

Accountability and Evaluation of Aggregate Effects of Through Faults
On Power Transformers
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Keywords – Electrical, Operability, Fault, Transformer

Abstract – This paper examines proposed methodologies and recommendations to prevent failures of power transformers due to the aggregate effects of through faults on transformers.

A 1000MVA Three Phase Generator Step-Up (GSU) Transformer at a Generating Station suffered a catastrophic electrical fault in October 2005. This resulted in a significant impact to the Operating Companies revenue stream as this base-loaded facility, minus a functional GSU Transformer could not export Power for 17 days until a temporary (De-rated Output) Transformer was installed. Another full rated spare transformer was installed in early 2006 during the scheduled plant shutdown to replace the smaller unit. The new replacement Transformer (with an up-rated power rating) is scheduled for installation in early 2008.

1. INTRODUCTION

Power transformers are designed and built by manufacturers to withstand the large mechanical and electrical stresses imparted on the transformer due to the maximum electrical fault energy postulated for that transformer.

Secondary side transformer faults also expose the transformer to elevated mechanical and electrical stresses that are functions of; a) the nature of the fault (3 phase fault, ground fault etc.), b) the magnitude of the fault (function of the equivalent system reactance where the fault occurs), and c) the time necessary for a protective device to clear the fault.

Consequently, the challenge is to identify all transformer through faults, capture the energy profile of each individual through fault, and ascertain the consequences of the aggregate effects to the transformer.

2. ANATOMY OF THE POWER TRANSFORMER FAILURE

A root cause evaluation was conducted and the most significant contributor to the fault was believed to be the aggregate effects of through fault events since the transformer had undergone internal inspection and repair in 1996. Due to the mechanical and electrical stresses and physical shock imparted on transformers upon exposure to each through fault, it is theorized that these aggregate effects caused by forces over time manifested in looseness of the low voltage bus bar supports enabling the bus bars of two of the low voltage phases to migrate towards each other to the degree that the dielectric properties of the oil alone could not preclude a phase to phase fault from propagating.

A broadness review was instituted as a component of the root-cause evaluation and it was discovered that there are recent documented instances where cumulative through faults have led to comparable transformer faults.

As a corrective action for the event, the existing maintenance program has been improved by requiring consideration of the frequency, the magnitude, and the duration of through faults experienced when evaluating maintenance indicators that would lead to more detailed inspections and repair actions for transformers.

3. EXTENT OF THIS PROBLEM

As an extension of the aforementioned root cause evaluation, additional searches were conducted to ascertain failure correlations within the nuclear industry. There were several instances where it was suspected that a power transformer failure was attributed to aggregate through faults. One utility transformer maintenance group has observed a pattern of transformer failures following ice storms that is believed to be highly correlated to an accumulation of through fault events on the failing transformers.

A review of IEEE papers revealed some potential correlations with this phenomenon, however for the sake of brevity, the following case study entitled ‘Analysis of a Generator Step-Up Transformer Failure Following a Faulty Synchronization’ is offered to emphasize the

cumulative effects of through faults. See Reference 1

Abstract - This paper presents the details of an in-depth analysis carried out: to investigate an out-of-phase synchronizing condition which resulted in the failure of a 725 MVA GSU transformer. Using a technique described in this paper, the circuit breaker closing angle was estimated from oscillograph traces. This information was used with the Electromagnetic Transients Program (EMTP) to simulate the disturbance events and thereby produce a complete set of probable synchronizing currents and generator electrical torques experienced during the disturbance. The analysis of the simulation results, and further, the analysis of the failure of the GSU transformer have been viewed in light of the large number of prior system faults in the vicinity of the transformer. A brief review of the ANSI/IEEE standards on transformer fault withstand capabilities as related to this type of analysis is also presented.

Essentially the authors indicated that in this case there were 42 faults below the current rating on phase 2 for the Muskingum River # 5 GSU and 37 prior through faults above the 1.0 per unit value that individually should not cause a transformer failure; however the cumulative effect may have been sufficient to loosen the windings and mechanical blocking to the extent that the through fault capability had been reduced prior to the out of phase synchronization.

While the out of phase event in this case resulted in winding failure, we must also include the winding to bushing cabling, busses and flexible and solid connectors, as components that are repeatedly subject to severe mechanical stress as was the case with the failure of the 1000MVA

Three Phase Generator Step-Up (GSU) Transformer, which suffered a catastrophic electrical fault in October 2005, prompting this paper.

