History of Transformer Failures in the Nuclear Industry

by

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ABSTRACT

The Nuclear Power Industry is unique from others in terms of the way they operate, the mindset of the personnel who support them, and the communication throughout the industry. This research work provides a thorough look into the failure rates and types of many components including large oil-immersed transformers, which is unique in nuclear power plants. As the industry strives harder to obtain near perfect reliability with as little down time as possible, all components must be maintained at a high degree of safety.

This thesis work studies several types of failures that occur in transformers across the power generation and transmission being caused by mis-actuations of relays and the failures of bushings, or leaking oil, and losing coolers. Every failure that occurs contains some information to be gained to better increase the nuclear power generation reliability.

Data gathered from several industry events over the last several years has been grouped and analyzed. The failures are categorized based on the components which failed and includes the general consequence of each event. These events will later be broken down in groups depending on how each component failed in a general sense, allowing for further analysis.

Future ways to prevent these failures and forecast reliability trends of the nuclear power industry are discussed in detail with respect to newer emerging technologies.

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Chapter 1.0 Introduction

Transformers are among the most resilient, and longest lasting pieces of equipment in the electrical industry. If properly designed a transformer can last an extremely long time without needing to be replaced, hence in the nuclear industry the transformers are intended to last the entire life of the plant or about 40 years. However, nuclear plants are consistently lasting longer than 40 years with numerous plants lasting 60 years, and some potentially looking at 80-year lifespans. Many factors can affect the expected life out of the typical oil immersed power transformer such as their expected loading, the faults that occur on the system, the protection system around the transformer, and the maintenance done on them to ensure all the components work as intended. Being as heavily regulated as the nuclear industry is, most plants will replace their transformers before or around the 40-year mark unless a failure occurred previously. Additionally, the nuclear industry has seen various amounts of up-rating where an increase in power production was possible which has led to a lower design margin for some transformers. In the name of simplicity this thesis will focus on large power oil immersed in transformers in the nuclear industry.

This paper's applications will not be limited to the nuclear industry however, as transformer failure and design vulnerabilities can be applied throughout the entire power and energy sector. The general layout provided in section 1.2 will be used throughout this paper to help classify transformer failures, additionally each event will be placed in the group for the general failure mechanism that occurred, with the general groupings given in section 2. It is this paper's goal to utilize tools available to provide a list of transformer failures in the industry.

1.1: Transformer Types

Main Transformers

The Main XFMR's connect the generator to the grid. These transformers are large step-up transformers taking the generated voltage to typical grid voltages. Due to cost these XFMRs were sized with little margin in mind, which has caused complications down the line as more accurate sensors became available for the core, and other supporting equipment improved, it was possible to up-rate the plants, and remove what little margin XFMRs had, resulting in loss of design margin. Originally nuclear plants were designed with a 40Y life span in mind, however currently most plants are getting extensions to 60, and some to potentially 80Y. As a result all plants will need to perform a replacement of the main XFMR's at some point in their life. (~40Y Main XFMR lifespan expected)

Interbus Transformers

Interbus XFMRs will supply most plant busses and can be viewed as an additional step down from the Start-Up XFMR's. These XFMR's are typically large and would be sized around 60 MVA depending on plant design. They will be fed from the Start-Up XFMRs, and some of these will serve Nuclear Safety Related busses, while most will serve a variety of other loads through the plant. It should be noted these XFMRs are expected to be numerous on nuclear sites as every nuclear plant must have 2 separate offsite sources of power, and thus will require at least 2 of these transformers just for Safety busses. Voltage ratings for these XFMRs should be 13.8kV-4160V, however this depends on plant design.

Start-Up Transformers

Nuclear plants require two separate sources of off-site power, typically the utility supplies two separate high voltage lines to the plants switch yard. The high voltage lines are then run to two separate step-down XFMRs. These XFMRs are only loaded under the event of a plant shutdown / outage, or in the event of an accident. In the event a single Start-Up Transformer loses its ability to provide power, it can result in an entry of a 72-hour LCO (Limiting Condition of Operation), where if it is not restored within 72 hours the plant must be shut down until restored. In the case of both sources of offsite power being lost, it requires the diesel generators to actuate, and immediately SCRAM's the plant. These XFMR's will be sized to feed all necessary plant loads, and will step down grid voltage (365kV, or potentially 138kV) to 13.8kV for distribution and use.

Auxiliary Transformers

While the Auxiliary Transformer is similar in purpose to the Start-Up Transformers, the Auxiliary Transformer is not directly needed for the operation of the plant. In the event of a shutdown, it does not provide power (unless being used as a back feed) and is not used to mitigate accidents or transients, however it is cheaper to use the plants own power rather than buy it from the grid. The Auxiliary Transformer is taking power from the main generator at that voltage and takes it a voltage to power the plant during operation. This is usually accomplished through an additional connection with the Isophase bus. Some plants may have a way of disconnecting the Auxiliary Transformer, however this is rare, and typically this isn't an option as the connection would be extremely difficult to break. This provides a major vulnerability to the plant, as in the event of an issue to the Auxiliary Transformer, such as a fault, or a fire, it would cause the Main Generator to trip, and the plant would automatically shutdown the turbine, and hence induce a reactor SCRAM (rapid shutdown of a reactor). To continue power operation soon, it would require relying on the Start-Up Transformers to take power from the grid resulting in increased cost of operation. Even though these transformers are not required for operation of the plant, and do not fulfil a function in the case of nuclear safety, they are required for the cost-effective operation of the plant and can force the plant into an (forced) outage.

1.3 Definitions:

BWR – Boiling Water Reactor. A General Electric Design which boils water directly in the reactor vessel. This resulted in a simpler design, and a significant reduction in components. This, however, also resulted in a poorer response to transients, as the reactor would need shutdown if the turbine were to trip.

PWR – Pressurized Water Reactor. A Westinghouse (and others) design of light water reactor, which relies on keeping water under a large amount of pressure to keep it a liquid, and several heat exchangers (steam generators) to generate steam and remove heat. This design has its own separate advantages such as an ability to change power faster, as well as tolerate some trips of the turbine.

CANDU – Canadian specific reactor type. Has the ability to refuel online and is another style of light water reactor. This reactor type is similar to a PWR in terms of response to a turbine trip, and changing power levels.

EPRI – Electrical Power Research Institute

SCRAM – A rapid shutdown of a nuclear reactor. Typically accomplished via rapid insertion of control rods to lower reactor power rapidly.

OIP – This term specifically related to a bushing design (Oil Impregnated Paper)

RIP / RIS / RIC – These terms are other types of bushing designs available. (Resin Impregnated (Paper / Synthetic / Composite)

MCCB – Molded Case Circuit Breakers. This is a common type of circuit breakers, which are encased in a molded plastic case.

1.33 Common Transformer Relays:

There are numerous relays, and monitoring devices which can be identified on transformers, all of which can degrade of fail. Several monitoring devices are monitored daily at a minimum during plant walkdowns, are mounted on transformers, and these devices / indicators include top oil temperature, winding temperature, liquid level, sight glasses on oil filled bushings, and cooler indicators. The above-mentioned indications mounted locally are all extremely reliable and are very unlikely to fall out of calibration. Some instrumental agitation maybe occasionally be necessary as some gauges can stick potentially. It should also be noted that the only local indicator which would potentially have the ability to trip a transformer is the liquid level indication, and this depends on the specific station. Additionally, the liquid level indication is heavily dependent on oil temperature, hence the level indication reads in a temperature or has other methods of correlation between level and oil temperature.

Several common relays which are present on the transformer can include relays such as sudden pressure relays, and Buch Holtz relays. These relays monitor pressure changes in the transformer which would indicate a large amount of gas formation in the transformer. Sudden pressure relays actuate exclusively off a large pressure difference in transformers, which is typically an indication of a significant event occurring in the transformer, however over the years it has been identified these relays can provide false alarms, and hence have been either removed from the protection scheme or have had additional redundancy built in such as a 2/3 scheme. Buch Holtz relays monitor specifically for gas formation on transformers with conservator tanks. These are usually mounted near the conservator and are on top of the transformer. They can detect both rapid gas formation, and slower gas formation over time.

The last major relay type which will be covered would be relays which monitor electrical characteristics, these relays will typically have current transformers on the inputs and outputs of the transformer and will be mounted inside control cabinets or inside buildings. These relays can include overcurrent, differential, and lockout relays. Among those listed, typically differential relays are the fastest to operate and monitor for phase differences. Overcurrent relays monitor for overcurrent conditions, and lastly lockout relays will actuate when the differential, overcurrent, or any other protective device trips which is tied into it. For this reason, lockout relays are among the most important relays, as if they fail open the transformer may not be able to trip as rapidly as possible.

Table 1 identifies the ANSI designations for the most common transformer relay types.

ANSI Device / Relay Designations	
Relay ANSI Designation	Relay Type
26Q	Top Oil Tempature
27	Undervoltage Relay
49	Winding Tempature
51	Time Overcurrent Relay
59	Overvoltage Relay
63	Sudden Pressure Relay
71	Liquid Level Indication
86	Lockout Relay
87	Current Differential Relay

Table 1 ANSI device / Relay Designations

Chapter 2.0 Power Component Failures

This section will explore several transformer components more in-depth and explore the potential degradation mechanisms, and potential modes of failure. The Electric Power Research Institute's (EPRI) guide to Online Monitoring of Transformers section 2 contains a list of various components of transformers which can fail, and though they may not cause immediate failure, they can lead to further degradation of the transformer. The following components will be discussed with their respective aging / degradation mechanisms: tank, windings, core, insulation, bushings, cooling system, tap changers, and protection system / devices [11].

2.1 Tank

As per the EPRI guidelines, the significant aging mechanisms for the transformer tank are material degradation, deterioration of organic sealing components, metal fatigue, and the loss/over torquing of fastening components[4]. Most of these degradation mechanisms can be observed on the tank itself, being rust, leaking from any seals such as the connection points of the cooler groups, wear on the protective coating (paint), or leakage from the tank itself.

2.1.1 Material Degradation

Material degradation can include but is not limited to rust, or corrosion of the tank itself commonly visible on most aging transformers in service, and physical damage that can occur due to human interaction or sever conditions. Typically, large transformers are located outdoors, and thus are exposed to the typical weather conditions including temperature, humidity, wind, and UV exposure. Overtime exposure to UV, wind, and snow can lead to the breaking down of the protective coatings, or paints used to protect the typical low-quality steel of the tank. This issue can be observed on almost any painted structure, including buildings, various holding tanks, etc.

Once the protective coating chips, peels, cracks, rusting can begin to occur, and start weakening portions of the tank. This may lead to increased leakage around the joints and could eventually lead to larger issues with oil level.

Typically, this is protected against by periodically inspecting transformers, and painting them as nessacary to ensure proper protection. In the nuclear industry transformers are typically observed at least daily on Operations walkdowns where all available indicators are checked including, nitrogen pressure (if applicable), winding temperature, liquid temperature, and liquid level, operation of the fans, and the bushings are checked as well. However, this is expected to occur over a large passage of time so things such as the chipping of paint may be missed or written off as common especially with the frequency this is performed. Other walkdowns are commonly performed to close these gaps including engineering quarterly walkdowns, etc.

2.1.2 Deterioration of Organic Sealing Components

On large transformers typically there is an organic type of material seal such as rubber weather seals around electrical enclosures to prevent the entry of moisture into the enclosure. On large oil filled transformer cork neoprene seals are common on penetrations into the transformer such as for cooling groups, plugs, any penetrations even for gas monitoring. Over time it is common for these materials to degrade, being particularly vulnerable to UV exposure and extreme cold causing embrittlement, and these seals may be exposed to high temperatures causing further degradation. These seals may also degrade if disturbed during maintenance activities. As stated in EPRI’s Aging Management Guideline for Power Transformers these seals should be replaced periodically [4]. However, on oil filled transformers replacement of these seals may require draining the transformer making replacement extremely difficult. It is generally recommended by contractors to replace any leaky flanges or seals on the transformer whenever drained for other purposes. This is still a rarity, and it is expected for a transformer to almost never need to have its oil drained so these seals may be in service for over 40 years. While this is not a noteworthy degradation it should still be noted and tracked.

2.1.3 Metal Fatigue

According to the EPRI Aging Management Guideline for Power and Distribution Transformers "metal fatigue can result of cyclic vibration or thermal stresses such as on heat up's or cooldown cycles and during operation of the cooling system, and even the ac induced hum. This can lead to high areas of localized stress such as on welds resulting in tank leaks at these points [4]." Generally, these are rarer than the degradation of organic components as noted in section 2.1.2, however they can still occur. In Generation, ideally transformers are less subject to repeated heated and cooling as they can be expected to run at a relatively constant rate only being subject to a change in conditions during outages. Most notably main transformers the cooling groups (fans and pumps) can run almost constantly.

Typically, this aging is inevitable, and it can be minimized by catching minor material defects, such as cracked welds early. This event would be accounted for on periodic walkdowns by Operations and Engineering respectively. Another way this could be accounted for is if a Nitrogen blanket is maintained by monitoring Nitrogen pressure, as cracked welds, or seals could lead to the loss of pressure leading to a greater frequency of nitrogen supply replacement.

2.2 Core Degradation

Cores are essential parts of a transformer primarily meant to guide the magnetic field induced from one winding to another. Transformer cores can age and degrade in similar ways to the other components being aging and major faults. According to the EPRI's Aging Management study the main failure mechanisms are the loosening of the core mounting system, and core embrittlement [4].

2.2.1 Core Mounting System

The core mounting system holds the core in place and seems like an unlikely failure mechanism. However, during transport, they can loosen, and fail, however it is much more likely in the event of a major fault the forces exerted by the fields forces the core supports to fail. This event occurred at Perry Nuclear Power Plant, where a major line fault occurred on the transmission side, and during the fault the Auxiliary transformers core shifted completely disabling the transformer. At Perry, this later necessitated the addition of a large shunt resistor bank to hopefully limit the forces induced in the core. In newer transformers, cores may be supported to better deal with events.

