Instrument Transformer Failures Due to an Internal Vacuum Phenomena

By

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INSTRUMENT TRANSFORMER FAILURES DUE TO AN INTERNAL VACUUM PHENOMENON

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Abstract

In recent years, there has been an increase in the number of instrument transformer failures that appear to have no apparent root cause. Investigators have focused their attention on the electrical properties, the manufacturing construction, the oil and insulation but have not found a logical explanation for some failures. Recent investigations have revealed a new type of phenomenon caused by internal vacuuming of the system and it may explain some of these failures. This paper investigates and explains the failure mode and offers methods of detection and prevention. It looks at the way the failure mode manifests itself in Current and Voltage Transformers and why this mode can go largely undetected until it is too late. The results of this study and investigation may have an impact on the way that end users perform some maintenance on in-service instrument transformers and how they perform installation checks and tests. By reviewing and understanding the findings in relation to distribution and small power transformers it may also help prevent the premature failure of these types on units.

Introduction & Background

Current transformers (CTs) are used for the protection, control and metering of the power system by transforming the system high currents into much lower currents with almost negligible voltage. Voltage transformers (VTs) on the other hand transform the voltage from very high voltages down to levels that can be utilised for control and metering. There have been several failures of in-service CTs where the cause appears to be either a manufacturing defect or arcing discharge associated with the CT DLA tap lead. Similarly, the VT frame to earth point has been suspected of failing and causing excess gas which leads to a flashover and failure. When there were only a few failures, they were considered as not common and so further investigations into the trues root cause was not warranted. In more recent years the number of failures of this type had increased to a level that demanded a thorough investigation.

To understand the failure mode a little more it is important to understand the type of CT and VT in which it occurs. It is also important to note that this phenomenon is not exclusive to any specific manufacture of CT or VT and so diagrams presented in this paper are for demonstration only and not an indication of any specific manufacturing brand. The failure mode has been identified as occurring in only CTs & VTs where there is a headspace at the top of the unit. Typical types and their construction are explained in the paragraphs and shown in the figures below.

The impact of a VT or CT failing can be profound as it can damage adjacent healthy equipment and will result in power interruptions with longer than normal outage durations which in turn increase the revenue loss. Catastrophic failures can result in a fireball as a result of the oil being under a high pressure within the failed unit and there have been numerous examples of this throughout the world. Additionally, the pressure wave can shatter the porcelain and send large shards as far as 80 metres from the equipment's origin.

Current Transformers

Figure 1 shows the CT hair-pin construction with the secondary windings located in the base. Often these CTs are filled with special quartz sand to help with mechanical strength, cooling and lower oil volumes. The headspace is normally hermetically sealed and often has an expansion bellows to allow the oil to expand and contract into an air space that is about 10% to 15% of the volume of the total head volume. When the oil is not filled to the correct level that air expansion air space may be much greater or in some cases almost nil. Either way having the correct air space is vital to the correct long term operation of the CT.