4. SYSTEM CONFIGURATION AND FAULT TYPES

A commonly used station one-line configuration is shown in Figure 12, where the generator and the step-up transformer have essentially the same rating. This is from Reference 3. We should recall that the location of a fault will determine the severity or level of fault current. With a fault postulated at C1, the fault current through the Step-up transformer is mostly due to the generator contribution with auxiliary system contribution (generally negligible). In the case of a fault assumed at B1, the fault current through the Step-up transformer is mostly due to the system contribution but also has additional short circuit contribution from the auxiliary system. Yet, the highest available fault current tends to be at the Auxiliary system transformer due to the contribution of both the System via the Step-Up Transformer and the direct connected generator. It is noted that the auxiliary system fault will subject the Auxiliary system transformer to a few cycles of short circuit forces, while limiting the longer term thermal input associated with generator coast down, even when the Generator breaker is included in the system configuration.

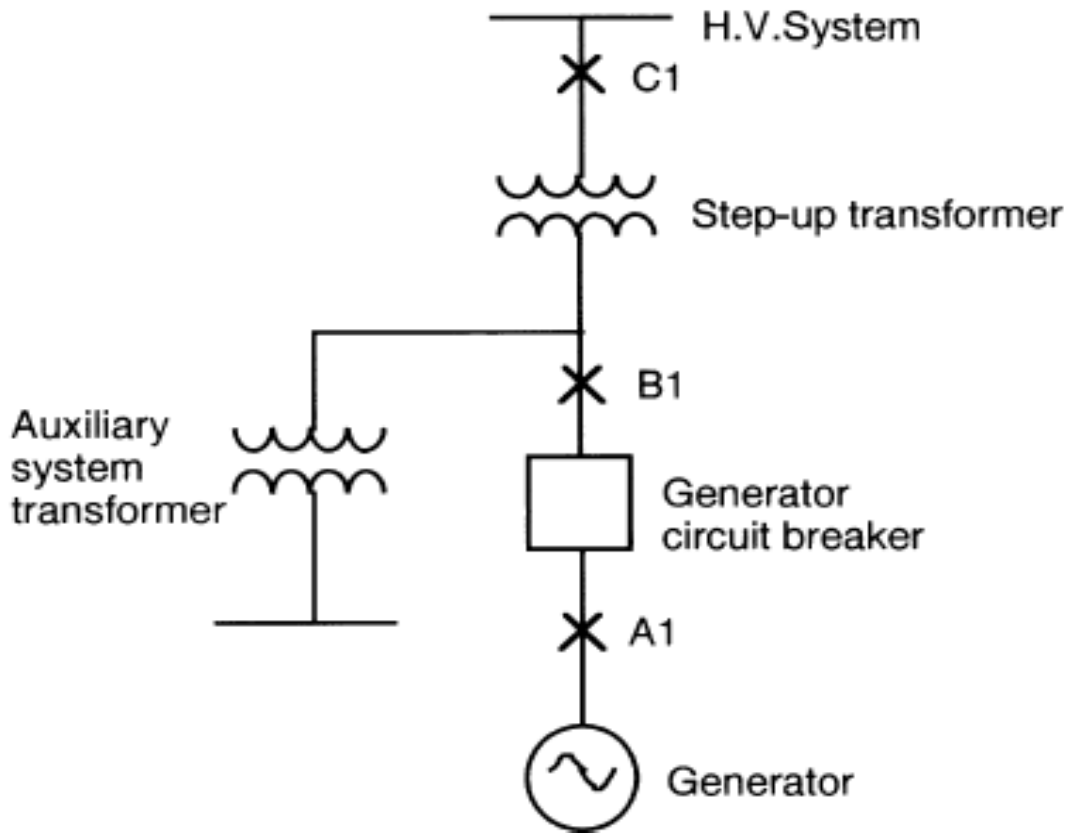


Figure 12— Single-line diagram of unit generator system
From Reference 3 - IEEE C37-013

We also want to briefly consider the possibility that faults may not be randomly distributed across the three phases. In the one case study, it is believed that the area of failure was related to one individual phase, which was subjected to higher faults and / or experienced the initial asymmetrical component of the fault. While the IEEE C57.12.90 states:

12.3.4 Number of tests - Each phase of the transformer shall be subjected to a total of six tests satisfying the symmetrical current requirement specified in 12.3.1 or 12.3.2, as applicable. Two of these tests on each phase shall also satisfy the asymmetrical current requirements specified in 12.3.3.