2.2.2 Core Embrittlement

According to the EPRI study "core embrittlement can occur primarily in older cores, because of high thermal exposure from core, and winding losses. Embrittlement can result in the weakening or failure of the laminations by which individual core segments are held together, which will create increased eddy current losses and core losses" (Gazdzinski and Toman 2012). Essentially, once the core's laminations start to degrade it will cause increased heating which leads to faster continued degradation of the core. This event can start as a simple hotspot in the windings, or in the core. According to the IEEE standard for DGA monitoring this can be observed and trended as rising CO/CO2 levels in the transformer. [8] It is expected in general that as a transformer age more gas will be generated in it, and increased gas generation will occur at the end of its life [8].

2.2 Bushing failures

Transformer bushings are among the most common causes of catastrophic transformer failures, as a failure of these bushings can occur semi randomly, and if not caught quickly fires can occur. Bushings can fail for a variety of reasons including but not limited to transformer vibrations, which can lead to overheating, partial discharge via a dielectric breakdown of the insulating material, commonly oil, or loss of a seal on the bushing. Commonly, these bushing failures can be corrected in a few days if a failure is detected during its early stages, such as if oil is observed leaking from the bushing. Once observed the transformer should be isolated, and the bushings will need to be replaced. Typically, the bushings can be quickly disconnected and removed from the transformer as some just sit in penetrations on the transformer such as the Westinghouse Type O Condenser bushings, which are common for use in HV applications.

Bushing failures due to seals are relatively common as most bushings are filled with oil, and as the bushings age, the seals can degrade, becoming more brittle eventually leading to complete failure. One point of cation for seals on older bushings is to be cautious during doble testing, as it is possible that during testing of the bushing some degradation could be aggravated and lead to a loss of the seal, which has resulted in extended outages and can potentially lead to catastrophic failures.

2.3 Winding Failures

According to the EPRI Aging Management Guideline for Power and Distribution Transformers, windings can degrade in several ways: Degradation of Organic Materials, Formation of Localized Hotspots, loosening of the winding mounting system / winding connection failure [11]. Most aging degradation is caused by the continued in-ability to displace heat away from the windings however some of these failures can be caused by manufacturing defects or can occur during shipping as per usual.

2.3.1 Degradation of Organic Materials

The degradation of Organic materials is one that occurs as a side effect of aging. As per the EPRI Aging management guidelines, the degradation of organic materials can be caused by "exposure to heat, and chemicals as well as dielectric stresses induced in operation… the protective coatings on the windings themselves are subject to thermal degradation due to heating… however generally the protective coating on the windings have no insulating function and therefore are not necessary on the standpoint of maintenance" [4]. It can be commonly observed that during the operation of transformers winding temperature leads fluid temperature, and that winding temperature will typically be several degrees hotter than the fluid temperature.

This event is important as it shows most heat in a transformer is going to occur around the windings causing this type of degradation. Heat can be additionally generated by the formation of local hotspots, this event would lead to more rapid degradation of the protective coating in the general area, and potentially lead to increased degradation. It is important to note that while this is degradation, it is expected to have relatively little if any consequence to the life of a transformer.

This type of degradation can be detected by the formation of some gases in DGA analysis, it is expected to see generation of CO and CO2 as that typically indicates a localized hotspot and general break down of Cellulose insulation due to overheating [8].

2.3.2 Formation of localized Hotspots

Local Hotspots can be caused either by aging or via the formation of blockages around the windings. Over time it is commonly known oil can degrade and breakdown. It is noted In the Aging Management guidelines that sludge can be formed as a side effect of either impurities or exposure of the fluid to oxygen. The sludge that is formed could potentially cause blockages of the cooling system, or rest on the windings themselves resulting in loss of flow ultimately leading to the formation of a hotspot overtime [4]. Additionally, the EPRI Aging Management Guidelines note that high resistance areas can be formed from sharp bends, and variations in conductor diameter, however it also notes transformer windings are manufactured such as to minimize these conditions. It also notes high resistance points are more likely to be caused by loose connection points. These loose connection points can be on the connections to the bushings or caused by the typical vibration's transformers are subject to [4].

Generally, it would be expected to see some formation of sludge over time, however some transformers are kept under a nitrogen blanket. This event would make the occurrence of oxygen in the transformer itself an abnormality and this event would be minimized. It is common to see some transformers held under pressure by a holding tank mounted on top the transformer. This oil, or fluid would be more subject to the contamination of oxygen. This event can be clearly demonstrated by dissolved gas testing, as it is common to rarely see oxygen in transformers held under pressure by nitrogen. Additionally, Dissolved gas analysis would help with the detection of hotspots in the transformer, and any formation of excessive heat. Any high resistance points caused by vibrations should be detected by Acoustic monitoring of the transformers. If the above-mentioned test has been performed, and a declining trend is identified further investigation may require entry into the transformer, however entry into the transformer is typically not recommended as great care must be taken to avoid damaging the insulation system, and extreme care must be taken to ensure moisture intrusion is minimal. Some transformer entry guidelines can be observed from Entergy's Large Power Transformer Inspection Guidelines. The guidelines note "extreme care to avoid moisture intrusion, and ensuring no foreign material is not left behind in the transformer. Furthermore, the guidelines provide information on what to inspect and look for inside the transformer, which includes the general condition of the core and coils, broken leads or frayed insulation, any signs of moisture intrusion, among other components internal to the transformer." [1]

2.4 Relay Failures

Currently in the industry many ageing mechanical relays are being replaced with newer microprocessor relays, however both relay types are expected to have vastly different failure mechanisms. Mechanical relays are more subject to false trips due to accidental bumps, however the mechanical relays can also have contacts not operate more frequently, as the contacts would be more subject to ageing effects such as corrosion. Additionally, it is expected these types of relays would be more subject to potential shorts. These relays can be affected by warmer temperatures'; however, it is expected they would be able to withstand them for a period without an issue occurring.

New Digital Relays again namely the SEL series of relays. These relays can be seen as highly reliable and are used frequently through the power industry. Per SEL the SEL relays have a Mean Time Between Failures of ~500 (1 failure in a group of 500 per year), and a Mean Time Between Returns for Repair (includes misuse, mishandling, confusion, weather, fire) of ~200 (for every 200 relays in service 1 will be returned annually). [5] Further from this data we can predict most issues with relays, will have to do with outside sources of degradation, such as weather, or maintenance issues. Furthermore, we can predict a much smaller number of issues such as defects, and internal issues. It is expected other manufacturers of digital protection devices will have similar rates of failure.

The newer solid state, and microprocessor relays offer different failure modes, being subject more to excessive heating than the mechanical relays. Additional care is required to be taken to ensure these relays are not subject to excessive temperatures inside control cabinets, among other enclosures. These relays are intended to have approximately a 20-year life span, with an example being SEL style relays. Per the SEL Product Reliability Report specifically for SEL-387-0 relays it is stated that the relays are expected to be removed from service after approximately 20 years. [6]. This, however, also requires less maintenance overall, this is mainly due to the microprocessor relay's ability to store and retain event reports which can be analyzed in addition to the self-checks the relay will run through. This can help predict and detect failures which occur that are internal to the relay. For SEL relays the following maintenance is recommended per SEL Recommendations on Periodic Maintenance Testing of Protective Relays: Per form comprehensive testing for commissioning, monitor the self-testing alarms in real time, monitor for potential failures not detectable by self-test, analyze event reports to the root cause level, and observe all product bulletins. [13] It can be seen most of the testing is passive elements such as monitoring for self-testing alarms and evaluating event reports. It can be inferred if the maintenance recommendations are followed as recommended by the vendor these will be extremely reliable pieces of equipment, with their ability to self-monitor for internal failures, and ability to collect data for analysis.

It should be noted that even though the newer microprocessor relays are expected to be highly reliable they will be subject to ageing wires, seals, and other mechanisms such as water intrusion. Additionally, microprocessors being digital come with specific challenges in the nuclear field, which makes accessing, and obtaining data from these devices much more difficult. (They would be considered Critical digital assets, and would hence require special laptops, and procedures. Additionally, these relays are extremely easy to change settings on, which may cause human performance issues where people do not return settings as expected, and so on.)

Chapter 3.0 Records of Power Plant Operating Events

This section is where events will be gathered for review and presented. Section 4 will go into an analysis of the events provided.

3.0.1 Format of Events

An example of how events shall be documented in this thesis is shown below with a brief explanation of each. Each event will include a title, date, description, and a comments section.

Title:	Example of an event entry.	Date:	X-X-XXXX
Description	A description of the event based off information obtained from the nuclear industry.		
Comments	A section provided for general comments; however, the general discussion will be contained in **Section 5 "Conclusions and Predictions"**.		

3.1 Cooling System Failures

Title:	Main Transformer Cooling Issue Requiring Unit Power Reduction	Date:	09/03/2022
Description	On 9/3/2022, a Boiling Water Reactor (BWR) was coming up from a separate down power when a fuse tripped, causing the loss of all transformer cooling power. The loss of power was caused by a ground being caused on 2 motor starters, which alarmed the control room. It was identified 2 of the 5 cooling groups tripped. As a result, the plant required a *down power by 16%* to ensure the transformers would not overheat. Previously 2, other cooling failures (one in 2014 and another in 2017) had occurred in the same cabinet causing a more limited loss of cooling for the transformer and thus did not require a de-rate. It was later determined these failures were caused by excessively high temperatures inside the control cabinet caused by a design issue.		
Comments	It is clear this failure was due to partial or incomplete actions from previous failures. This event shows the importance of finding the cause of the issue and fixing it rather than just the issue itself. It was due to a lack of the "find it and fix it forever" mentality.		

Title:	Main Power Transformer Cabinet Resistor Failure	Date:	11/18/2021
Description	A BWR's control room received multiple alarms from the Main Transformer bank early 11/18/2021 in addition to a 125V battery ground alarm. An inspection by the operators, maintenance and engineering visually identified charring or heat damage on one of two heaters as well as on 480V cables going to the Contactors for cooling groups 1 and 2. Additional inspections after the transformers were de energized (forced outage) identified damage on cables going to annunciators in the control room. The cause of the event was determined to be due to one heater's open circuiting allowing for the full current to pass through the other heater, eventually leading to overheating and a small fire in the cabinet. After the control panels were de-energized and transformers removed from service, the control cabinet was promptly fixed and returned to service 2 days after the event.		
Comments	This occurred on a transformer which was originally a spare unit, however due to a separate issue, it was placed in service ~ 1Y prior to failure.		

Title:	Cooling Fan Motor Failure on Main Transformer Phase 'B'	Date:	05/20/2021
Description	A BWR's control room received multiple alarms from the Main Transformer bank early 11/18/2021 in addition to a 125V battery ground alarm. An inspection by the operators, maintenance and engineering visually identified charring or heat damage on one of two heaters as well as on 480V cables going to the Contactors for cooling groups 1 and 2. Additional inspections after the transformers were de energized (forced outage) identified damage on cables going to annunciators in the control room. The cause of the event was determined to be due to one heater's open circuiting allowing for the full current to pass through the other heater, eventually leading to overheating and a small fire in the cabinet. After the control panels were de-energized and transformers removed from service, the control cabinet was promptly fixed and returned to service 2 days after the event.		
Comments	This event shows that typically Main transformers or GSUs are sized close to their operating limit, the nuclear plants received uprates which removed some of the design margin they have. The Main Transformers are 22kV - 345kV single phase units and are plant original. The Main Transformers are to be replaced starting in 2029 as of now and will include a slight uprate to restore design margin and will upgrade the cooler scheme.		

Title:	Turbine Removed from Service from Lack of Transformer Cooling	Date:	01/05/2020
Description	On 1/5/2020 a US BWR was starting up from a forced outage, and shortly after the generator was synced to the grid operators found the Main Transformers Cooling system breakers tripped out leaving the Main Power Transformers with no active cooling available. It was later determined that the inrush current tripped both breakers. Per the station's procedure at the time the *generator was taken out of service again* before further investigation occurred. This resulted in an *estimated 2500MWH loss.*		
Comments	This event is a cooling failure because the cooler groups had tripped on high inrush current. This failure shows the need for good human performance and a questioning attitude.		

Title:	Failure of Breaker Reduces Cooling to a Main Transformer	Date:	09/01/2014
Description	On 9/1/2014, a US PWR experienced a transformer cooling system breaker trip, which resulted in a loss of half of the Main Transformers Cooling Capacity. The breaker which failed was installed 3 years prior to the failure during a system upgrade, which eliminated the transformer cooling system as a single point vulnerability to the station. The cooling system was redesigned in such a way that loss of half the cooling would not result in a de-rate to the plant, thus there was no consequence other than the *loss of half the transformers cooling.* As a result, the station replaced the Molded Case Circuit Breaker (MCCB) and restored all cooling to the transformer and sent the previously installed breaker offsite for failure analysis. Failure analysis identified the internal poles installed within the breaker showed a much higher resistance than others, additionally it was identified the failed breakers' coil appeared to have been shorted with discoloration noted on the pole. It was also noted the failed breaker did not trip as expected when overloaded, and instead exhibited smoking.		
Comments	If This event had happened a few years prior, it could have resulted in a substantial de-rate, as the plant revised the cooling system to be more redundant.		