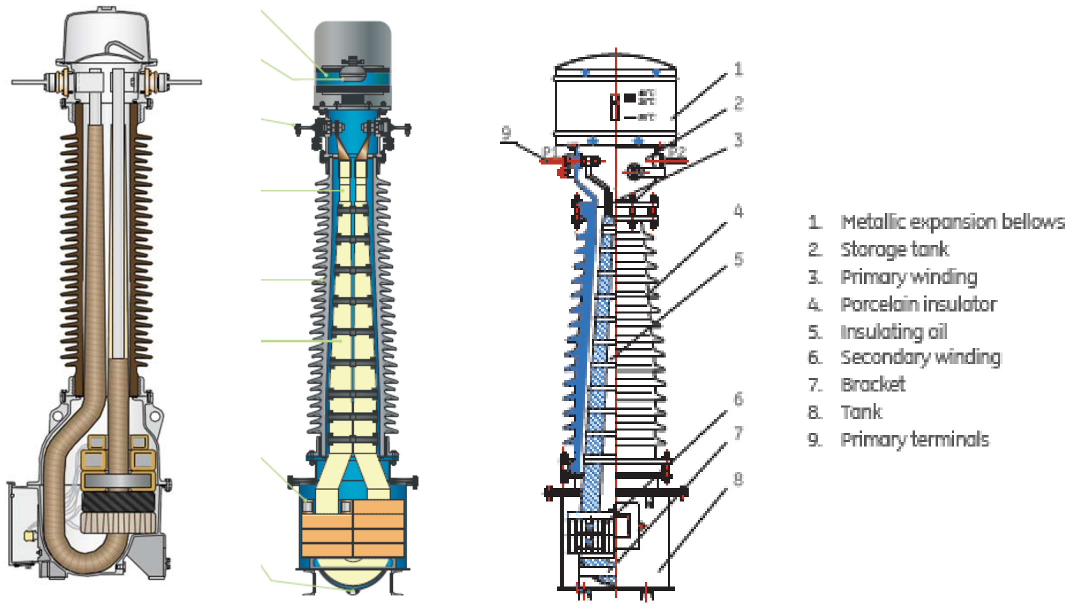

Figure 1
Typical Hair-Pin design CTs with headspace

The headspace allows for the expansion and contraction of the oil with temperature variations and is often designed as the pressure relief device. Therefore, under an internal fault the head can "pop" and release the pressure wave into the atmosphere. They are designed with the intention of avoiding the porcelain outer shattering and causing damage to other equipment, injury or fire. As will be explained in this paper this may not happen in some cases.

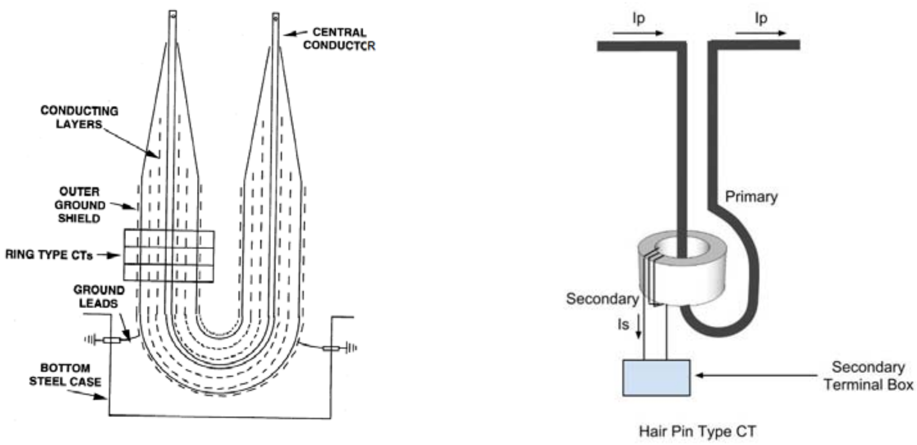

Figure 2
Construction of hair pin type CTs

The construction of the CT is somewhat equivalent to that of an oil impregnated bushing with graded insulation. The inner solid rod is insulated by layers of paper and aluminium foils (conducting layers) specifically graded to meet the insulation levels. The last layer of foil is bought out with the secondary wiring into the terminal box and earthed. This lead allows for the testing of the capacitance (C1) and power factor of the CT. The power factor of the graded insulation is the ratio of the capacitive or charging current to the resistive or leakage current and therefore gives a direct indication of the watts loss within the primary insulation of the CT. This indicates the degree of moisture content within the CT paper insulation and provides a good indication of the insulation degradation. The lead also helps with testing the dielectric dissipation factor which provides a means of determining the relative condition of the paper-oil primary insulation within the CT.

Voltage Transformers

Figure 3 shows the typical construction of VTs with the core and windings located in the base. These VTs are oil filled with the headspace hermetically sealed and often with expansion bellows as seen in the construction of the CTs. Just as with the CTs, when the oil is not filled to the correct level the air expansion space is vital to the correct long term operation of the VT. The VT utilises the conventional electromagnetic transformer principle and the HV and LV windings consist of multilayered coils of insulated copper conductors. Due to the high voltage ratio between the HV and LV the primary winding has a very large number of turns using fine stranded wire. The HV lead from the HV winding often passes through a metal tube, with graded insulation, to the HV terminal. The secondary winding has a relatively small number of turns with a larger cross section and there can be more than one secondary winding. The secondary leads are bought out to the secondary terminal box for connection to relays, meters or other devices. The major insulation between the primary and secondary windings and to earth must be a high-quality contaminant free Kraft paper which has been dried and oil filled under vacuum. The core is manufactured from grain oriented steel as in a power transformer however due to the low power rating (VA) the core is relatively small. There is a core to tank (frame) earth which is connected inside the tank and not normally accessible.