The real world has shown that the asymmetrical current does not always follow the pattern of

being evenly distributed events where one out of every three (or two out of every six) occurs evenly or randomly across the phases. In the real world case it was observed through the historic records that the failed phase had been subjected to multiple faults that involved downed lines and a high voltage breaker failure. One may postulate that if the fault current with a high degree of asymmetry occurs repeatedly, or consecutively, on the same phase; then a close inspection and verification of fitness for service is warranted. Reference 3 the figures of IEEE C37.013 that provide good visual references of how the high mechanical stresses are imposed on the phase that receives the maximum asymmetrical component of a through fault.

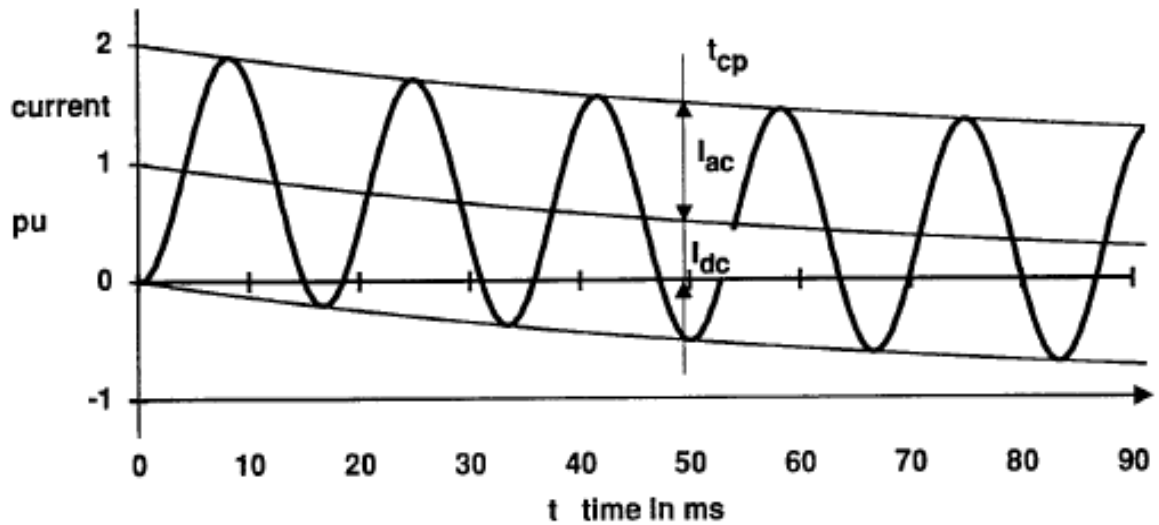


Figure 7— Asymmetrical system-source short-circuit current
From Reference 3 - IEEE C37-013