Title:	Main Power Transformer Cooling Fans Supply Breaker Trip	Date:	03/28/2017
Description	A Pressurized Water Reactor (PWR) was at 90% power ramping up from a refueling outage in early 2017 while a MCCB, which protected a cooling bank on a Main Transformer tripped. The tripped breaker was identified by operators on walkdowns during the start up, and as a result increased monitoring was performed on the transformers temperature sensing equipment (49Q and 26Q relays) The temperatures continued to rise and the operators decided it met criteria to shut down the plant, and hence *the plant entered a shutdown as the* failed breaker was replaced. The operators responded poorly in this scenario as per the stations report as they did not need to shut back down. Procedural guidance was found lacking, and the vendor provided untimely feedback to the station which contributed to the station shutting down for a slightly extended outage.		
Comments	The breaker was 32 years old at the time of failure and was likely an age-related failure. It should be noted MCCB's tend to fail in different positions depending on design. Some fail over time as the spring tension degrades, which then opens the breaker creating false trips and difficult resets. Others may not open unless manually operated.		

3.2 Bushing Failures

Title:	Manual Reactor Trip Due to XFMR Fault	Date:	11/15/2021
Description	At *47% Power the reactor was tripped* due to a main transformer lockout due to a failure of a center phase bushing. This event caused a Fire on the main transformer, which was put out in 19 minutes of actuation. In the following morning, it was identified the transformer oil overflowed from secondary containment and was spilling into a lake before being contained by a boom and was cleaned up. It was later identified Isophase Bus silver plating, and the bus duct was damaged in a ground fault. The transformer was replaced in the following forced outage and the unit was restarted. (Low Voltage bushing failure)		
Comments	N/A		

Title:	Oil Leak on Main Power Transformer	Date:	09/23/2019
Description	Operations at a BWR on 9/23/2019 identified a bushing leaking oil on a GSU (Main Transformer) neutral bushing, and it was further determined the flow rate was ~ one gallon per hour and was originating between the flange and the upper porcelain casing. The decision was made to take the plant offline and replace the bushing. *This event had resulted in a unplanned shutdown (4 days) and a Maintenance Preventable Functional Failure.* The bushing was replaced, and to prevent a similar failure in the future an extension plate was installed to ease tension on the ground lead. The affected transformer was tested and promptly put back in service on 9/27/2019. The root cause had eventually determined the failure was a random midlife bushing failure.		
Comments	This was a leak from the base of the bushing, the seal between the bushing and tank likely degraded over time. This was on an OIP bushing, and it would have been extremely difficult to determine if the leak was from the bushing or the tank. If it was from the bushing and they did not shut down promptly it could have failed catastrophically.		

Title:	Start Up XFMR Removed from Service Due to Bushing Leak	Date:	06/10/2019
Description	At a PWR on 6/10/2019 identified an oil leak on one of the 4160V inter-bus transformers, that supplied power to Safety Related buses. The oil leak was found on a bushing connecting one of the phases, and it was discussed with input from engineering, and operations, which led to the shutting down of the inter bus transformer. The Interbus transformer had supplied a source of offsite power to a safety bus, which then required entry into a 72-hour LCO leading to shut down. A shutdown was necessary as to replace the bushing the transformer was required to be drained and opened. The bushings were originally replaced with spares the plant had in stock. (2 dated in 1991, 2 dated in 2001) A failure analysis was performed on the failed bushing, and it was found the seal between the transformer and bushing had been a cork seal, which aged and became brittle over time allowing oil to seep out. When the new bushings were checked it was found that one of the new 1991 bushings had been leaking in the same place due to the same issue, which necessitated removal of all bushings again, and the bushings were rebuilt and refurbished with new nitrile rubber gasket seals to prevent a future failure with the support of the transmission portion of the business for expertise on the matter. After bushing seal replacement and re-termination, no other oil leaks were observed, and the transformer was placed back in service. The transformer was taken out of service on the 10th, and it was returned to service on 6/22/2019 *indicating a ~12-day forced outage.*		
Comments	This event was a bushing failure on an Interbus XFMR Bushing due to ageing which was identified by a Engineering walkdown in the 4.1kV switchyard at this station. Ageing cork is a common problem on old XFMR seals, it is common to see oil leakage from gaskets on the ageing XFMR's not just the bushings.		

Title:	Down Power due to Cooling Tower Losses from Start-Up Trip	Date:	08/03/2022
Description	Breaker tripped due to the actuation of a transformers Sudden Pressure Relay (SPR) which was caused by from the transformer Overheating due to the transformer oil level is low enough to restrict the flow through the radiators. The oil level in the transformer was low due to a Bushing leak the transformer had developed. Due to the higher temperature, the pressure in the transformer increased and the pressure release setpoint was reached resulting in a relief valve to actuate which resulted in a dramatic drop in pressure causing the SPR to actuate. This event occurred on a Start Up Transformer, which was 42 years and 161 days old at the time of failure. *The trip of the beaker resulted in a loss of cooling tower capacity and required a 10% de-rate.*		
Comments	N/A		

Title:	Main Transformer High Voltage Bushing Failure	Date:	08/27/2022
Description	At *28% power,* the operating crew received the annunciator for *a turbine trip without reactor trip,* and at 8:12 a report came in regarding a Fire in the North Yard due to Main Transformer A, experiencing an upper bushing failure. The station fire brigade was dispatched, and off-site assistance was requested, however the fire was put out before assistance arrived. The RSE at the plant responsible for the transformers stated the bushing was a ABB Type O Plus C bushing, the direct replacement for the Westinghouse Type O Condenser Type Bushings installed throughout the industry. The bushings were not of considerable age at the time of failure (16 years, and 328 days old), and this failure was likely induced by Maintenance error as the expected service life of the bushings according to ABB is ~27 years. The Westinghouse / ABB Type O bushings are Oil Impregnated Paper (OIP) bushings. Additionally, a portion of the oil made it to the ground.		
Comments	Documents another midlife failure of a OIP type bushing.		

Title:	Unplanned De-Energization of the Start-up Transformer	Date:	05/24/2019
Description	On 5/24/2019 a PWR experienced a loss of an offsite source of power along with a safety bus. The safety busses Diesel Generator kicked in and restored the safety bus, however the offsite source was lost. As a result, an LCO was entered, and unit power slightly decreased over the next few days. The offsite source was lost due to birds nesting inside a rodent cover installed over all bushings on the Start Up Transformer's. When birds nested, they created a path between 2 low side bushings and created a fault along with a small fire. To resolve this issue, bird nesting materials were removed, and the bushing covers were customized to prevent bird entry. The event stated that originally unit load was reduced to 96% power for a day and then was raised up to 98.5% power for the rest of the event. The transformer was placed back in service on the third day.		
Comments	This failure was due to animals nesting in a termination box.		

Title:	Fire On 500kV Transformer Bushing in Switch Yard	Date:	01/03/2022
Description	At a US PWR Operations received an alarm in the control room at 0942 for a grid disturbance and were notified of a *fire on B phase of a transformer in the switchyard.* The area affected by the fire was de-energized, and eventually put out by 1633, and reflash's occurred at 2320, and 0957 the following day. The transformer the fire occurred on was a 500kV 3 phase transformer, and the station determined the most likely cause of failure was a sudden short / ground on the bushing. Since the transformer was one of many in the switchyard the consequences were limited, and the switchyard is located outside the fence / plants critical area. This event did not cause a loss of offsite power.		
Comments	The Bushing was 9 years and 105 days old at the time of failure and was manufactured by SMIT. This event is an unexpected mid-life transformer bushing failure.		

Title:	*Defective Neutral Bushings on Start-up XFMR Cause Outage Delay*	Date:	04/26/2019
Description	During a refueling outage a PWR was performing Doble (Power Factor) testing on a Start Up Transformer and 2 neutral bushings, and a lightning arrestor showed elevated results. The original round of Doble testing was performed in relatively poor conditions (stormy) and originally it was thought the elevated results may be due to conditions or dirt on the bushings. An additional round of testing was performed the following day after a cleaning and in better weather, and was worse than the original. It was decided that the bushings were to be replaced as they could cause a failure of the transformer if they were to fail, and the lightning arrestor was replaced. The replacements *added 36 hours* to the outage and delayed start up. The bushings were manufactured in 1994 and 2006 and placed in service in 2008 as ABB Type O Plus C bushings. During analysis, it was found the bushings most likely failed due to water intrusion due to the seal on the tap connection point on the bushings. (The seals were found cracked / degraded) To further reinforce the consideration of moisture intrusion one of the bushings seals showed evidence of moisture intrusion having occurred. The lightning arrestor was found slightly discolored and showed signs of tracking and is thought its failure was most likely due to a lightning strike.		
Comments	This failure is highly notable as it was on an OIP ABB Type O Plus C bushing. The approach in this event is proper as current weather, dirt, and debris can have a huge effect on Doble test results thus they should be retested.		

Title:	Start-up Transformer taken out of Service due to Bushing Leaks	Date:	05/30/2013
Description	At a PWR on 5/19/2013 Doble testing was performed, in which the test plugs were removed to perform the testing. The testing was performed SAT, and the test plugs were re-installed, and the startup transformer was placed back in service. On 5/29 oil was identified leaking from the test plugs on the bushings, and by 5/30 it was decided to *remove the startup transformer from service* again to tighten all test caps. All test caps were tightened, and oil was added to all 3 bushings to make up for the lost oil. Additionally, all bushings were cleaned again. This experience was incorporated in future work orders as Operating Experience, and additional guidance was added in station procedures.		
Comments	Shows a shortfall of OIP bushings: susceptible to maintenance issues.		

Title:	Planned Shutdown to Repair Oil Leak on Start-Up XFMR	Date:	10/06/2018
Description	On 10/6/2018 a PWR was shutdown manually due to a 60 dpm oil leak originating from a low side bushing on a Start Up transformer. The *forced outage lasted 5 days* and was taken to investigate the source of the oil leak and correct it. After the transformer was removed from service, the bushing was determined and was examined for any signs of movement due to the release of mechanical stress, however, none were observed. Upon removal, a crack on the base of the bushing (where the porcelain meets with a seal, and the transformer casing) was identified. It was determined the leak was due to this crack in the bushing which was determined to be most likely there since manufacturing. It was therefore considered a manufacturing defect that was exacerbated by multiple de-terminations and re-terminations for testing. As a result, all low side bushings on the transformer were replaced, and during the next refueling outage additional time was taken to inspect all other similar transformer bushings on site for similar flaws.		
Comments	The transformer was a 36kV-6kV unit with the leak occurring on the 6kV side. The bushing was ~46 years old at the time of the leak. (Ageing Failure)		

Title:	Automatic Scram Due to Transformer Failure and Fire	Date:	10/16/2021
Description	A US BWR *automatically scrammed* due to a failure and *fire on Main Transformer A's HV bushing*. The oil fire was put out rapidly, and there was a reflash in the control cabinet and was extinguished. There was catastrophic damage to the bushings, control cabinet, and the lightning arrester. The rest of the transformer and other components suffered differing amounts of damage. As a result, the plant entered a forced outage to replace the transformer. A root cause team was formed and determined the failure to be due to a sudden catastrophic failure of the HV bushing. The company determined sudden bushing failures have happened across the industry regardless of the manufacturer. The bushings that failed were Trench COTA HV OIP bushings. Failures of these bushings are attributed to an unknown material or manufacturing defect by the manufacturer; however, this is typical for a bushing failure. The unit was restarted on 11/2/2021.		
Comments	Unexpected midlife OIP type bushing failures are an obvious trend in the industry, and Power Factor testing has a chance to catch it. The bushing was ~11Y old.		

Title:	Main Transformer Fault Causes Turbine and Reactor Trip	Date:	10/16/2021
Description	While in operation a PWR experienced a sudden failure of a HV bushing on a Main Transformer. The fault caused a trip of the turbine and plant shutdown. The Main Transformer was isolated and actuated the fire suppression system which subsequentially put out the fire. The fire had damaged the bus bar, and the area around the transformer. During the subsequent outage, the transformer was inspected, bushing replaced, bus bar fixed, and the plant started-up in 12 days. The root cause report looked at multiple failure modes for the bushing, however, was unable to pinpoint the root cause due to the bushing failing catastrophically. The study examined porcelain failure, bushing oil leak, water / air intrusion, degraded paper, an issue with the test tap, or oil parameters as the potential cause.		
Comments	The bushing documented in this event is an ABB Type O Plus C OIP bushing (successor to the Westinghouse Type O condenser type bushing. The plant performs power factor testing on a 3 year / 2RO basis, and they were unable to detect this failure. This test was performed last on 12/2018. The age of failure was 12.5Y.		

Title:	Shutdown to Address Bushing Oil Leak on Auxiliary Transformer	Date:	06/05/2021
Description	A Nuclear power plant upon start up from an outage identified a LV bushing oil leak on their auxiliary transformer and were forced to continue shutdown, with all loads being transferred back to the start-up XFMR. During the extended outage period, the plant repaired the connection and made epoxy repairs as required and started up. Failure analysis concluded the cause of the leaky bushing was due to stress at a flexible link connecting the isophase bus to the auxiliary XFMR's LV bushing. To prevent this from occurring in the future, the procedure for installing and maintaining flexible links was changed to add tolerance checks. *The consequence was failure to startup and an outage extension of 3 days.*		
Comments	This failure was deemed as a maintenance aggravated failure, as the flexible link had high stress, however ageing of the seal at the bushings base could be an additional contributor.		