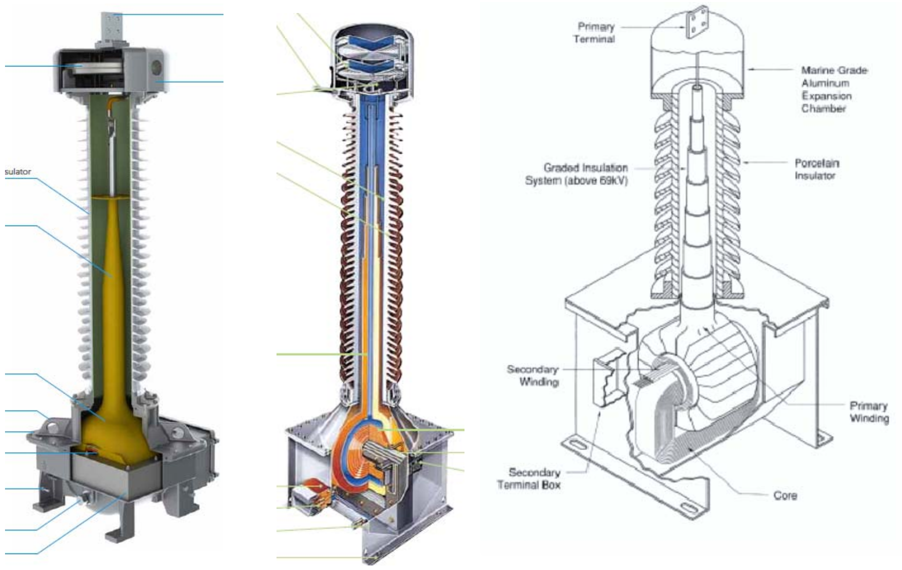

Figure 3
Typical VTs with base windings and top headspace

Failure Modes

For some time, CT and VT failures have been attributed to the earth lead areas or suspected to be degradation or breakdown of the capacitively graded primary insulation. Insulation, from the HV of the power system to earth potential, is provided by means of capacitively graded (paper-foil) layers immersed in oil. It is normal to assume electrical or dielectric breakdown as the main reason for failure due to the obvious signs of a flashover or discharge.

Within the VT the core to frame earth lead has been found to have been "broken" and so the core is "floating". This can be detected by a rise in hydrogen and acetylene gas if samples are taken but in most cases samples there is no valve or samples are only taken about every 5 or more years. With the core floating there is a voltage rise to earth and eventual flash-over or failure of the insulation between the core and windings to earth.

With the CTs, the DLA tap lead is sometimes found broken or burnt away from the foil and so the obvious conclusion is that the join was a poor connection and overheated. Again, this can be detected if oil samples or electrical testing is done. Unlike the VT the DLA tap is bought out and used for testing but that testing may be once every 2 to 5 years or more. When the DLA tap is broken, there is a potential rise in the insulation grading foils and this creates high electrical stresses which in turn break down the dielectric strength of the system.

A New Failure Mode

In recent years, a new type of failure mode has been identified and it appears to be very much the same as those mentioned above. The problem can start from the time the unit is manufactured or can be introduced in the field during maintenance depending on the type of unit. As mentioned previously by over or under-filling the headspace the system dynamics are altered. In the case of under-filling the unit will start to overheat, which if left unattended could lead to insulation breakdown. Whilst all the components in the head of these types of CTs & VTs are at the same potential, the breakdown would need to occur further down the centre stem of the insulation and would take a considerable length of time to occur unless the oil level was extremely low. On the other hand, overfilling to the point where there is little or no air space creates a very different scenario.