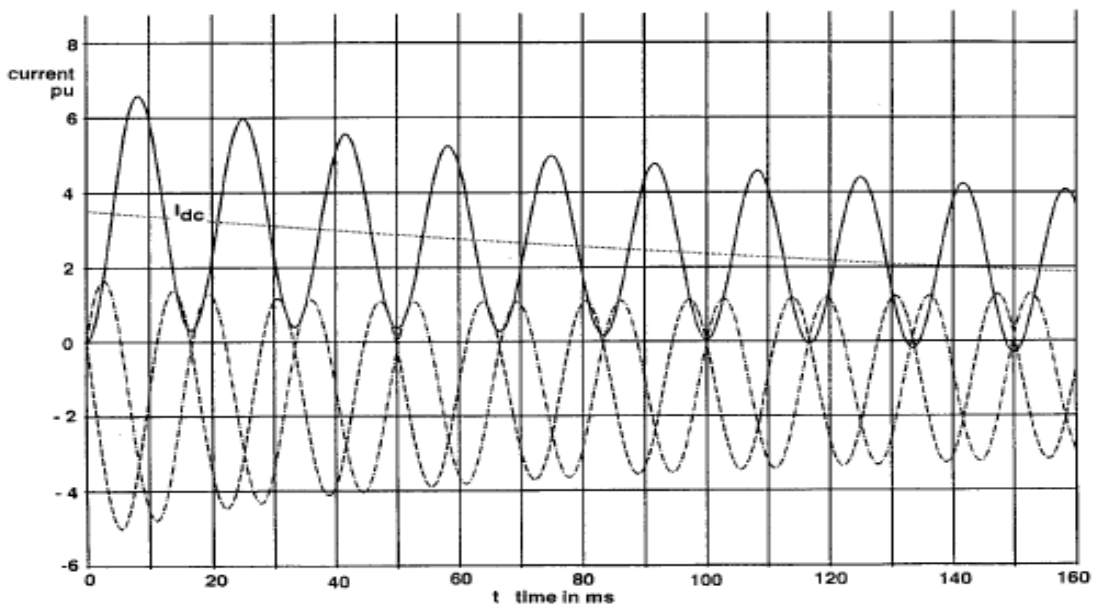


Figure 10— Short-circuit current for generator-source fed fault
From Reference 3 - IEEE C37-013

5. INDUSTRY GUIDANCE REGARDING THROUGH FAULTS

Although there is specific industry guidance established in IEEE C57.12.00 with respect to the number and magnitude of maximum calculated faults that a power transformer must be designed to withstand, there is no well

established rule that is universally adopted by transformer manufacturers regarding thresholds for evaluating the accumulative effects of less than maximum through faults. There are some recommendations recently offered by some manufacturers as outlined in Section 10 to support this paper.

6. FAULT TRACKING PROGRAM ATTRIBUTES

The increased sensitivity to the effects of through fault currents on large transformers has motivated some individual plant sites as well as the organizations responsible for the utility distribution system to evaluate the effectiveness of their maintenance programs. A major contributor to an effective program for inclusion of through fault tracking and analysis is to identify and obtain the base-line data needed for future analysis. It is most desirable of course to obtain this data while the transformer is in a healthy state. Preferably this will be performed in the manufacturers shop prior to delivery. It can also be established after a transformer has undergone major refurbishment or maintenance. Another major aspect of a through fault monitoring program is the identification of the through fault event and the capturing of the data necessary to support the analysis. There can be two parts to capturing this data. The primary source for a power plant is the protective relaying and on-site Fault Recorder data acquisition system. It should be verified that the Fault Recorder data acquisition system is set up to be triggered (start the data acquisition) at the proper level of fault current (recommendations may be as low as 0.25 per unit, or at a threshold level commensurate with the transformer design margin) and that adequate voltage and current readings will be taken for the three phases at the appropriate locations. A secondary source of valuable data can be secured from the transmission system group. Operational Experience (OE) has documented cases where events on the grid, which happened away from the plant site, contributed to transformer failure at the site. Formal communication with the appropriate contacts within the transmission system group could provide information about grid events where the magnitude of the event as seen at the site of the transformer is under the threshold for triggering the data acquisition system, but which would be useful in analyzing the accumulated effects of through fault events on a transformer.

Supplemental data necessary for the analysis of the transformer health is the result of periodic oil samples, Dissolved Gas Analysis (DGA), power factor testing, Frequency Response Analysis (FRA) testing, and infrared imaging thermograph readings. Proper trending of this data should support the analysis performed in response to a

through fault event and over time help to validate recommendations for continued operation.

There are numerous inputs, which need to be considered when performing the post through fault event analysis of transformer health. Transformer age, electrical loading, any movement due to physical relocation, physical design, OE, maintenance and inspection history, as well as the through fault event data and results of subsequent testing are a few considerations. The physical design of the transformer will help to determine the failure modes that might be possible. Differences between transformer designs may necessitate the use of different strategies in the specifics of post event testing and analysis. While comparison of testing results taken after a through fault event to the base-line data can show potential movement or shifting of the coils, it may not show movement of bus bars or other internal components, which can eventually cause failure of the transformer. OE has shown that oil sampling and DGA will not always detect transformer degradation of this type either. OE has also shown that some transformer designs are physically more robust than others and alternatively others are more sensitive and as such are more likely to experience these failure modes. This will introduce an additional degree of subjectivity into the engineering analysis and weight the decision for instituting an internal inspection.

6.1 Preparation Prior To Fault

Some of the actions which should be incorporated into a transformer fault tracking program are as follows:

- 6.1.1. Identify the responsible department and individual(s) for implementing a strategic program designed to foster long term operation of Power Transformers as described below to ensure focus and accountability.
- 6.1.2. Determine what testing has been performed on the existing transformers and initiate actions to fill any gaps to ensure a compliment of test results are secured as outlined in 6.1.9 below.
- 6.1.3. Verify the base-line data that is available for the existing transformers and determine what actions can be taken to fill any gaps to ensure a compliment of test results are secured as outlined in 6.1.9 below.