Title:	Plant Start Up Delayed Due to Transformer Oil Leak	Date:	11/03/2020
Description	In 2017, a BWR was in a refueling outage, and was performing maintenance on the Main XFMR's HV bushings. During the maintenance, coking was observed in the oil of the test tap of the Westinghouse Type O Condenser bushing which is used for Doble testing. The maintenance also documented the seal of the test tap was in good condition. The test tap on the Westinghouse Type O bushing is constructed such that prongs are taken directly from the core of the bushing. The prongs are at the voltage of the bushing, and require insulation, which the space where the prongs are is filled with oil and is sealed using cork neoprene. In 2019 the station obtained new bushings and scheduled replacement in 2021, however on power up oil started leaking from the test tap, and the plant was shut down to replace the bushing. This *significantly delayed plant start-up due to refueling outage.* Due to the bushings being onsite replacement could be accomplished within a couple days. Upon inspection, it was observed that the cork neoprene seal had been damaged, and due to partial breakdowns inside the tap chamber the rear wall of the chamber fractured, which allowed oil from inside the bushings' main chamber to leak into the tap chamber, which then leaked out of the bushing. At the time of failure, the bushing was 33 years old, and per Westinghouse, the service life of the bushings was ~27 years. This event was classified as *a loss of generation potential due to untimely action.*		
Comments	This event was investigated extensively. The summation is written in chronological order. It is important to note, ABB purchased Westinghouse, and updated the bushing design to ABB Type O Plus C, and several failures of these bushings have been observed in the industry.		

Title:	Trip due to Phase-Phase Fault of Main Transformer	Date:	03/03/2015
Description	On 3/3/2015, a US PWR was operating at 100% power and experienced a *SCRAM* due to a fault on one of the Main Transformers. Before the trip, the plant was experiencing freezing rain as well as lowering temperatures. The freezing rain caused ice formation on the several bus bars, and a few hours later, the conditions changed which allowed the ice to begin melting. As a result, the ice on the bus bar had fallen onto the high voltage bushing directly below. The ice was long enough to connect the A and B phases resulting in a phase-to-phase fault resulting in a Differential relay actuation and Main Generator lockout.		
Comments	This event is marked as a Bushing Failure, as the bushings sustained damage because of falling ice formed on bus bars at the station. Damage to the bushings was limited due to the resulting phase to phase or phase to ground relay trip.		

Title:	Outage Delay Due to Startup XFMR Bushing Degradation	Date:	02/22/2023
Description	At a power plant in 2023, Doble testing was performed on a Start Up Transformers bushing. Both the high side and low side bushings were being tested, and it was found the low side bushings showed signs of degradation. The station conservatively decided to replace the bushings which showed higher Doble values than predicted. This additional maintenance *work added 72 hours onto the refueling outage.*		
Comments	The bushings were 5 years old at the time. It should be noted that Power Factor testing is highly susceptible to contamination such as dust or salt on the bushings, and environmental conditions. A cleaning can significantly improve Doble test values, and a retest should have been performed. (Though not noted) The bushing was in an application for 4160VAC.		

Title:	Turbine Trip on Differential Lockout	Date:	08/28/2017
Description	On 8/28/2017 at a US Plant, a lightning arrestor on a GSU experienced a phase to ground fault on the center phase (catastrophic). Due to *the lightning arrestor catastrophic failure, the bushing on the GSU was damaged and required replacement* in addition to the arrestor. The failure was due to water intrusion on the upper end gasket seal due to end clamping bolts being inconsistently torqued (manufacturing defect). *This event resulted in a 11-day forced outage.*		
Comments	The lightning arrestor was ~10 Years old at the time of failure. Additionally, it is common for bushings, as well as lightning arrestors to either last their lifetime, or fail midlife. Since a lightning arrestor has some failure mechanisms in common with bushings and are monitored in similar ways, it will be counted as a bushing failure for this paper.		

Title:	Failed Neutral Bushing Seal on Main XFMR results in Power Reduction	Date:	01/26/2014
Description	At a PWR in the US during Operations daily rounds, an operator observed an oil level gauge on the neutral bushing on the Main Transformer B was reading low, and identified oil leakage. The plant decided to execute a *planned down-power which included removing the generator and Transformers from service to make repairs. (~3-day outage)* The failure mechanism was declared as age related degradation of the bushing seal as the bushing was ~28 years old at the time of failure. It was later determined that oil most likely leaked out of the test tap which is common for these bushings.		
Comments	The bushing was a Westinghouse Type O Bushing with a 115kV rating. The station was able to identify this leakage quickly and avoided a catastrophic failure as a result. It should be noted the bushing's shell was cooler than the other bushings at the time of failure.		

Title:	Fire on Aux XFMR and Shutdown Due to Cable Damage	Date:	04/04/2021
Description	On 4/4/2021 a fire was reported on a Main Transformer, which had resulted in the output breakers opening, causing *a turbine trip and a plant SCRAM on both units 1 and 3.* The fire was put out within an hour. Significant damage was found on 3 Main XFMRs from the fire, and an Auxiliary XFMR had instrumentation wiring damaged. *Unit 1 entered a scheduled outage early, while unit 3 was down for an additional 25 days to affect necessary repairs to the damaged Auxiliary XFMR instrumentation.* Later failure analysis found that the fire was caused by a short circuit on the U1 Main XFMR bushing due to high contact pressure.		
Comments	This catastrophic failure is notable as the Main XFMR bushing had damaged the rest of the transformers in the bank and caused damage to the Aux XFMR of another unit.		

Title:	Thicker Spring Washer Resulted in Main Connection Hotspot	Date:	06/25/2019
Description	A PWR on 6/18/2019 had a high wind event which prompted operators to perform thermography of the offsite power connection points and identified a hotspot on a GSU. Operators reported one bushing was hotter, and by 6/26 it was noted to be heating up, and a decision was made to shut down. After the unit *was taken offline,* it was found the bushing had a spring bolt which was .125" vs .089" which caused a higher resistance at the connection. The connection was corrected, and the unit reconnected to the grid on 6/27.		
Comments	This event is classified as a maintenance related event.		

Title:	Elevated Temperature on Main XFMR B High Side Bushing	Date:	06/10/2019
Description	A power plant identified during thermography the Main 'B' HV bushing was nearly double (115C) of the other 2 phases (59C) on 5/19/2019.Maintenance was last performed in the Nov. 2018 outage. It was found the cause was a poor connection between the aluminum and copper connectors. During the outage, maintenance made the connections to the transformers over the grid operating company. The outside contractors had made a procedure that would assist in making the connections, however it lacked adequate guidance, and contained several errors. This resulted in a poor connection. The procedure was revised to provide adequate guidance, torque values for all bolts, and cleaning and mating techniques. Guidance was provided to perform a DLRO reading as a check. The plant was forced to desync from the grid and correct the connection.		
Comments	This occurred due to inadequate procedural guidance regarding the tightening and handling of connections. Also, this event shows the importance of performing thermography after any major work is completed on a transformer on any connections available.		

3.3 Relay Failures

Title:	Open Phase Detection System Cabinet Alarm	Date:	05/19/2022
Description	A US PWR, a *Start Up Transformer Trouble Alarm* came in due to the Open Phase Trouble alarm and would not reset. Operators then responded attempting to reset the OPPS system and could not get it to reset. Analysis showed the Variable Frequency Drive had failed. Failure analysis showed that in the summer months the cooling on the cabinet was insufficient, and exposed the VFD to high temperatures, which led to the failure of the device.		
Comments	OPP systems became a requirement for all nuclear plants to have installed on offsite sources as OE showed an Open Phase may go undetected and cause damage to all devices connected. As a result, all nuclear plants had installed a similar system. This failure shows a potential issue with the system and is an important bit of operating experience.		

Title:	Turbine Trip due to Main XFMR Differential Trip	Date:	02/11/2023
Description	A CANDU PHWR experienced a false differential relay trip on the Main Transformers. The trip was found to be due to fretted wires contacting a junction box. This event *tripped the turbine, and the reactor power was lowered to 55%. A 59-hour forced outage occurred.* The cables were corrected, and maintenance practices were revised.		
Comments	It is likely that many more similar cases occur throughout the industry that are not recorded as the consequence is low. These issues can be rectified by examining connection points on a fixed basis.		

Title:	Startup XFMR Sudden Pressure Relay Found out of Position	Date:	12/10/2022
Description	A PWR identified that a toggle switch for a SPR relay was in the cut-out position on a Startup XFMR. It was determined that the 87 Differential relay provided adequate protection against internal faults. This event was classified as a human performance error. The switch was repositioned, and a discussion was held with operations.		
Comments	This layout seems like it could be common in the industry as many newer XFMRs are coming with toggle switches to isolate individual alarms. This provides an ability to isolate individual alarms that can't be rectified immediately.		

Title:	XFMR Lockout Due to Breaker Failure Relay Spurious Actuation	Date:	01/26/2022
Description	A US PWR following restoration of a switchyard breaker, one of the two startup XFMRs locked out. The lockout was determined to be a spurious actuation due to a faulty breaker failure relay. Testing showed the breaker failure relay wouldn't operate after the event. The original relay was replaced, was sent for failure analysis, however no cause could be identified, and it was determined it was a internal failure of the relay. The consequence was *a loss of a source of offsite power and entered a 72hr LCO resulting in plant shutdown.*		
Comments	This was a plant original relay. This occurred on a mechanical relay, which has proven they can last forever however require calibration and can't perform self-checks.		

Title:	Power Reduction Due to Failed Transformer Relay	Date:	12/02/2020
Description	While a US PWR was at 100% power, a digital protective relay scheme for the transformer was found smoking and arcing. Operators of the station conservatively decided to decrease power to 50% *(50% De-rate)* Upon de-energization it was determined the damage was limited to the relay and wiring on said relay, which the relay was replaced, and the failed relay was sent for failure analysis by the vendor. It was determined to be caused by an unknown internal relay fault. Per the NRC, this event is classified as a level 4 reactivity event.		
Comments	This was a GE B30 relay, which had experienced a high energy event at the terminal block. The damage continued inside the relay leading to internal damage. An additional note is GE digital B30 relays are designed in such a way the front cover acts as a door, and all cards are readily accessible and are mounted on racks allowing for quick replacement.		

Title:	Reserve Start-Up XFMR 345kV Tie line connection failure	Date:	06/17/2021
Description	A PWR identified a vertical drop fell off a Start Up's disconnect resulting in an Open Phase condition. The offsite source inoperable entering *a 72-hour LCO.* The transition from schedule 40 aluminum bus to the disconnect switch had separated due to a fracture on a weld that existed originally. The weld was replaced with a new swage bus connector and was put back into service. Failure analysis found it failed due to porosity, and lack of fusion to the root. The OPPS did not actuate as designed due to how the line fell onto the bus.		
Comments	This is an event where a condition occurred and was not identified by an Open Phase Protection System (OPPS).		

Title:	Start-Up XFMR Relays Actuated	Date:	04/27/2020
Description	A PWR was testing back feed capabilities and started a Reactor Coolant Pump for flushing during a outage and the 87T, and 50/51 devices tripped on the auxiliary XFMR, which actuated the deluge system. As this lineup was being tested, the station expected a trip might occur, and was easily recovered from with no impact to critical path. All breakers that were aligned to facilitate back feed operation tripped and loads automatically transferred to its Start-up buses.		
Comments	One of the relays was a SEL 387-5 (a newer digital 87T).		

Title:	Off-site Source Lost Resulting in Reduction of Power	Date:	01/15/2019
Description	A US BWR was installing a DGA System on a Start-Up, and a member of the Maintenance crew had bumped an auxiliary relay, which actuated the SPR relays, then the XFMR responded as designed and started the delude system. Operators were dispatched and no smoke or fire was observed. The relay was not identified as a potential risk when performing work, as the SPR relays were all isolated from the relay. It is highly likely the SPR relays would actuate this relay in the case of an actual event in the XFMR, and an accidental actuation would cause an XFMR trip. The station performed an oil sample for DGA and verified good results, and the unit was placed back in service. No down power was required, however operators decided to *derate the plant as a conservative measure.* The trip was caused by the work group not performing an adequate risk assessment which would have identified this relay. On another note, the relay in question is a GE HEA relay, which has a poor track record in the industry.		
Comments	GE HGA relays failing are a common theme in the industry, now more and more relays are being replaced with Digital Type relays which are less susceptible to these events.		

Title:	Offsite Source Loss Results in Actuation of Class E Electrical Systems	Date:	03/24/2020
Description	At a US PWR U1 was at 100% power, and U2 was on an outage while the transmission authority was conducting relay testing at the transmission station. During testing, the technician connected the leads of the test set to the wrong relay, which was not isolated, and injected the signal, and caused a lockout of the bus, and the *loss of offsite power to both units.* Safety buses were lost resulting in a 24hr LCO due to the loss of 2 safety buses in U2, and a 72-hour LCO as 1 safety bus was lost in U1. U2 was able to restore 1 safety bus within 2 hours, and the last offsite source was restored later along with U1's last safety bus. This event was classified as a partial loss of offsite power, and caused actuation as designed of multiple diesel generators. The root cause was determined to be a human performance error of the transmission operators.		
Comments	This event is being included in the relay section as a difference in design may have prevented this. A 2/3 logic scheme potentially could have solved this.		

Title:	Reactor SCRAM Due to Main XFMR Trip	Date:	05/18/2018
Description	A US BWR incurred a main XFMR trip due to the actuation of a Buch-Holtz relay. The trip actuated a *Main Generator lockout.* The relay actuation was due to a phase 'A' to ground fault, which occurred about 9 miles away from the station on a 500kV per the utility, and the station contributed ~ 7000 Amps peak through the XFMR. Failure analysis determined the Buch-Holtz relay was too sensitive. The relay was identified as a Comem BR80 and was determined to be too sensitive when supplied to the vendor. (Manufacturing defect)		
Comments	Buch-holtz relays are relays that operate on the concept of during a fault in a XFMR the oil breaks down and forms large amounts of gas. The formation of gas will set off a Buch-holtz relay.		

Title:	Aux XFMR Relay Found Failed During Preventive Maintenance	Date:	09/30/2019
Description	During an outage a US PWR was performing relay calibration and testing when *the relay was found to have failed*. The relay was a 51N, which was a plant original and was obsolete (~33 Years old). The failure was attributed to ageing, and a new fleet guidance document for zone 1 and 2 protection was created.		
Comments	The relay was on a 20.9kV to 6.9kV auxiliary XFMR. The failure was discovered in a typical exercise and calibration maintenance, and in case of a transformer fault, differential relays still likely would have functioned along with other relays. Ageing tends to make most protective relays not function instead of mis operating.		