Figure 4 shows a diagram of a CT or VT head as it should be with an expansion space at the top. The units are designed to allow the oil to expand and contract within the headspace but if that space is no longer there then the unit will start to create a hydraulic effect when the temperature rises. The oil expands, however as there is insufficient expansion space the pressure increases, which may force a leak. In some cases, it has been observed that even though a unit has not seen service leaks have developed. In these instances, it was assumed that the bolts on flanges and gaskets had not been correctly tightened as the torque settings were very low or the bolts could be undone by hand. However, it is more likely that the bolts had worked loose by the unit head

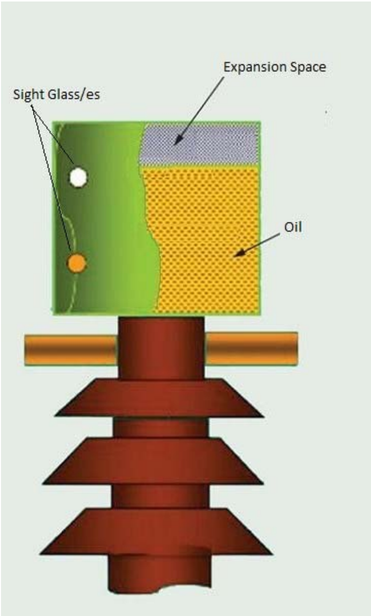

Figure 4
Diagram of an Instrument Transformer Headspace.

expanding and contacting with normal ambient temperature variations when stored outdoors. The real problem was not obvious as the increase in oil pressure had been relieved by the leak. Once the unit was repaired, the oil level was corrected and the unit would operate as it should. If the overfilling does not completely fill the headspace, then it is unlikely that the pressures may be large enough to create leaks in the flanges. This situation causes another phenomenon when the temperature variations occur.

During manufacture, it is possible to overfill the headspace but not completely. The unit is in most cases, filled under vacuum and at around 55^oC to 60^oC. When the vacuum is released some air enters the headspace until the operator closes the valve. When the oil temperature drops, the headspace creates its own vacuum as the air expands into the headspace and the pressure drops. Later when the unit is in service it experiences this heating and cooling throughout the day as the load changes and as the ambient temperature varies from day to night and season to season.

What is occurring inside the headspace is a continual cyclic vacuum treatment of the internal system. This vacuuming of the system draws gases dissolved in the oil to the headspace to balance the pressure. These gases are those generated by the paper-oil dielectric system and are often the combustible gases such as hydrogen, methane ethane and ethylene. It has been observed that acetylene is not generated in significant quantities in this process because there is no initial arcing or burning within the system. All these gases are generated from within the paper and oil insulation system and the cycling temperature causes changes in the gas pressure in the headspace. Therefore, as the pressure in the headspace changes, gases move between the paper, oil and then into the headspace. The process continues and as the gases are drawn from the oil and eventually the paper, the try to move between the two but only create larger volumes of gas that turn into bubbles. These bubbles can create a chain which reduces the dielectric strength of the oil gap. In the case of the type of instrument transformers studied in this paper, the live head tries to arc to the only internal point within the system, which is the DLA tap or the core to frame earth. Given the distance that these arcs must travel the energy associated with the arc creates a huge pressure wave that damages the unit. Interestingly the arc is travelling down the inside of the bushing and so the pressure wave is also pushing down into the bottom of the unit. This, along with the top internal bellows, prevents the head cap from acting as the pressure relief device and so the force of the pressure wave bursts the porcelain or bottom tank structure causing an explosion and fire. In the case of quartz sand filled CTs the arc hits the top of the sand and the pressure wave creates an extreme pressure at that point and bursts the porcelain forcing the sand and oil out as the arc tries to get to the earthed base.

Understanding the Phenomenon

As mentioned above the dynamics set up inside the system causes cyclic vacuuming, and this draws the gases from the paper and oil into the headspace. It is important to understand how this happens and why it is not normally detected.