- 6.1.4. Review the existing maintenance procedures to insure that the desired oil analysis, DGA, thermal readings, are being taken in accordance with manufacturers recommendations and/or governing IEEE recommendations.
- 6.1.5. Verify that the onsite Fault Recording data acquisition system is capable of securing all of the necessary data required to facilitate a complete evaluation.
- 6.1.6. Establish a communication protocol with the proper individual(s) that triggers communication between transmission and the designated plant representative(s) for incidents that could adversely influence the health of the transformer.
- 6.1.7. Implement procedural requirements to track faults on the system, identifying the location, magnitude, etc.
- 6.1.8. Review the maintenance history and through fault events experienced by the existing transformers and initiate actions to perform any future testing or inspections as necessary.
- 6.1.9. For new transformers, ensure that the procurement specifications include requirements for execution of relevant baseline testing such as, Insulation Resistance, Winding Resistance, 10kV single phase excitation (Doble), Induced Voltage, Turns Ratio, Frequency Response Analysis (FRA), and Insulation Power Factor, to be conducted in the manufacturer's shop.
- 6.1.10. Once the new transformer is received, perform a 10kV single phase excitation (Doble) test, Ratio test, and FRA test. Also, if there is any indication based on external testing, conduct an internal visual inspection or when assembling bushings or other components removed for shipment. If the transformer is stored and subsequently moved again to another location, the appropriate subset of these tests and internal inspection should be repeated depending on the details of the move.

6.2 Post Fault Actions

All of the above recommendations of course are just the preparation for dealing with a transformer through fault event. Once one

occurs, a recommended course of action would be as follows:

- 6.2.1. Determine what relay actuations were received on protection systems.
- 6.2.2. Obtain the data from the Fault Recorder data acquisition system.
- 6.2.3. Obtain data from any other data acquisition system available.
- 6.2.4. Obtain the operational history for the transformer, including through fault legacy information.
- 6.2.5. Contact the appropriate transmission group to determine what other transients may have been experienced on the grid at that time.
- 6.2.6. To the degree possible, determine the initiating event, the location, and the magnitude of the fault as seen by the transformer.
- 6.2.7. Pull maintenance history and trending analysis for the transformer.
- 6.2.8. Secure vendor information for the transformer.
- 6.2.9. If the protective relaying isolated the transformer from the system, perform the following tests as dictated by the analysis of the event data:
 - DGA
 - Oil Power Factor
 - Insulation Resistance
 - Insulation Power Factor
 - FRA
 - Winding Resistance
 - Turns Ratio
- 6.2.10. If the transformer remained in service, review the data secured in step 1 through 8 above to determine if the Unit should be removed from operation and the above testing performed.
- 6.2.11. Perform an engineering analysis using the specific transformer design and considering the data obtained in the steps above. This analysis may recommend continued operation as is, more testing, or an internal inspection of the transformer.
- 6.2.12. Consult with the transformer manufacturer if available and communicate the findings and recommendations to gain a consensus opinion.

7. CURRENT TECHNOLOGIES TO SUPPORT COMPREHENSIVE THROUGH FAULT PROGRAM

There are many relay platforms that are capable of waveform capture of system faults on both the high and low side of large power transformers. There is increasing use of digital fault recording on the transmission side as well as the generation side. However, one key aspect of all the data collection available from the various data acquisitions and event capture equipment is the organizational and management structures that are required to be present to analyze and act on the collective aspect of information that is derived from the analyzed data.

7.1. Data Management over Lifecycle

The first obstacle to overcome is the long life spans that many large power transformers are capable of achieving. Many in service units in North America are twenty, thirty and in some well established infrastructures even forty years old. Considering the IEEE C57.12.00 standard (Reference 2) regarding short circuit capability, a new transformer is expected to be able to withstand at least six (6) through faults. So there

could be reasonably long periods of time between faults, say five to ten years, or more, without significantly consuming the original manufactured ability to withstand through faults. This requires a transformer lifetime commitment by the end user to record and track significant events from the perspective of the transformer. In the world of analogies, this is the equivalent of our own lifetime medical records whereby the input of multiple care givers, doctors, parents, spouses and children are involved across generations to maintain an accurate historic record of the significant events in our lives. Similarly, the health of the transformer should be recorded and reviewed to allow for preventative measures and to assess the projected remaining life. The second obstacle is the multiple parties, groups, or even companies that may be involved in providing data to a possibly virtual data Owner. Refer to Figure 7A depicting an organizational arrangement of data collection groups that may be typical due to the specialized functions of these groups and their inherent charter. There is a distinct possibility that no one individual, group, or assigned entity is required to compile and analyze the collective data, although that should be the objective to ensure program accountability.

