physical mechanism alone, the entirety of the range of potential degradation modes cannot be realistically captured in this analysis. Therefore, the definition of failure will need to be informed by the current treatment of examining transformer life, which are contained in the industry standards for transformer performance. Generally, these standards have not been developed using a physics-of-failure based approach; however, because they must be applied for transformer operation, they must be considered in this evaluation. Therefore, in the application of this fragility analysis, the definition of ultimate failure may not be different than in prior treatments. The value of its application, however, lies in its ability to make more realistic statements about the current level of degradation and the assignment of that degradation to specific components within the transformer, which can be used valuably to support better asset management.

Therefore, the complete development of the fragility analysis will require a review of the current transformer standards associated with the life-limiting components/events, such as through-faults. The limits set by these standards will be used to inform the failure definitions for each mechanistic failure mode.

The fragility factor, F , will be calculated by considering the various levels of component degradation present for all components that are considered to be life-limiting for the transformer. Eqn. 4 is the definition of the fragility factor,

$$F \equiv \frac{\sum_{i=1}^n [\% \text{ Component Degradation}]_n}{n}, \quad (4)$$

where, n , is defined as the number of components. The percent of component degradation, P_D , is defined by Eqn. 5,

$$P_D \equiv \text{MAX} \left[\frac{\text{Degradation}}{\text{Degradation Limit}} \right]_m, \quad (5)$$

where, m , is the number of modeled degradation modes and the percentage is defined as the maximum percentage of all degradation modes considered, since that mode of degradation will likely be the first to induce a component failure.

Using these two equations as the basis for the development of the fragility factor allows for the inclusion of many degradation modes and components in the fragility analysis. By developing a physics-of-failure interpretation of the degradation associated with the life-limiting failure

mechanisms, a more realistic understanding of the remaining useful life will be revealed through the results of the fragility factor analysis.

3.2.2. Reliability Predictions

The benefit of developing a scientific basis for the derivation of the fragility factor is that it can provide a means to formulate improved reliability predictions, providing improved asset management capability to the utility. The reliability prediction is made by using the knowledge of the frequencies of the occurrence of the external events in order to make predictions about the levels of degradation expected to be induced over time to specific transformer components.

In order to make the reliability prediction, a defined set of relevant external events must be categorized by both their level of induced degradation and their frequency of occurrence. This information can then be combined in order to calculate a predicted level of induced degradation per unit time. Combining this with the historical record of induced degradation as indicated by the fragility factor analysis, a more informed prediction can be made of both the transformer's characteristic failure frequency and expected time of end-of-life.

5. CONCLUSION

A review of the impact factor analysis performed on seven large power transformers at a nuclear power plant demonstrates that there exists evidence to suggest that a more scientifically based analysis of the degradation effects of external events on the reliability of transformers is warranted. A strategy for the development of this analysis was shown to include the mechanistic relationship between the occurrence of the internal event and the level of induced degradation in the transformer. The proposed analysis focuses on the life-limiting transformer components, as they are the most likely to influence the asset management capabilities of the fragility analysis. Reliability predictions can be made by implementing the physics-of-failure based model in order provide for a more realistic understanding of the timing of future transformer failures.

Nomenclature

$\Delta\lambda_R$ = increase in random failure frequency due to occurrence of transient

λ = failure frequency due to both random failures and the occurrence of the transient itself

λ' = failure frequency of the component after the occurrence of a degradation-inducing transient

λ_R = failure frequency due to random failures

λ_T = frequency of the degradation-inducing transient

σ = fatigue-induced stress level

N = number of fatigue cycles

$P(\text{failure}|T)$ = probability of failure given the occurrence of the transient

$P(\Delta\lambda_R|T)$ = probability of degradation occurring as a result of the transient occurrence

t = time

t_T = time of transient occurrence

t_s = time of planned shutdown

Acknowledgements

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References

[1] B. L. Guyer and M.W. Golay, "The Reliability Effects of Transient Induced Degradation," *Transactions of the American Nuclear Society*, Vol 109, No. 1., November 2013, pages 2045-2048.

[2] IEEE Power and Energy Society, 2011, "IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators," IEEE Standard C57.91-2011, New York, NY.

[3] IEEE Power and Energy Society, 2010, "IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformers, Switching Device and System Interaction," IEEE Standard C57.142-2010, New York, NY.