Paper samples from failed and close to failing CTs showed interesting results. The inner layers were measuring a degree of polymerisation (DP) of 1000+ whereas the outer layers were as low as 320 DP. Additionally, the oil samples showed the furan levels were only slightly elevated as compared to a good CT. The combustible gases were at extreme levels with low levels of acetylene (<20ppm). With the CTs being only a few years old there was clearly something abnormal happening within the system to cause the rapid aging of the insulation.

By looking at the way paper ages it becomes a little clearer in the understanding of this phenomenon. As is commonly known the strength of the paper insulation in electrical equipment is dependent on the bonding of cellulose chains that make up the paper. As the cellulose chains break in normal situations they can form furans and other gases along with small amounts of water. In this instance, the presence of moisture was not above that expected of an instrument transformer in good condition.

An in-service 132kV CT was oil sampled and the results analysed as shown in Table 1 below. The table compares the results of the oil analysis to the typical concentration ranges and the maximum values before action for sealed instrument transformers as indicated by the IEC 60599 (1) interpretation guidelines.

Installed mid-2011 Oil tested late 2016	**ppm Levels**	**Typical Ranges**	**Maximum values for action**	**Total Combustibl e Gas %**	**Ratio Values**	**Likely Fault Type**
Hydrogen H_2	**12722**	6 – 300	300	**90.91%**	CH_4 / H_2 = 0.0486	<0.1 = Corona
Methane CH_4	**619**	11 – 120	30	**4.42%**	C_2H_2 / C_2H_4 = 1.33	>1.0 = Energy Discharge
Ethane C_2H_6	**48**	7 – 130	50	**0.34%**	C_2H_2 / CH_4 = 0.006	<0.3= Corona/ Thermal Decomp.
Ethylene C_2H_4	**3**	3 – 40	10	**0.02%**	C_2H_6 /C_2H_2 = 14	>0.4= Corona/ Thermal Decomp.
Acetylene C_2H_2	**4**	1 – 5	2	**0.03%**	C_2H_4 /C_2H_6 =0.063	<0.2 = Discharge / Thermal
Carbon Monoxide CO	**61**	250 - 1100	300	**0.44%**	CO_2 / CO = 8.73	>3<11 =insulation ok
Carbon Dioxide CO_2	**539**	800 – 4000	900	**3.84%**		
Oxygen O_2	**2780**	n/a	n/a			
Moisture H_2O	**7**	2 – 10	20			

Table 1
Oil Test Analysis of a 132kV CT Exhibiting a Change of State.

After investigating some engineering papers (2) on the effects of continuously vacuuming insulating papers when subjected to varying temperatures it was determined that the normal aging process that is seen in power transformers was not applicable to instrument transformers. It may be possible that the constant vacuuming was creating a type of micro-movement within the paper structure. This micro-movement along with the gas depleted oil, could affect the cellulose chains and allow them to more readily breakdown. As seen in Table 1 the gases most prominent are Hydrogen(H_2), Methane (CH_4), Ethane (C_2H_6), and low levels of Ethylene(C_2H_4) and Acetylene (C_2H_2). Using Doernenberg or Rogers ratios, the levels of hydrogen and methane being generated would indicate a low energy, partial discharge or corona type fault and this also holds true for the ratios of the other gases. There was a marked decrease in the Carbon Dioxide and Carbon Monoxide gases that indicated these gases were being absorbed into the system. However, the ratio of CO2/CO is 8.73 and this would be considered as not an indicator of cellulose degradation (3). In all, the way the gases were formed did not fit normal behaviours for internal problems and the moisture levels were within normal levels when there were no visible leaks. If, moisture levels had been elevated then it is likely dielectric breakdown would be further accelerated. It also needs to be noted that as this degradation process does not involve arcing or surface tracking it is not able to be detected using partial discharge measurement tests. Overall it appeared as if there was a discharge and insulation decomposition but when inspected internally, the paper DP results indicated the decomposition but there was no indication of any discharge.

Figure 5 shows a typical structure of the insulation grading system within the high voltage terminals of the instrument transformers. The insulation structure in the instrument transformers is somewhat like that of a HV bushing, particularly when looking at the structure of a CT. Here C1 represents the layers of graded insulation and foil that make up the major HV insulation system from the top terminal to the bottom of the instrument transformer. C2 represents the last foil layer between the graded insulation and the DLA tap measuring point. This tap position is not present in the Voltage Transformers.