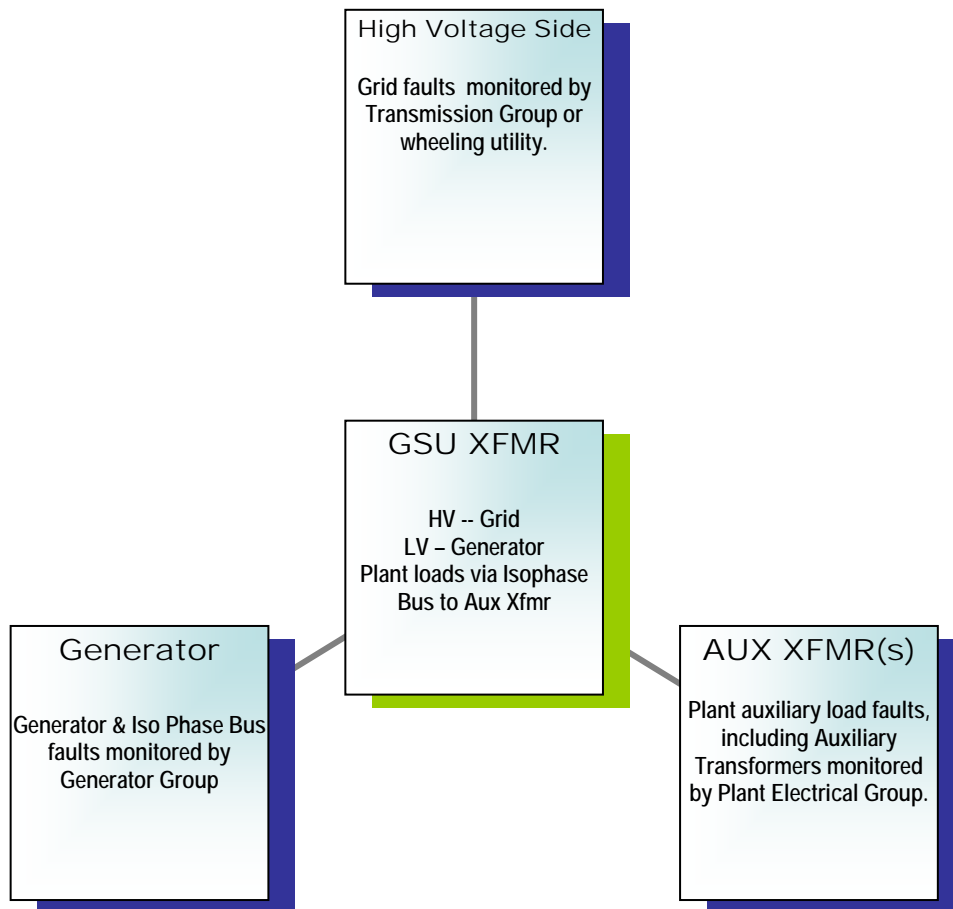


Figure 7A -- Radial

The ability of the transformer to fully withstand the next through fault is clearly dependant on the history and present health of the transformer. While the technology to capture and accumulate data may best be served by the radial functional groups that interface with a power transformer, the ownership and guardianship must also be a circular one of empowerment as shown in

Figure 7B. Asset managers and those that may require external companies, or even outsourced services, should ensure that the data is collected, analyzed and actions implemented to maintain or restore the power transformers ability to withstand the next and the requisite accumulated through faults.