Title:	Main XFMR Trip Due to Moisture in Monitoring Equipment	Date:	05/10/2019
Description	At a US PWR on 5/10/2019 a Main Transformer experienced a transformer trip resulting in a *forced outage.* The relay found tripped was a "gas protection relay" (most likely Buch-Holtz) and as a result the PWR took a DGA oil sample from the XFMR to determine if a fault had occurred, which was SAT. Further investigation showed signs of moisture ingress and heavy corrosion of the conductors. It was determined the failure was due to moisture build up bridging the contacts, actuating the relay. Moisture intrusion was most likely from a degraded seal on a conduit entering the box and condensation build up.		
Comments	It is likely ageing related degradation of the seals caused the event.		

Title:	87T Relay Actuation During Energization for Back feed Operation	Date:	03/25/2019
Description	At a US BWR a unit Auxiliary XFMR was being put in service for back feed operation. When the station's Main Generator Breaker was closed, the phase 'A' 87T relay actuated, causing a Main Generator Lockout. This actuated the plants safety systems causing energization of all 4 Diesel Generators at the station. The plants Engineering department produced a white paper explaining the in-rush current properties associated with the energization of a transformer. The paper mainly explains older XFMR when energized had increased 2nd order harmonics compared to newer XFMRs of similar design. This event is stated to be due to design differences, as XFMRs are now produced with more modern construction techniques. 87T relays rely on this 2nd order harmonics to help filter XFMR energization and grid events from actual faults in the protected zone. The plant had its Auxiliary XFMR replaced ~12/12/2000. The mis operation was due to not revising the 2nd order harmonics set point of the 87T. Immediately after the failure the station performed a multitude of testing on the transformer to determine its integrity and ensure it was tripped due to a mis-actuation over an actual event. This resulted in the *actuation of all safety systems, and a short-term loss of offsite power.*		
Comments	87T relays operate on the following principles: It monitors the current going into a node and if it exceeds a certain % of typical current it will actuate. It uses 2nd order harmonics as usual during XFMR actuation 2nd order harmonics are present, and they wouldn't be present in a fault. This is accomplished by blocking the output of the relay with an input from the 2nd order harmonics.		

Title:	Open Phase System Injection Source Alarm	Date:	09/22/2022
Description	At a US PWR during the work to restore an Open Phase Protection System (OPPS) from an issue that occurred earlier in the year where the injection source failed due to high heat in the OPPS enclosure. (<122F) The system experienced another failure of the Fuji Variable Frequency Drive (VFD) the OPPS uses to inject a signal. This event caused an additional alarm to the control room, the system taking a Maintenance Preventable Functional Failure, and resulted in an extended OPPS outage. The station is planning to improve the OPPS cabinets HVAC system to ensure proper cooling, attempt to reverse engineer the Fuji VFD to obtain a better solution, as well as test the OPPS system annually.		
Comments	This event is an extension of the previous event noted in this paper regarding the OPPS system. It is notable and included as a separate entry because the system failed when placed back in service after maintenance had finished.		

Title:	4.16 kV XFMR Gas Detection Trip Results in Generation Loss	Date:	04/28/2019
Description	A CANDU reactor on 4/28/2019 an inter-bus XFMR tripped due to a sudden pressure relay becoming shorted out because of water intrusion into its enclosure. *This resulted in a momentary loss of a safety bus before it transferred, and a power reduction from 100% to 55% until repairs were complete.* Evidence that this relay failed due to water intrusion was identified as the gas relay showed corrosion signs due to water entering from a seal, and the XFMR had been tested via DGA which showed no evidence of any gassing that indicated a good XFMR. The SPR was sent to forensics for further study on the failure.		
Comments	This is common on Interbus XFMRs as they are not critical pieces of equipment and have very limited-service windows. Often, the original seal on transformer enclosures fails from ageing and continues to worsen over time.		

Title:	Main XFMR Trip Resulting in Forced Outage	Date:	05/22/2023
Description	At a nuclear power plant, a Main Transformer SPR relay tripped resulting *in an entry into a forced outage.* Why the SPR had actuated is currently unknown, however, it seems likely it could have been a SPR relay malfunction. It could also be indicative of a failure internal to the transformer.		
Comments	N/A		

Title:	Main XFMR and Start-Up XFMR Trip Resulted in Shutdown	Date:	08/30/2018
Description	On 8/30/2018 a CANDU reactor had a relay in the circulating water system intermittently operated causing vacuum breakers to operate which caused an increase in air pressure in the condenser, which vented water onto a floor at the 254' elevation, which flowed down through conduits to a lower elevation into a junction box, which contained Sudden Pressure relay's for both the Main and Start Up Transformer that shorted *out and tripped both transformers out and Scrammed the plant.* It should be noted that this was a design vulnerability that was identified in 2017.		
Comments	This event is a relay failure as the relays failed.		

Title:	Offsite Source Loss Occurred during Start Up XFMR Lockout	Date:	01/08/2018
Description	On 1/8/2018 a US PWR experienced a Start Up Transformer Lockout, which resulted in a partial Loss of Offsite Power due to a SPR seal in relay. The trip was caused by a short circuit between contacts on the SPR itself, which actuated the SPR seal in the relay, which tripped the transformer. Operators had received a DC ground alarm shortly before the transformer tripped out, which then forced the transformer to be declared inoperable*, placing the station into a 72-hour LCO.* This event was determined to be a *Maintenance Rule Functional Failure.* The short circuit occurred due to a cable which had failed, which caused a ground fault on a DC system. The station has since implemented a modification to disable the trip function of the SPR relay and restored the transformer to service shortly after and exited the LCO. This event was under investigated with the last update in that the wire was pulled apart somewhere underground, and water was identified in the conduit.		
Comments	XFMR SPR's are important even though the existing trend seen in the industry to only have them sound an alarm. The cable and relay were ~34 years old.		

3.4 Containment Failure

Title:	Failure of Common Service Station XFMR	Date:	11/10/2021
Description	A US PWR was replacing a XFMR, which supplied power to a warehouse, and it was found the XFMR was *missing about 90 gallons of oil.* After the removal of the XFMR, the vault was inspected, and signs of leakage were identified through a cable trough. The replacement was delayed as efforts were made to clean up any oil and licensing notifications were required. This XFMR was inside the owner-controlled area and did not affect any nuclear aspects. The oil leakage was not detected due to slow seepage through bushing seals, and the bunker design of the vault, which made inspection difficult. It was confirmed the oil did not contain PCB's.		
Comments	This event was not a failure of a major transformer at the site and shows an issue with some designs of XFMR vaults, as they should facilitate proper inspection. This issue plagues the industry due to the use of cork seals in older designs when the transformers are lightly loaded and get colder, the cork seals shrink, and often causes leakage.		

Title:	Start Up XFMR Declared Inoperable Due to Low Oil Level	Date:	02/07/2019
Description	A US BWR's control room received a XFMR Trouble alarm, and Min Oil Level alarm came in on a Start Up XFMR. Operators were dispatched and confirmed the transformer had a low oil level. The *transformer was removed from service and declared inoperable, forcing the station to enter a 72-hour LCO to plant shutdown. The transformer was filled and returned to service, the LCO was exited.* The oil level was identified as low since 2017, however was unable to be filled online, and no action would be taken until the next outage. This event did not normally cause issues, however on 2/7/2017 extremely cold weather lowered the oil level enough to where the oil level fell below the minimum and caused the alarm.		
Comments	The XFMR was 35 years old at the time of this event. Leakage should be monitored and trended over time by an engineer to ensure negative trends are identified.		

Title:	Start-Up XFMR Cooling Pump Cable Failure	Date:	08/18/2020
Description	On 8/18/2020 a US BWR received an alarm that indicated a trouble alarm on a Start-Up XFMR. (25-13.8kV) Operators found a *small fire on one of the cooling pumps.* It was determined that the fire was caused by a small oil leak on the radiators, which caused oil to drop on a cooling pump wire. The cooling pump wire eventually failed, and the fault was strong enough to light the oil on fire. The fire was quickly put out, and the cooling pump wire was replaced returning all pumps to service. The damage caused by the fire was extremely minor.		
Comments	This event will be considered a tank failure because oil was leaking onto the power cable to a cooling group which eventually caused the insulation on the wire's insulation to breakdown. This event is not a cooling system failure event though it resulted in one. It should be noted correction of leaks may entail the replacement of seals, which would mean draining the transformer is necessary which has its own risk and should be avoided.		

Title:	Moisture in 230kV and 500kV class Transformers	Date:	04/18/2019
Description	At a CANDU reactor in 2018 a Main Transformer (single phase) failed resulting in an *oil spill as well as a 23-day forced outage to replace the transformer.* Failure analysis determined the failure to be due to excessive moisture in the transformers "solid" / paper insulation, which resulted in a dielectric failure internal to the transformer. The site performed an investigation in 2019 which identified 7 other transformers, which showed high amounts of moisture in the paper insulation. The plant reprioritized repairing Serveron DGA monitors, as well as Hydran moisture monitors for enhanced monitoring for all transformers and scheduled drying activities during the next available outage (forced or planned).		
Comments	This event is classified as a containment failure as moisture had to intrude into the XFMR. Usually, XFMRs are designed such that all leakage is out leakage rather than in, which ensures no moisture intrusion. The older method of doing this was by using a nitrogen blanket, i.e., keeping the internal pressure slightly high. This event indicates the transformers were low on nitrogen for a period. Winding failure due to high moisture content in a transformer is quite rare. This indicates improper monitoring was performed on the transformers or the moisture content in the oil was not monitored (since water must first go through the oil to get to the paper.) Moisture in oil is monitored online by either sampling (dielectric test) or via the online monitors, which are typically monitoring for H2 in the oil.		

3.5 Other Failure / Manufacturing Defects:

Title:	Failure of Common Start-Up XFMR	Date:	07/31/2022
Description	At a US PWR on 7/31/2022 differential relays detected a fault on a Start Up Transformer (161kV - 6.9kV) resulting *in a loss of an offsite source of power and therefore entering a 72hr LCO.* It was found the cause of the event was Noryl insulation on a phase was degraded due to a crack, and consequently failed. *Both units had to shut down from full power* to maintain NRC requirements.		
Comments	The Noryl insulation was 26 years, and 65 days old at the time of failure.		

Title:	Trip due to Generator Step-Up XFMR Failure	Date:	11/12/2020
Description	On 11/12/2020 a US PWR experienced a full reactor SCRAM from full power operation due to a major internal fault on the Main Transformer 'B'. The exact cause of the trip is currently unknown, however operators found that the differential relaying tripped, the overcurrent relaying tripped, and the sudden pressure relays actuated relieving pressure internal to the transformer. The transformer was found to have oil spilled inside and outside containment from the sudden pressure relays actuating and found the transformer bowed around the deenergized tap changer with the paint in the area showing signs of heating. After the trip, the spare Main was aligned as Main XFMR 'B' and the faulted XFMR was isolated allowing for Start Up 6 days after the event. Additionally, to ensure Main Transformer 'A' and 'C' where SAT power factor testing was completed. Investigation showed there was a high impedance, low energy fault on the high voltage side of the transformer, and a manual DGA sample was taken showing high amounts of Acetylene and Hydrogen (primary electrical arcing gasses, and elevated gasses were not present prior to the fault. It is likely this event was an electrical arcing fault around the deenergized load tap changer, and the fault occurred with a little precursor. Further investigation is required to find out the root cause. Additionally, it should be noted the transformers are in the middle of their service lives after being manufactured in 2000. (~20Y old)		
Comments	The cause of this event is not identified. While we can speculate, the cause is most likely a manufacturing issue on either the windings, core or tap changer. It is most likely its either a tap changer issue or windings (due to the overheating observed, and the actuation of Sudden Pressure Relays).		

Title:	Cable Fault Caused XFMR Tertiary to Ground`	Date:	07/22/2021
Description	On 7/22/2021 a US PWR experienced a fault on a cable going from an Interbus Transformer to an auto transformer, which fed safety busses. The buses' auto transferred, and the plant entered a 72-hour LCO for a loss of a single source of offsite power to the safety busses. The cause was determined to be the 'B' phase (13.8kV) fault, all cables were tested. 'A' and 'C' phases were determined to be good, and the line was replaced.		
Comments	It was on a 345/161/13.8kV XFMR on a 13.8kV line. This event was included as the line can be seen as a component that supports the transformer. The line was ~47.5 years old at the time of failure.		

Title:	SCRAM Caused by Subcomponent Fault in Main XFMR	Date:	05/03/2020
Description	At a US BWR during power ascension a Main Turbine Trip occurred. The ground overvoltage relaying was found tripped, and testing indicated a current transformer used in sensing winding temperature in Main B was the cause. The current transformer had been replaced during an outage since the existing one was failing. Failure analysis determined that the cause of the fault was a defect on the new current transformer. The defect which caused the fault was the new current transformer not having an adequate clearance between a winding and a busbar while having inadequate insulation between the two components. A potential cause was epoxy was found poured into the gap between the bus bar, and the winding, which had blocked the transformer oil from filling the space. The plant replaced the faulty current transformer with a bus bar and started up again. The direct *consequence due to this was a Reactor SCRAM at 76% power and an additional forced outage.* It is likely this outage took longer than 5 days to recover from, as the component was internal to the XFMR. Care must be taken during work inside a XFMR to ensure no FME, and moisture intrusion.		
Comments	The transformer is a 26kV-230kV, and the current transformer was mounted inside the main XFMR on the low voltage winding. This is considered a manufacturing defect.		