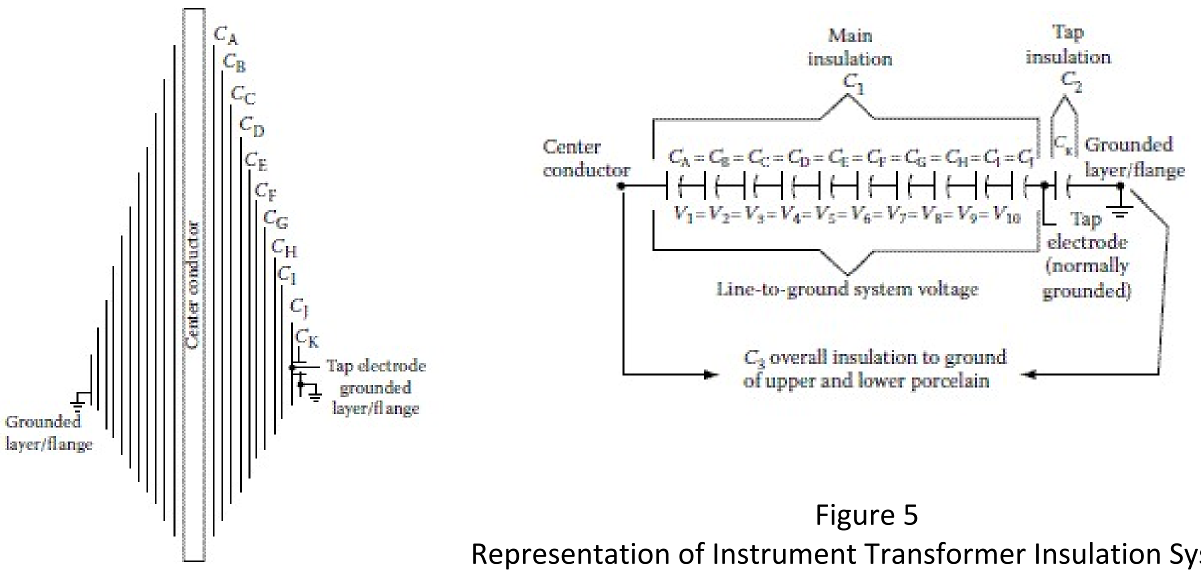

Figure 5
Representation of Instrument Transformer Insulation System

A rising dielectric dissipation factor (DDF) is an indication of oil ageing or oil contamination. Aging and degradation of the insulation increases the amount of energy that is converted to heat in the insulation albeit very small and these heat losses are measured as the dielectric dissipation factor (DDF). Changes in capacitance (C1) indicate mechanical displacements of the internal components or a partial breakdown in the insulation structure.

Year of Test	DDF @ 10kV overall %	Cap @10kV Overall pF	DDF C1 @ 10kV in %	C1 @ 10kV pF	DDF C2 @ 0.5kV in %	C2 @ 0.5kV pF
Mid 2011	0.221	923.35	0.221	894.76	1.863	550.35
Nov 2016	0.57	925.61	0.511	894.47	2.017	539.89
% Change	158%	0.24%	131.2%	0%	8.27%	-1.94%

Table 2
Electrical Testing of a 132kV CT Exhibiting a Change of State.

Table 2 shows a set of results taken from a CT installed in mid-2011 and tested again in November 2016. It shows significant changes in the Dielectric Dissipation Factor (DDF) values whereas the values of the power factors have very little change. The most significant change is the DDF of the C1 system which indicates the insulation system is deteriorating rapidly. The values of C2 have a small change and this is reflective of the proportion of insulation covering that last layer of the foil grading rings. The high DDF values also indicate that the oil has an elevated level of contaminates due to the degradation of the paper. The lack of change in the Capacitance values C1 and C2 provide some evidence that the connection to earth has been maintained along with the overall mechanical structure of the CT. Therefore, it is reasonable to assume that the quality of construction has been maintained and that external system influences such as through faults or lightning strikes have not contributed to the deterioration of the system.