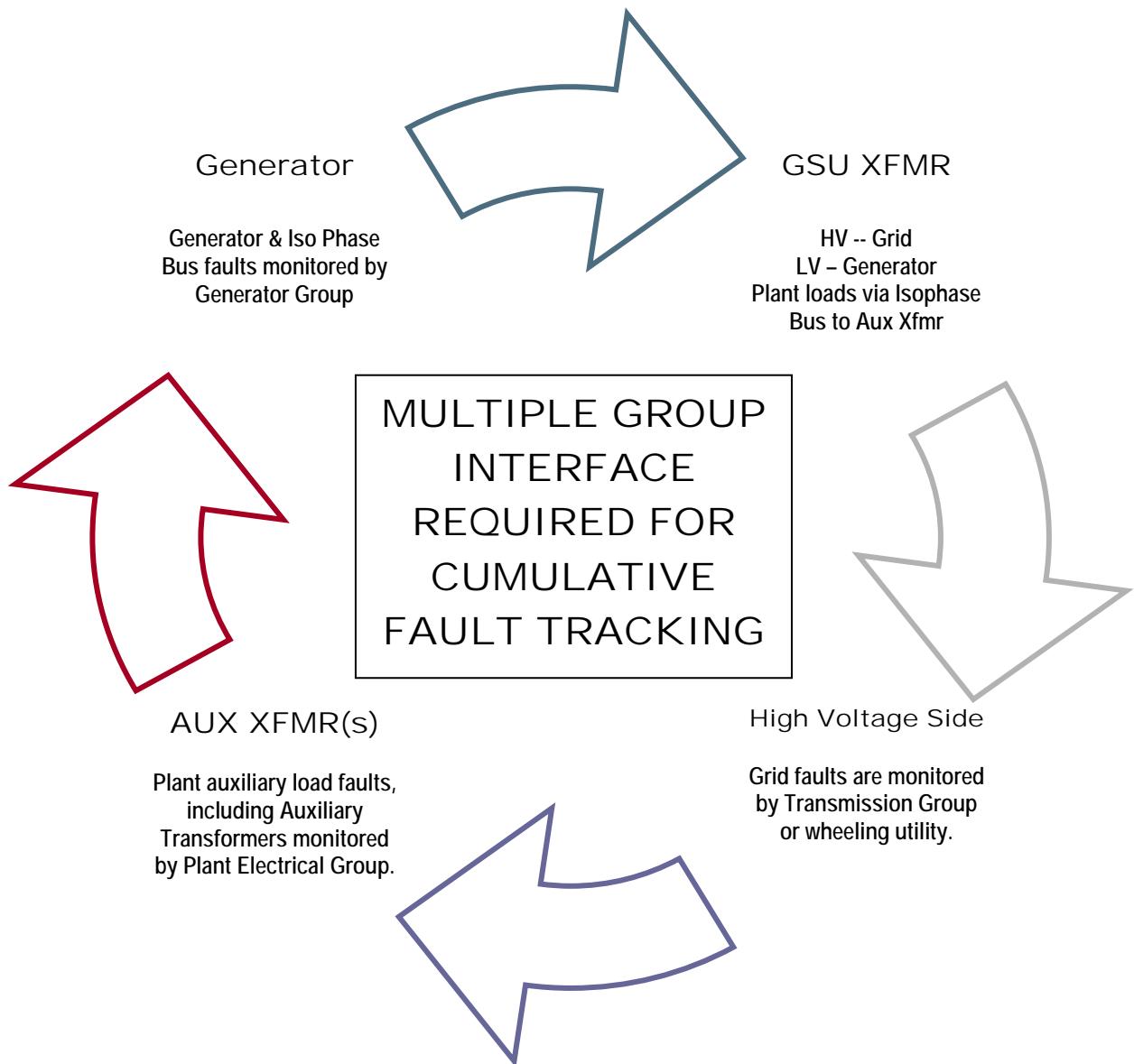


Figure 7B – Circular

7.2. Fault Levels and Remnant Fault Capacity

When attempting to find concise and / or consensus type guidelines in the industry and via the standards regarding the degree of effect of accumulated faults ranging from a full design basis or type test fault, several manufactures provided helpful guidance, design practice and their experience based on end user feedback. For the purposes of this paper we considered or defined a full design basis or type test fault as the one hundred percent fault (100%) level located at the transformer terminals and the lesser fault

levels to just be a percentage of full fault level, say three quarters (75%), half (50%) and one fourth (25 %). The question or expectation that is attempting to be confirmed is: Assuming that short circuit forces are basically a squared function of the current, then can one postulate that the transformer can be reasonably expected to successfully endure a numerous mathematically proportional number of lesser faults that would constitute a full design basis fault level. In a more classical mathematical relationship, if the transformer could accept one 100% through fault, then could it be expected to

accept a mathematically equivalent number of lesser through fault events as shown in Table 1?