3.6 OLTC Failure

Title:	System Service Transformer Load Tap Changer Failed	Date:	03/22/2019
Description	At a US BWR on 3/22/2019 the control room received a *Transformer Trouble alarm* on a Start Up Transformer, and dispatched operators to investigate. It was identified that the *OLTC on the transformer had its controller failed and continued to lower the voltage until the tap changer hit the lowest tap. While this event did not directly impact the unit as the tap changer was taken out of automatic control and was changed to its normal position*, a safety bus could have been lost due to degraded voltage, or potentially plant equipment could have been run at a degraded voltage. The cause of the shift to the lowest position was due to a failure of a relay within the LTC, which was a plant original, and had not been replaced previously or maintained.		
Comments	The relay was 34 years old at the time of failure.		

Title:	Start-Up XFMR Failure	Date:	12/06/2018
Description	At a CANDU reactor, a Start Up XFMR (70MVA, 500kV-Dual 13.8kV) experienced a *fire, and oil leak.* The Start Up XFMRs *tank had ruptured and containment was lost.* The XFMR was one of 4 separate Start Up Units, and the currently supplied loads were briefly interrupted and transferred. The direct cause was determined to be due to the tap changer selector switch, which caused overheating and thus gas formation and a pressure rise in the XFMRs, tank. The increased pressure would eventually cause the tank to rupture, which caused the air, gas, and oil to mix and ignite, forming the fire. A SPR alarm was also issued 12 seconds before the tank ruptured, pointing to the event being a rapid unexpected failure of the tap changer selector switch, as gas formation was rapid.		
Comments	Other information such as when the fire was put out, or a more detailed failure analysis was not provided. The specific tap changer which failed was produced by Maschinenfabrik Reinhausen.		

Title:	Start-Up XFMR Tap Changer Malfunction	Date:	10/21/2018
Description	At an US PWR an operator identified a Start Up XFMR tap changer would not change taps in the event of an elevated voltage, since the tap changer was *unable to perform its function in auto, a 72-hour LCO* was entered, and the tap changer was *placed in manual mode,* exiting the LCO. The tap changer was still able to function as needed in manual mode. The failure of the tap changer was most likely due to moisture intrusion due to a faulty cabinet seal, as evidence of water intrusion was present. The water had corroded the cam switch contacts increasing the contact resistance until the "LOWER" circuit could not be actuated, hence preventing the tap changer from changing positions. The issue was resolved after the cam switch contacts were cleaned, and the LTC was tested to verify it was back in working condition before being placed back into service fully. Additionally, the cabinet seal was replaced, and is now required to be routinely inspected.		
Comments	Another failure due to a failing gasket. Gaskets are often overlooked in operations and tend to be agitated quite frequently, especially on normally entered enclosures. The control cabinet was estimated to be 5 years old at the time of failure.		

Title:	Start Up XFMR LTC Primary Controller Failed	Date:	03/02/2020
Description	A US PWR had an incidental actuation of the start-up XFMR (115kV) deluge system, which caused an XFMR trouble alarm in the control room. An investigation by operators revealed no fire existed and determined the cause was due to a detection circuit failure. As a result of the water spraying on the XFMR water was able to intrude into the tap changer control cabinet due to the failed seal, which then fell on the primary controller resulting in a *tap changer failure.* This event resulted in the operators originally declaring the *startup unit inoperable,* however this event was quickly exited as they were able to manually operate the tap changer. The plant resolved the issue of a tap changer failure by using manual tap changer control, replacing the tap changers controller, and applying weather seal stripping to the tap changers cabinet, and fixed the deluge system.		
Comments	This failure was included due to it being a failure to maintain the Tap Changer controller's cabinet, which caused a failure of the controller. This failure should have been prevented if maintenance or walkdowns identified poor seals on the cabinet.		

Chapter 4.0 Operating Failure Event Analysis

There was a total of fifty-nine separate event reports documented in this thesis, each of which was investigated with an approximate failure mechanism and type identified. To simplify the collection and analysis of data, events were grouped together. An example of this is the inclusion of another category.

4.1 Generalized Analysis

There was a total of fifty-seven events investigated, and each was classified into a certain category based off the subsystem, which had failed on the transformer. (Cooling, bushing, relay, On Load Tap Changer (OLTC), Containment, Other, and manufacturing defects) This section will analyze the failures collected as a total to identify, which the greatest number of failures and most severe of the failures has occurred. The below table and graph represent each category.

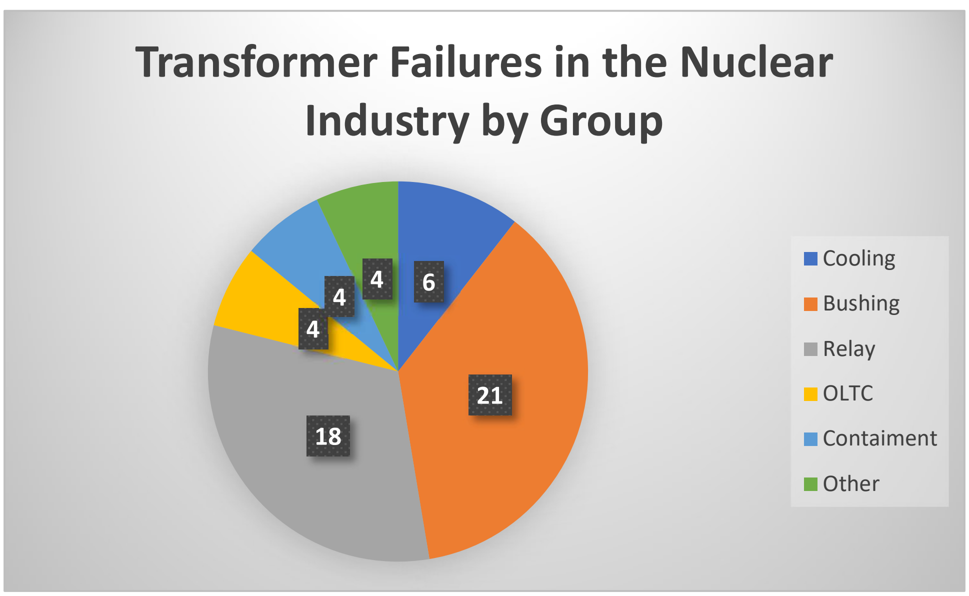

Figure 1 Transformer Failures by Group

From the table, it can be stated the two largest failure categories are Bushing Failures (21), and Relay related failures (18). In addition, out of all the failure types presented bushing failures are especially notable as every bushing failure resulted in a minimum of isolating the transformer. Relay failures are less notable as their failures had more of a tendency to either provide nuisance alarms or trip the transformer temporarily.

4.2 Bushing Failure Analysis:

The groupings used for classifying bushing failures were decided as the following:

Midlife Failures: A failure of the bushing during ~4 years – ~20 years. Typically, bushings have a design life of around 28 years with respect to vendor specifications. These failures tend to occur with little precursor and have the potential to result in catastrophic failure if not identified in a timely manner.

Maintenance Related: A failure type that was either caused as a direct result of maintenance performed on the bushing which resulted in a loose, or poor connection which resulted in overheating of the bushing, however, also includes fittings on the bushings not being tightened adequately such as when a bushing leaked oil out of the test tap connection due to the cap being loose.

Ageing: Failures, which occurred because of the bushing not being replaced in a timely manner and exceeding the manufacturers expected lifetime of the bushings. Typically, these can be seen occurring after the 28-year mark and resulted in the bushings leaking oil from inside the bushing. (Commonly seen leaking from a crack, or out of the test tap area)

Failing / Ageing Seals: While like the previous category Ageing, as they both result in an oil leak forming, this category refers to a seal between the bushing and the containment / tank of the transformer, and as such results in the transformer leaking oil rather than the bushings.

Other: This failure group was created due to several failures which occurred due to a variety of conditions, such as ice falling on said bushing, animal intrusion, or because of a stressed connection.

The consequences of bushing failures ranged depending on when the failure was identified and exactly what failed, even though all bushing failures resulted in a trip of the transformer. There were six instances resulting in transformer fires, nine that resulted in an oil leak. (Being either from the containment of the transformer or the oil in the bushings) There were instances where potential failures that were detected before the bushing showed any obvious degradation. (Three found via Doble testing)

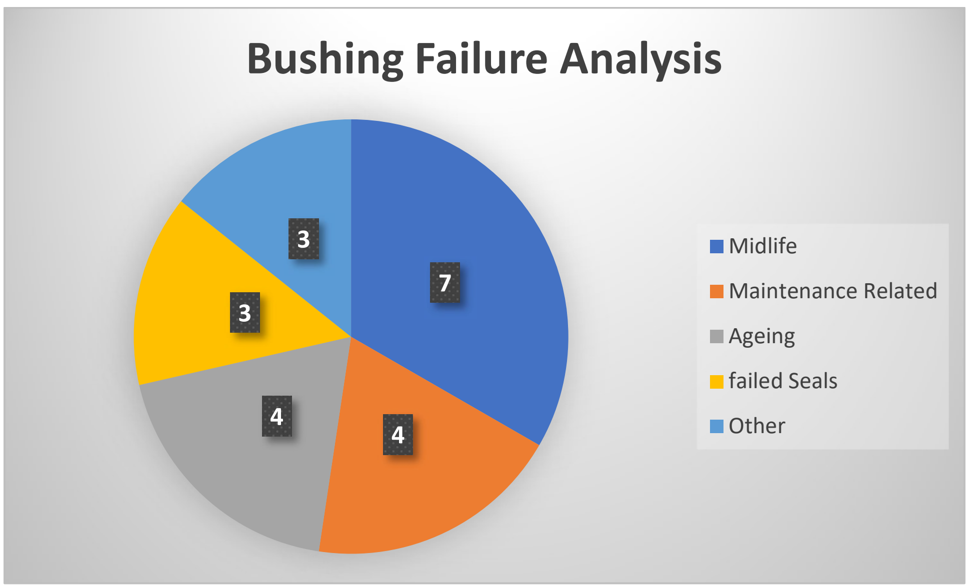

Figure 1 Bushing Failure Analysis

From the events collected Midlife failures appear to be the most common. Out of the seven midlife failures four failed catastrophically causing a transformer fire, one was identified leaking, and the transformer was isolated before a catastrophic failure could occur, and two were identified during an outage via Doble testing.

Another common failure mode identified was ageing in general. The ageing of the bushing resulted in 4 failures, which had a variety of consequences, 3 of which resulted in an oil leak, which was identified and isolated before a major failure could ensue. One of the events was unable to be identified and resulted in a dielectric failure of the bushing, however it should be noted the bushing that experienced a dielectric failure was inside the plants isophase bus, which likely greatly reduced the chance of it being identified. Additionally, most of these bushings have failed well over their design life with only one occurring at 28 years.

Maintenance related failures occurred in four of the events identified in section 3. Out of the four events, 3 were due to poor connections, which were all identified by thermography after the outage via the bushing heating up. The odd maintenance related failure was due to oil leaking from a test tap after doble testing had been performed. It was identified that the test tap cap was looser than it should have been. This category is notable as it is the easiest to correct. Work orders should always follow recommendations in vendor manuals for torque values, and often should be used as a basis for maintenance performed.

Based off the data referenced, most events could have been prevented, or at least mitigated substantially. The following table identifies 4 potential ways each failure could have potentially been mitigated against. The four potential categories are as follows:

Better design: This is regarding the type of bushings utilized mostly. Recently, in the industry new bushing technologies are becoming available for use on almost every transmission voltage in the United States. ABB's, Micafil, (Resin Impregnated Paper) and Hitachi's Easy Dry (Resin Impregnated Synthetic) series are excellent newer options, ABB's being Resin Impregnated Paper (RIP) and Hitachi Energy's Resin Impregnated Synthetic (RIS). Using this type of bushing over Oil Impregnated Paper (OIP) will completely negate oil leaks from the bushing eliminating the risk of oil leaking causing a dielectric failure and eliminates potential bushing detonation. This event would indicate it would substantially mitigate midlife failures, oil leaks and the consequences of bushing failures (fires) as well as removing the shrapnel created via detonations.

Proper replacement frequency: Replacing bushings based off ~30 lifespan or per vendor recommendations would negate ageing type failures, and in addition should replace the seal between the bushing and the containment system negating that failure as well. In addition, newer seal materials are less prone to shrink with regard to temperature hence mitigating tank leakage as well.

Detailed Orders: This would mitigate against maintenance leaving bushings with inappropriate connections, as well as leaving test cap connections to lose. (Caused an oil leak from the bushing)

Other: This category is for failures which couldn't have been mitigated as easily as they were caused by some external force such as animals or falling debris. Walkdowns could have potentially helped however would have been unlikely to have identified the issues.