In CTs that had quartz sand as a filler it was noted that gas levels from oil samples from the bottom of the tank differed considerably from those taken from the top of the CT. It has not been fully investigated as to whether the sand tends to prevent the even distribution of gases within the system, however, there is some evidence that the sand locks the combustible gas bubbles closer to the surface of the paper. This was observed by the inspection of a CT which had not been blown completely apart by the internal arc. There was clear evidence that the arc used the surface of the paper to travel down to the DLA tap. This was observed by the burning of the paper and the limited discolouration of the sand and oil nearest the paper, yet the sand further out from the centre stem was clean of any carbon deposits.

Within the VTs inspected it was more difficult to understand the way the arc travelled as there was no sand to act as a barrier or retain discolouration. In each case the VT catastrophically failure and caught fire so most clear evidence of the arc direction was lost. One area that was observed was that there was little discolouration of the inside surface of the porcelain which indicated that there was little or no build-up of contaminants that could attach and arc along the surface. In VTs that were oil sampled; some displayed increased gas levels that indicated an abnormal condition but not yet at levels that would warrant removal from service. When further investigated, the headspace appeared to be either under high pressure or as in one case a lower than atmospheric pressure. This was deduced as the same phenomenon as that of the CTs and so these units needed further checks to prevent a premature failure. Unfortunately, due to outage time constraints the electrical testing could not be performed at the time oil samples were taken and so the internal condition remained unchecked for some time. It is also difficult to obtain DDF and capacitance values of a VT as very few if any have a DLA tap on the HV insulator and the core to frame earth is not bought out.

Halstead's thermodynamic model[5] suggests hydrogen is generated almost independent of the temperature but gasses such as acetylene start at above 1000°C. Halstead based his work on what can be described as an isothermal equilibrium but could not be formally proven due to the dynamics of such a system. In these types of occurrences, it is possible that Halstead's model could well be correct when we look at the gases generated at lower temperatures but higher pressures we find that Hydrogen, Ethane and Methane are those gases. Figure 6 below shows Halstead's thermodynamic model and overlays the temperatures at which gases in this phenomenon have been generated and interestingly those gases most prominent in the CT's and VT's have been the same gases that Halstead has suggested are most likely to forma at lower temperatures but higher pressures.

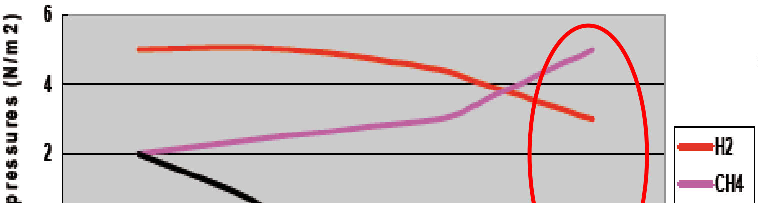

Figure 6
Halstead's Thermodynamic Model

The Manufacturing Process

Whilst the in-service units may have been experiencing this phenomenon it also needs to be understood how the situation can without detection. For this it needs a small understanding of the manufacturing process. The internal windings and core are dried normally using an autoclave process and then immediately placed into their base tank. In the case of the CTs the dried and hot (80^{o}C) quartz sand is filled over the windings and centre stem. In both instrument transformer types the units are then placed under vacuum and filled with oil at a temperature of around 55^{o}C to 60^{o}C. Once the oil has reached the required level the vacuum process continues for a short period then the unit is sealed off and allowed to cool prior to testing.

The oil gauge is used as a guide for the correct filling, however, if a gauge is not required or the type of gauge requires the sight glass to be totally filled then it is possible to over fill the unit. In some instances, the unit is filled when lying down or tilted at an angle to prevent oil spill. In these cases, it is much easier to over fill the units without realising the consequences. Filling whilst in the horizontal position is not uncommon as it is easier to manage the movement and access for working on the instrument transformer in the factory. The unit is then stood up and allowed to settle of a day or so before entering the test area. As the units are new they will test accordingly and show no signs of an abnormal internal issue.