Table 1

Fault level (%)	Fault level at per unit value	Square of per unit value	Inverse of per unit value squared	Postulated mathematical capability of equivalent through fault events
100	1	1	1	1
75	$\frac{3}{4}$.5625	1.7777	~2
50	$\frac{1}{2}$.25	4	4
25	$\frac{1}{4}$.0625	16	16

After performing some research of various standards, reviewing various operating and maintenance manuals, and discussing the topic with a consultant, we believed there was a basis to expect the assumption to have some validity.

Upon contacting several manufacturers, one strong point of consensus offered was that the winding clamping force, and the original (as manufactured) condition of the windings, insulation, key spacers, blocking, and other cellulose products that are subject to short circuit forces during a through fault must be within the design margin values for the specific design for any transformer to successfully withstand a through fault event. There are services such as the Mature Transformer Management Program in Reference 5 and in conjunction with Advanced Diagnostic Testing Services offered by Reference 5 that can provide unit specific transformer design and condition assessment for shell and core form transformers. The short circuit strength analysis would consider the various stresses such as, buckling, crushing, hoop, and tipping, acting on the radial and axial directions of the winding for a specific design in combination with the historical loading, operational history and diagnostic data and would assign a relative risk category proportional to the design margin.

One major manufacturer confirmed that their design rules for short circuit withstand have a section relating to this matter, and based on these rules the following number of short circuits per year would be acceptable for one of their designs from a specific manufacturing location: 100% level - 1 per year; or at the 75% level - 5 per year; or at the 50% level - 20 per year; or at the 25% level - 100 per year. While this supports the postulated mathematical relationship of the probable number events at less than a full design

basis event as the inverse of the percentage squared of full fault current levels, it must be emphasized that the manufacturer included a minimal time interval between repetitive through faults at higher levels. The recommendation is for through faults at levels of 50% and above there should be at least 15 live relaxation days between events. While there must be a time constant for a deformable but resilient component to return to a point of mechanical stress equilibrium after having a force exerted upon it, it is reassuring to know that some manufacturers are able to quantify such relaxation or recovery time between higher level through fault events. This relaxation time is most likely obvious for the manufacturers and industry consultants, and does make good practical sense. The question that users should ask is: Is the relaxation time between events, appropriate due to higher through fault level accounted for in operating procedures? We know there are thermal time constants (recover time) associated with numerous hot starts of large motors, and that some of the intelligent relays have algorithms that will block the next restart based on the thermal characteristics and recent operating history of a motor. For some specific situations, should a user similarly consider operating procedures that recommend a minimal relaxation time prior to re-energizing a unit that has had a severe fault, or numerous consecutive lesser faults? This question can only be answered by the responsible entity in charge based on a multitude of considerations. The question is only asked to: a) provide a possible mechanism to reduce operating risk by adopting conservative operating practices, b) to further illustrate the possible adverse consequences of not factoring this variable into the decision making process, and c) to highlight that there are service life reductions that might be accompanied with immediate attempts to re-energize a recent faulted unit.

7.3. ECONOMIC CONSIDERATIONS

Considering the current robustness of the Power Industry, typical quotes for new large power transformers are in the range of 15 to 18 months (and for some specific large capacity and high voltage, or special application factories, the lead times are over 22 months) for GSU Transformers and 12 to 15 months for auxiliary and station service transformers. Some larger base load Units are subject to revenue losses of approximately 1 million dollars a day after a

transformer failure. Consequently, if the Utility does not have a spare power transformer readily available, the economic consequences are substantial.

7.4. CONCLUSIONS

Based on a review of industry data, it is apparent that there are opportunities for original equipment manufactures and industry organizations to establish a formal program to better predict when a Power Transformer is at risk. This paper illustrates the salient attributes of such a dedicated and structured program to assist the operating and maintenance departments in protecting themselves from significant economic risks due to failed power transformers as a consequence of the accumulative affects of through faults.

In other words, instead of implementing a plan to ensure operability and reliability of the power transformers, one could find themselves working a plan for an unplanned outage.

7.5. REFERENCES

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7.6. ACKNOWLEDGEMENTS

We wish to acknowledge the contributions, opinions, and guidance provided by the following companies and their technical experts with respect to this paper:

1. ABB
2. AREVA
3. Hyundai
4. Southern Nuclear Company
5. Bechtel Power Corporation