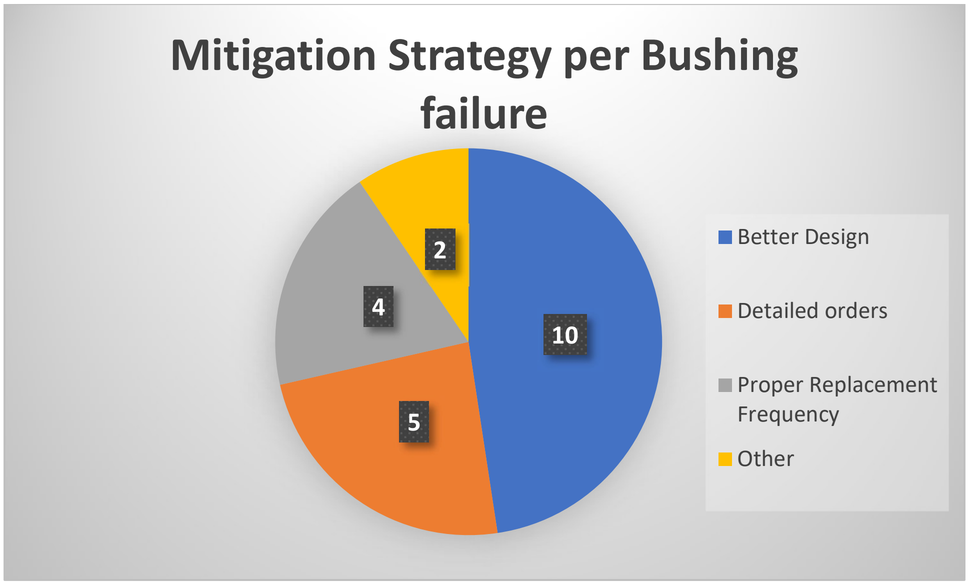

Figure 2 Mitigation Strategy per Bushing Failure by # of mitigated

The above figure represents the number of failures which could have been potentially mitigated / prevented regarding the failures identified in section 3. From the above, it can be seen utilizing a better design would have likely mitigated against roughly half of the potential failures identified. While this would help mitigate against a substantial number of failures, it can be expensive as swapping bushing types may necessitate draining the transformer, hence this should be performed when replacing the bushings to help minimize cost and downtime. Replacing the bushings should be performed on a fixed basis, and it should be noted that this category is most likely misrepresented to an extent as the nuclear industry is currently performing bushing replacements and usually bushings do not reach an old enough age.

Including more information to orders regarding proper bolt torque requirements or adding details to inspect for a stressed connection could likely have mitigated against several failures identified in section 3 and is among the cheapest thing that can be done to mitigate against potential failures. The cost to benefit of this recommendation is extremely notable as it would help eliminate the need to shut down for a loose connection.

4.3 Relay Failure Analysis:

The groupings decided for relay failures are as follows:

Human Error: This category refers to failures, which were inadvertently caused by human error while on the job. This failure accounts for performing testing on the wrong relay, bumping relays, leaving the wrong set points, etc.

Age: This refers to relays failing due to excessive age, with the relay being a plant original or has aged substantially. Typically, this sort of failure results in the relay failing to operate when desired and is identified during functional testing of the relay, however, can potentially result in a mis operation as well. This category also includes fretting and fraying of wires.

Defects: This category refers to the new relays being identified as failed, or the installation of a faulty component causing a failure of other components. This issue can include the failure of a cooling system on a panel being found defective, which resulted in other components in the cabinet overheating. Additionally, this refers to components which did not operate as expected due to factory error.

Internal: This section is meant to include relay failures, which occurred due to some unknown defect internal to relays which could not be identified.

Water Intrusion: This category includes relay failures, which occurred via some issue whether design or ageing enclosure seals allowing water in leakage, which created high corrosion or shorting of the internal equipment causing a false operation.

The consequences for relay failures are dependent on the relay which failed. Most relay failures noted in this paper resulted in a trip of the transformer and were commonly due to mis-operation. There were a significant number which resulted in relatively small consequences for their respective stations as well. Relay failures due to no operation may be more common than discussed in this paper, and this issue is due to the significance of those events. Not all events due to relays not operating would meet the reporting requirements.

A failure of an 87T, 63, or 50/51 relay will typically be more consequential than a failure of an Open Phase Protection System, as the previous relays are directly related to transformer protection so a false operation would more commonly result in a trip or at least an alarm. Additionally, two of these failures resulted in relays not operating and were found during testing.

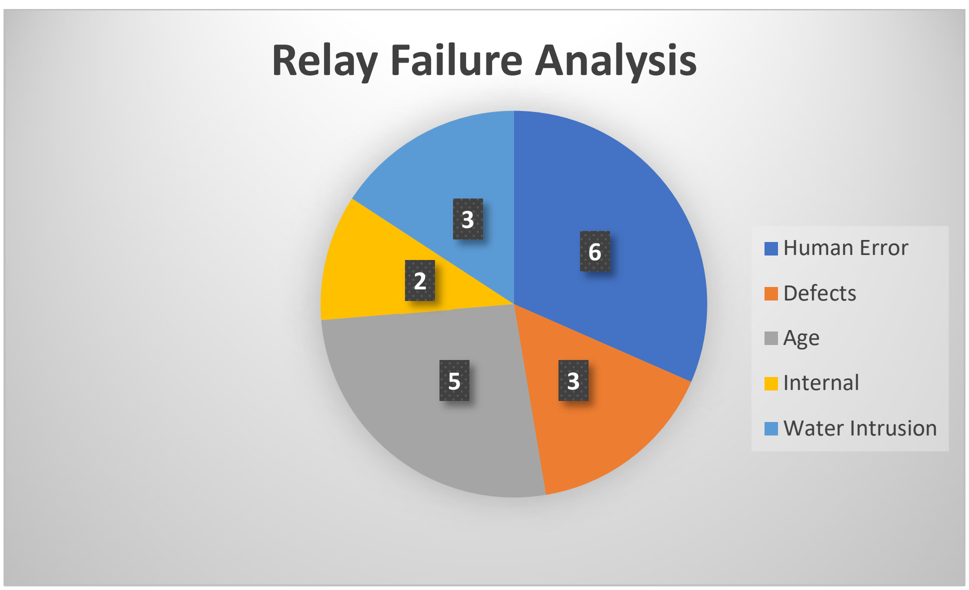

Figure 3 Relay Failure Analysis

Out of the eighteen relay failures that were included in the study, six were due to some form of human error. This is notable as failures which are caused by human error are some of the most avoidable. In addition to this, many of the events changed the way stations performed testing, increased the amount of peer checks, and updated their procedures to better incorporate potential human performance concerns. Several of the human performance related events were due to personnel bumping or working on a in service relay, some were due to a design oversight when a transformer was replaced. (Not changing setpoints) These errors typically resulted in a transformer lockout temporarily except for two which were either identified in a walkdown or were expected.

Age was another major category of relay failures, typically resulting in relays failing to operate, or wires being found degraded. While two of the identified failures could not be easily mitigated, degrading wires, or connection points can be identified during inspections to places where regular maintenance would be inspected.

Water Intrusion events commonly resulted in creating a false trip of the transformers' protection system, causing a lockout of the transformer. Two of the water intrusion events resulted in corrosion in compartments / terminal boxes and were due to ageing seals. This type of failure mechanism can be identified by regular inspections to the terminal boxes on the transformers, however most of the terminal boxes this occurred in cannot be accessed online making inspection windows limited and challenging to meet. The last water intrusion event was due to a defect in the plants design and was identified via a visual engineering inspection of the box, and due to untimely action, the event still occurred.

The last failure mechanisms classified in this paper were manufacturing defects, and internal failures of the relay. Defects were limited in consequence with the most consequential one being from a new Buch Holtz relay being found to sensitive and tripping on a false occurrence. The other two defects were on an Open Phase Protection System (OPPS) which was caused by a faulty HVAC system. Lastly, internal failures accounted for an additional two failures, both resulting in the trip of the transformer. One was due to an ageing relay, and the other was a newer GE B30 busbar protection relay. It should be noted that internal relay failures are random events which are unpredictable in nature, and difficult to diagnosis typically occurring more frequently on newer digital relays, and defects are only typically found during either acceptance testing or in service, however performing acceptance testing on a Buch Holtz type relay or a cabinet HVAC system is extremely challenging. Both failure mechanisms will be treated as random events for the purposes of this paper.

Several failures identified can be seen as random events due to manufacturing issues, or random internal relay failures, however most relay failures identified could be detected via occasional inspections to difficult areas to reach on transformers, additional functional testing, or peer checks and maintaining good situational awareness with the job at hand.

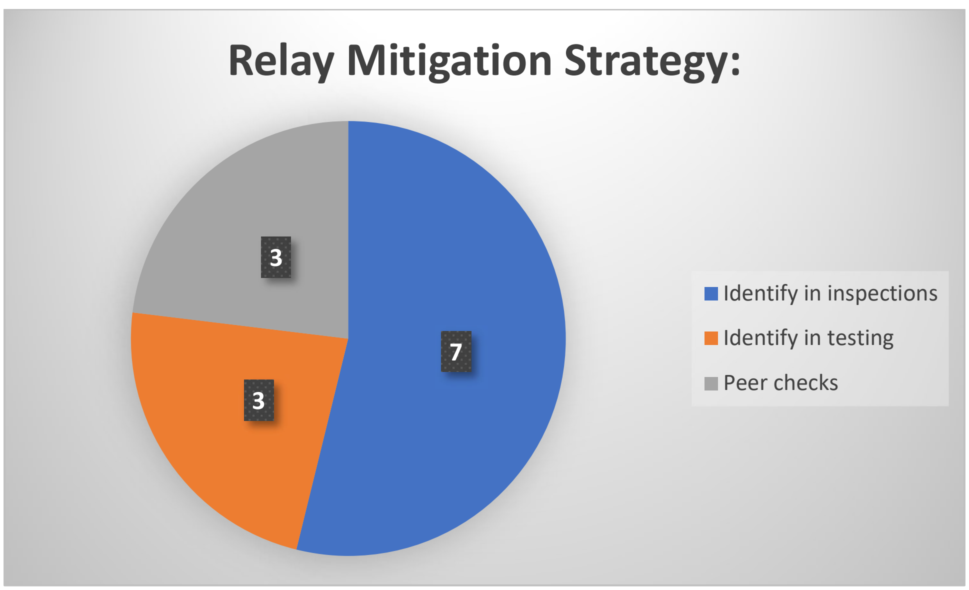

Figure 4 Relay Mitigation Strategy

All water intrusion events could have been identified via inspections, as all had sufficient time to corrode the terminations inside or were identified via an inspection. Additionally, several ageing events were due to wires fraying and contacting other components, which could have been identified via additional inspections on uncommonly accessed areas of the transformer (such as terminal / junction boxes). Additionally, while these inspections occur the responsible system engineer should participate as well to bring a different viewpoint to the inspection.

An additional three events could have been identified quicker via testing of the relay; however, it would be expected this would add a little additional benefit over the current amount of testing performed on relays. It should be noted that the frequency of testing is also heavily dependent on the station's priorities. This response could help identify several ageing failures that resulted in relays not operating as expected due to sticking.

Three human performance events could have been prevented via increased peer checks and situational awareness. There were two events which were caused via personnel performing work or bumping into the wrong relay. It should be noted test performers working near live equipment must maintain proper situational awareness for the work to be performed without the possibility of causing additional issues.

4.4 Cooling System Failure Analysis:

Cooling system failures happened on a much lower frequency than bushing, and relay failures. This issue is potentially due to two possibilities considering either the reliability of the components used in most cooling system designs, and the consequences of most cooling failures. Cooling systems use fans, typically factory sealed, and oil pumps controlled by several contactors usually in groups, which is all supplied by typically two separate power sources a primary and an auxiliary and protected by Molded Case Circuit Breakers. Molded Case Circuit Breakers are extremely reliable and will typically last for around 20 years, while fans, and oil pumps can last for a significant amount of time. While transformers need significant amounts of cooling, the amount required varies with external conditions, and power. A loss of a single cooling group may not cause a significant rise in transformer temperature requiring a de-rate all the time, most notably in the winter, however in the summer it may be nessacary to de-rate the transformer based off a significant rise in oil temperature. Loss of a single cooler in the fall, spring or winter may not be reported, as it had little consequence, however in the summer it would be.

Most cooling system failures were typically failures of the Molded Case Circuit Breakers (3), contactors (1), or fan motor's (1). The most common failure mechanism is most likely fan motor failures, however, may not always be reported as discussed above, which is why only one of these failures was identified. The most identified failure mechanism is a failure of the Molded Case Circuit Breakers, being one of the more consequential failures. One failure was most likely caused due to excessive ageing of the Molded Case Circuit Breaker being around 32 years old at the time of failure, with another being due to excessive in-rush, and the last being due to a manufacturing defect. The latter two events occurred approximately five years after installation.

It should be noted that the consequences for these events typically are not significant, however the five presented all resulted in transformer de-rates, with two resulting in a shutdown of the generator. The last event was an outlier being tested during an outage, and consideration was given to the device failing and as a result the failure was rapidly recovered from.

Looking at the events provided with consideration of their consequences, replacing old Molded Case Circuit Breakers and performing checks on contactors can help lower the frequency of these events, however its unlikely additional maintenance over replacing Molded Case Circuit Breakers and performing checks on contactors on a fixed basis will prevent a significant number of failures. Possible improvements to cooling system design are more notable, such as individually fusing fans, and ensuring a failure of one will not cause loss of additional fans, or significant excess capacity.

4.5 OLTC Failures:

Load Tap Changer failures was another minor group identified in this paper with two events (out of four) occurring due to water intrusion resulting in failing seals on the control cabinet. Another was caused by a selector switch failing to make clean contact, most likely due to age related issues. The last Load Tap Changer failure was caused by the failure of a relay due to age-related issues.

The most common theme associated with the control system (water intrusion and the ageing relay) all resulted in relatively minor consequences such as a loss of automatic control, and entry into a short Limiting Condition of Operation (LCO). The loss of automatic control can typically be quickly countered by placing the unit in manual control. The selector switch failure resulted in the loss of the entire transformer, however it occurred at a site outside the United States and no adjustments were required to be made in terms of reactor output or power.

In reference to the events discussed in this paper, two of these events could have been identified during walkdowns, as failing seals which are relatively easy to identify if access can be obtained to the control cabinets or respective boxes. These are easy to prevent as the failure mechanism is easy to identify and correct. This inspection can be performed in cross functional walkdowns between engineering and operations, which are recommended to be performed annually with current industry guidance. The failure of the relay could also have been prevented by possible replacement of the relay. The failure of the selector switch could potentially have been discovered during an internal inspection of the tap changer; however, it is difficult to anticipate what maintenance could have performed without further discussion with the respective plants personnel.