During transport, they are quite often packed in crates in the horizontal position. In storage, they can be stored in a warehouse or left in the open but generally they are not given any attention other than a stores incoming damage inspection. Therefore, unless a leak or other damage is detected there is virtually no inspection or maintenance done on the unit until it is to be installed at site.

On site the unit is inspected and if it is free of defects it would be placed in position and have commissioning tests performed. The commissioning tests may include DDF and Capacitance but as the unit has not seen service many utilities do not perform these tests and utilise the factory results as the benchmark.

Prevention Before Failure

There is not a lot that needs to be done to prevent this scenario from occurring and the following are steps that can be taken to help prevent the premature failure of these units.

Firstly, when an instrument transformer of this type is to be provided by a manufacturer then the end user needs to request the manufacturer to perform and record checks that the oil levels are correct to their design and that at ambient temperatures the pressure should be at atmospheric. This is the easiest solution as it helps prevent situations where leaks can occur in storage due to very high ambient temperatures increasing the internal pressures. It is not practical to try to check all units upon delivery to a store as they would require uncarting and re-crating which can cause other damage and is a costly exercise.

For units being placed into service for the first time, they should have an oil sample preferably taken from the top of the unit. This way the oil level and pressures can be checked and a base line developed for the oil condition. Irelandes, Saha & Jones [(4)] found that the rate of mitigation of hydrogen and acetylene from oil/paper through an oil/sand mix to a sampling point was slower than that in conventional oil-only CTs and could render routine sampling results misleading. Therefore, care must be taken to be very consistent about the sampling point and time of sampling after in-service de-energising of a unit.

When doing the top sampling, it is then a good time to adjust the oil level to align with the manufacturer's recommendations and ensure all adjustments are recorded. Additionally, all bolts on all instrument transformers should be checked so that the torque settings are as per the manufacturer's recommendations and thereby helping to prevent any in-service leaks. Lastly, at the end of the first-year in-service another oil sample should be taken, again from the top, and analysed to ensure the unit is performing as expected and there are no abnormal gas levels present. After these measures are taken the unit may be considered as operating normally and therefore a normal maintenance regime may be adapted.

Can This Occur in other Equipment

At the time of writing this paper there is no evidence that this phenomenon occurs in any other types of HV equipment however, it may well be possible. As a hypothetical example, if a hermetically sealed distribution transformer were to be over-filled to a level that had almost no air expansion space then it may be possible that the internal environment to reflect that of the instrument transformers. With a modern distribution transformer though it is unlikely as the main tank is often designed to manage high internal pressures and so the flexing of the tank walls would give some relief to the pressure build up from high temperatures. Conversely when the temperature drops and creates a vacuum the tank should manage this within the design as it is normally designed to withstand vacuum processing during manufacture.

Within outdoor old filled circuit breakers there is no specific oil-insulation system that reflects the same arrangement as the CTs and VTs. Additionally, the modern circuit breakers rarely use oil as an insulating medium and so this phenomenon would have shown by now if it were possible in an old circuit breaker. Other substation equipment do not have similar internal environments as the instrument transformers and so again it is unlikely to occur.

Conclusion

This paper has outlined a new type of phenomenon that has caused catastrophic failures within instrument transformers. It has largely gone un-noticed due to the way it manifests itself and the rapid internal deterioration that occurs. End users can avoid these failures by reviewing their fleet of instrument transformers and implementing some simple changes to their oil sampling and maintenance processes and performing capacitance and DDF tests at appropriate intervals.

As mentioned in the early part of this paper, the failure mode is not necessarily manufacturer based and so intentionally no manufacturers are mentioned as this phenomenon occurs in specific styles of instrument transformers with use the headspace for expansion and pressure relief. The process can start from the time of manufacture but it may also be introduced in the field, if maintenance is not performed correctly and overfilling occurs. The speed at which this degradation process occurs is still not known however it is understood to be very rapid to the point where it may take only months or as much as 7 years to occur. Therefore, careful attention needs to be to the maintenance processes and test results to avoid a potential explosive failure.

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Biography

Kerry is a registered and chartered professional electrical engineer with 40 years' experience in the industry and managers his own small consulting business. He has an extensive and diverse background in utility substation asset management, refurbishment,

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