4.6 Containment Failures:

Unlike the other categories discussed in this paper, all containment failures are due to the failure of seals over a period and due to some sort of ageing degradation (events in this paper all occurred after 35+ years in operation), whether it's by the continued effect of heat overtime, or just generic ageing due to contact with various environmental conditions. Due to the limits imposed by consequential event reporting criteria only four failures in total were in this category most, resulted in relatively major consequences, such as a fire, the transformer being declared inoperable, or an environmental event where oil was lost. These, however, are serious events which all resulted in a notable consequence. Most plants deal with transformer oil leakage, however, do not track it as the consequence is extremely minor, or is nonexistent. It is expected that power plants will all deal with oil leakage routinely. Some plants have identified contractors to dam the leaks or have replaced seals to eliminate them. It should also be noted older transformers are more prone to these sorts of failures, as the use of cork gaskets contributes to oil leakage at lower temperatures, as well as the ageing of the material. Newer transformers are most likely more resilient against leakage due to a mix of better materials used to make the gaskets, the use of FR3 vegetable oil as an environmentally friendly option, and the increasing use of conservator type transformer designs.

It should be noted that oil leakage can be treated in various ways, either by installing oil dams, decreasing the pressure internal to the transformer, or via the replacement of aged seals.

4.7 Manufacturing Defects / Other:

This grouping is intended for either manufacturing defects or failures which did not fit into the other main categories. It should be noted that the events listed here were found noteworthy. For instance, one of the events was about a Main Transformer fault with little precursor with differential and Sudden Pressure relays actuating. An oil sample was later taken from the faulted transformer which showed C_2H_2 (Acetylene) and H_2 (Hydrogen) which is indicative of a dielectric failure. [8] Due to bowing found around the DETC (De-Energized Tap Changer) it is likely this could have been near the event inside the transformer. There was an additional noteworthy failure in this category which documented a failure of a current transformer used by the winding temperature monitoring system. This resulted in the loss of the transformer and the need to shut down. It was later determined the fault was caused by epoxy insulation taking up too much space which caused a dielectric failure. Gas trends can also be obtained off of Dissolved Gas Analyzers installed on the transformer itself. These analyzers are recommended for installation on transformers rated greater than 10MVA. [9]

The consequences of this section can be said to be high, as all these failures occurred with little precursor, and are difficult to predict. All events in this section resulted in the loss of the transformer.

Chapter 5.0 Proposed Future Preventive Mechanisms

5.1 Bushings

Based off the events described, and the analysis completed in section 4, many of the failures observed can be prevented or mitigated by utilizing a better bushing design. Currently, most large bushings installed are of the Oil Impregnated Paper (OIP) variety, and it wasn't until 2017 where Resin Impregnated Paper (RIP) bushings have become available at higher voltages (345kV), and as of early 2023 Hitachi has released, they're @Easy Dry series of bushings which are Resin Impregnated Synthetic (RIS) style bushings.

Swapping the bushing style to RIP eliminates several failure mechanisms regarding the oil contained in the classic OIP bushings, as resin is solid, it can eliminate seals, which if fail cause oil leak that can eventually lead to a dielectric failure of the bushing. In traditional OIP bushings, oil can circulate, which makes it so any defect can affect the entire bushing, with RIP bushings, the defect will remain localized. RIP bushings are also explosion proof / resistant as oil is combustible, and RIP bushings can be manufactured utilizing a composite outer shell, which eliminates the possibility of shrapnel forming in the case of a catastrophic failure. Additionally, since the new resin bushings do not have oil they lack oil level sight glass, this fact will eliminate a daily walkdown check point which can be hard to identify.

While RIP bushings are a significant improvement compared to OIP bushings, they still utilize paper and aluminum foil to create layers inside the bushings, which paper is hydroscopic. Since the paper is hydroscopic, these bushings are still subject to moisture intrusion if the end inside the transformer is ever exposed to humidity such as when stored as a long-term spare. The RIS bushings utilize a composite or synthetic material such as aluminum oxide which is immune to significant humidity intrusion. [2] This makes it immune to degradation via humidity intrusion as well as having all the benefits of being a solid resin bushing. The new (Resin Impregnated Synthetic) RIS/RIC (Resin Impregnated Composite) bushings are explosion proof and can be stored in any location. Additionally, they have superior performance in contaminated environments. [7] Per ABB the Easy Dry series of RIS bushings have a anticipated life span of over 30 years, and notes they can be used as spare bushings and kept in stock after transformers are decommissioned. [1]

Moving forward as resin bushings continue to gain prominence the older OIP (Oil Impregnated Paper) style bushings will most likely be phased out completely. This would indicate that moving forward the frequency of midlife bushing failures will decrease substantially, however it may take well over 20 years to fully realize these changes. Additionally, this is a newer technology, and it may potentially bring its own issues, such as an increase in the amount of transformer failures due to failing seals between the tank and bushing due to these bushings remaining in service for a longer duration.

The chance of seal failures between the bushing and tank could decrease going forward, as there has been a move away from cork seals to more reliable neoprene seals which do not degrade as quickly, however it should be noted that bushings will most likely be in service past the manufactures recommended dates. This would indicate the seals would be in service for a longer period as well, hence increasing the number of these failures seen over a given amount of time. This failure mode is unlikely to change heavily, as it would only be resolved by replacing the old seal during replacement of the bushing.

The odds of eliminating maintenance related failures are extremely low, with consideration to both stressed connections, and loose / tight connections as they are dependent on the craft, however the risk of such failures can be minimized by including proper torque values in procedures and work orders used.

The largest step to reducing the frequency and consequences of bushing failures going forward is swapping to (Resin Impregnated Paper) RIP / RIS (Resin Impregnated Synthetic) style bushings as seen in the paper the largest contributor to bushing failures was random mid-life events. The newer bushing design's, it is likely that failures would be easier to detect, since they would fail slower than similar OIP bushings. This would allow for more time for a potential failure to be detected by electrical testing (Doble).

5.2 Relays

From the discussion in section four most failures of relays could have been identified in inspections with many events being caused by a physical deficiency, such as in water intrusion events from degraded seals, wire degradation, and degraded support systems (HVAC). This indicates the easiest way to prevent several of these failures is by ensuring seals are inspected as well as boxes in the transformers for any signs of degradation. It should be noted that many enclosures contain very little in terms of the number of components, some on older designs holding terminal strips. These boxes should be included in maintenance plans on at least a fixed basis and should be identified. It also should be considered that transformers are walked down daily regardless as they should be included on operators' rounds. This would indicate the operators performing the walkdowns may not be performing as well as they could. Additional training for specific operators on objects to look for during rounds may be helpful in preventing many of these issues. The operators performing the walkdowns should note corrosion, seal conditions, any moisture or excessive heat inside enclosures, etc. Additionally, in most stations transformers are walked down by engineering on or around a quarterly basis, however its unlikely engineering walkdowns can check inside of cabinets. It is possible to obtain entry via paired walkdowns with operators to further enhance the ability to detect seals ageing, and wire degradation.

It is expected that moving forward the amount of relay failures that would be identified during relay testing will decrease as new digital relays are becoming more common as the older electro-mechanical style relays are being phased out. Most digital relays feature self-testing where the relay can monitor itself to a degree decreasing the likelihood of a failure going undetected or a mis operation. Additionally, digital relays are resistant to mechanical agitation increasing their reliability. It should be noted that while digital relays offer their own advantages, they are much more subject to human error as it is much easier to modify the settings of digital relays, and a laptop may be required to view all applicable settings. This makes it easier to adjust setpoints, and harder to check. It is likely strict configuration control is nessacary for digital relays to be successfully implemented. One challenge for the nuclear industry in specific is regarding the cyber programs involved with newer digital relays. A large amount of paperwork is currently required to connect to digital relays as they will likely require a specific laptop under special care. It is anticipated that a minimum of three hours would be required to prepare the special laptop as it will need to be scanned and more than likely have its virus definitions updated. Certain cases may take significantly longer. The newer relays have many features which require the relays to be checked at some frequency and have event reports pulled and analyzed, and currently cyber programs may not easily be able to support this.

Maintenance plans and regulations should support or reflect a shift towards digital protection as well. SEL recommends utilizing their relays self-check abilities and using its meter function to ensure the relay is reading accurately, and analyzing event reports as they are created and analyzed back to root cause. [12] Insurance companies like Nuclear Electrical Insurance Limited (NEIL) and the NRC (Nuclear Regulatory Committee) need to support the inclusion of these relays providing credits, and potential special testing requirements for them. Currently all relays on all covered transformers per NEIL are required to be tested every 6 years at a minimum. [10] For nuclear plants this is the site acceptance test typically, however this is not recommended by the vendor. NEIL should require these relays metering function to be tracked.

Overall, as predicted in section 2.4, most of the failures were due to other issues other than manufacturing defects, or relay failures. Other issues include excessive ageing, water intrusion, and human error. Any improvements to maintenance plans should include an inspection of all connection boxes on a basis with special attention to seals, and internal components.

5.3 Cooling Systems

As noted above this section is likely currently misrepresented due to the low consequence of this category of failures. Individual fan failures are expected to be extremely common and have virtually no consequence to the operation of the transformers, however as the performance of the industry continues to improve the reporting criteria is becoming lower.

Currently all plants perform thermography on at least some frequency which includes components inside the transformer control cabinet. While thermography may not be able to detect when a Molded Case Circuit Breaker may not operate or mis operate, it can be used to determine the connections current conditions, and there is a high chance a breaker will start to heat up prior to failure. It is expected this corrects any issues which occur with connections and has the potential to find Molded Case Circuit Breakers failing.

One failure that can be observed in this paper is a failure of a fan, which resulted in the loss of a cooler group as the fan experienced a ground fault and tripped the cooler group, which lead to a 10% de-rate. It should be noted that the same plant experienced another fan failure which did not result in the tripping of a cooler group, and only the fan was affected. The failure noted in the paper (10% de-rate) could have potentially been prevented by individually fused fans, or higher redundancy built into the cooling system. Adding a higher degree of redundancy may prove beneficial, but it would result in higher maintenance costs, and may not be recommended.

As previously noted, Molded Case Circuit Breakers should have a design life of around 20 years, however, depends on the type of Molded Case Circuit Breaker, as some can last only 16 years. The way Molded Case Circuit Breakers fail also varies heavily on the Molded Case Circuit Breaker in specific. Some tend to fail open, and provide false trips, it should be noted that this also makes the breaker more challenging to reset. This indicates a replacement frequency for Molded Case Circuit Breaker utilized in the cooler groups should have a replacement frequency of around 18 years. Additionally, thermography should be performed on a quarterly to bi-annual frequency to maximize the chances of identifying a poor connection. (This may help identify breakers developing poor contact pressure which would result in false trips)

The consequence of cooling system events is expected to decrease as a result to the current state of the industry. Many plants are replacing their Main Transformers because of the previous transformers reaching the end of their service lives, and the new transformers are expected to have a higher degree of redundancy built into their coolers, in addition to being slightly uprated to restore margin for the cooling systems.

5.4 Containment

As containment systems age some form of leakage should be expected, as ageing seals will most likely leak. Newer transformers will be less susceptible to oil leakage as newer seals are not expected to be as susceptible to thermal expansion / contraction as the older cork neoprene seals. Additionally, some plants have employed leakage dams where a seal is created outside the transformer, and the internal space created is held at a pressure to prevent leakage from occurring. This should only be considered as a temporary solution until the seals can be replaced at some point later. To replace the seals, it would be necessary to drain the transformer and enter it, hence it may not be recommended unless other work could be done such as for some bushing replacements and obtaining samples of solid insulation (cellulose paper), as draining the transformer could be potentially risky.

Chapter 6. Conclusion

In conclusion it is predicted the industry will experience a fewer number of catastrophic transformer failures going forward into the future, however, will likely result in an increased number of other potential failure mechanisms identified by some events identified.

The emergence of new Resin type solid bushings will eliminate internal bushing oil leakage failures, while increasing the resilience to other failure mechanisms as well. Their adoption will likely result in a decrease in the amount of transformer fires caused by bushing failures, as well as provide a significant increase in safety. While the resin bushings will likely lead to a major increase in transformer reliability, Power Factor Monitoring will still require performance to protect against bushing failures. It should be noted however that resin bushings degrade at a slower rate than similar oil filled bushings, hence this will allow for electrical testing to detect more failures before they occur allowing for more proactive replacements before failures occur. It is also anticipated that Online Bushing Power Factor monitoring systems will also greatly increase bushing reliability.

Digital relay protective schemes will continue to be adopted in the industry as more plants are forced to replace degrading and ageing original mechanical relays. This is expected to add to the strain associated with the current digital programs, however the upgrades will allow for greatly enhanced data gathering and analysis which will greatly expedite the diagnosis of false trips. It should be noted however that since the digital relays will allow for a large increase in flexibility, it will also lead to a significant increase in the likelihood of human performance failures.

It is anticipated that as the nuclear industry continues to improve the equipment reliability goals will continue to increase as well. Hence the rate of smaller and less consequential failures being reported such as those on cooling systems, and oil containment will increase going forward. It additionally should be noted that while the number of reported events with cooling systems will increase, the frequency of those events will decrease as newer transformers are being designed with a higher degree of redundancy in those coolers. For containment failures it is anticipated that the number reported will also increase while the overall frequency decreases, as newer transformers are being manufactured with newer less susceptible to degradation materials such as neoprene gaskets over the old cork gaskets.

Overall, it can be said the reliability of transformers in the nuclear industry is increasing with the emergence of the above-mentioned items, as well as other improvements in online monitoring capabilities. Further work and studies should be conducted on how to optimize cyber programs across the industry to make full use of new and emerging technologies, while maintaining an adequate level of cyber security.

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