Transformer Corrosive Sulfur Removal by Oil Reclaiming for Life Extension

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***Abstract*—Six large generator transformers had corrosive sulfur & DBDS in oil removed by oil reclamation process. This process extended the transformer life and allowed the transformer oil to be reused for a significant environmental benefit.**
***Index Terms*—Transformer oil, copper sulphide, DBDS, reclamation.**

I. INTRODUCTION

There have been documented failures of transformers due to the presence of corrosive sulphur compounds in oil, which is related to corrosive reaction with metal surfaces and formation of copper sulphide and deposits in the winding insulating paper [1, 2]. Transformers with content of corrosive sulfur compounds and dibenzyl disulphide (DBDS), have a much higher risk of failure depending on the winding design, loading and ambient temperature [3]. While metal passivator additions (such as Irgamet 39) to the oil can stabilize the effect of corrosive sulfur temporarily, any earlier copper sulfide penetration cannot be undone.

Six transformers at a generating station had high corrosive sulphur level 4b (ASTM 1275B) and DBDS content up to 76ppm – see Table 1 below. The transformers were all 420kV generator transformers with ratings of 300 to 350 MVA. Three mitigation options as counter/preventive measures to reduce the corrosive sulfur and DBDS were given which included replacement of the transformer oil, passivation of the oil and online reclamation of the oil (while the transformer is energized and in service).

The transformers had already received the addition of metal passivator additives, but the oil had remained corrosive. If performing only passivation without reducing corrosive sulphur to non-corrosive and DBDS to < 5ppm, then all added additives (2,6-ditertiarybutyl para-cresol [DBPC] & Irgamet 39) will deplete faster due to residual polar oil contaminants, corrosive sulphur & DBDS mercaptans (organic components of hydrocarbons with sulfur) present in the transformer oil.

It was decided to proceed with the online reclamation process on 4 of the 6 units with the main reason to avoid production loss at the power plant. The remaining 2 units had the offline process reclamation process performed.

Table 1 – Transformers Reclaimed for DBDS Removal

ID	Rating [MVA]	HV [kV]	LV [kV]	Oil Quantity [L]	ASTM 1275B Tarnish	DBDS [ppm]
1	300	420	20	114,000	4b	37
2	300	420	20	114,000	4b	33
3	300	420	20	97,500	4b	53
4	300	420	20	97,500	4b	55
5	350	420	20	132,200	4b	52
6	350	420	20	132,200	4b	76

II. OIL RECLAMATION PROCESS TO REMOVE DBDS

IEEE Standard C57.637-2015 [4] defines transformer oil reclaiming as "the restoration of oil to a useful state by the removal of contaminants and byproducts of transformer oil degradation such as polar, acidic, furanic, corrosive Sulphur, DBDS compounds or colloidal materials from used electrical insulating liquids by physical or adsorbent means". For the work done in this paper, this was performed by the process of adsorption where another material was used to attract the contaminants and degradation products including water from the oil. These materials (media) are typically fuller's earth clay or activated alumina (or bauxite). Both materials are effective however the activated alumina can be regenerated and reused many times (up to 300 times) and is well suited for continuous online processing. Oil reclaiming is performed by drawing oil through the media (activated alumina) in columns, then through a degassing chamber with (to remove gasses and moisture) and then returning the reclaimed oil to the transformer or oil tank. The media becomes saturated with contaminants after 8 – 12 hours depending on the level of degradation of the oil and then must be reactivated. This is performed by isolating the media columns from the circuit and reactivation to a required temperature to effectively burn off the contaminants in the media. This reactivation process takes approximately 12 – 14 hours. With 2 sets of media columns, reactivation in one set can be performed while the other set is being used to reclaim oil (parallel operation).

All this equipment to perform the oil reclaiming was contained in a single sea container. This includes pre-filter, the media columns, fine filter, degassing chamber, vacuum pumps, oil pumps, heaters, oil storage, connection hoses and overall SCADA control system.

Oil reclaiming is most often performed by draining the oil from the transformer and reclaiming the oil in tankers (or tanker to tanker). This facilitates work to be done on the transformer such as leak repairs, bushing replacement, internal inspection etc. where the oil must be drained from the transformer. In this case, the oil is reclaimed several passes to restore the oil to near new properties. Clearly all this work is done while the transformer is not in service.

However, there may be situations where it is not required to drain the transformer and it is more cost effective to reclaim the oil in the transformer by circulating the oil through the oil processor and returning the oil back to the transformer. The "clean" reclaimed oil will mix with the original oil but if enough passes are performed, eventually the oil will become fully reclaimed with near to new properties. While this may seem inefficient, there is a large cost savings due to not having to drain the transformer, store the oil in tank and vacuum fill the transformer (especially for high voltage transformers where the vacuum time can be 48 hours or longer). There is also a benefit of reduced time for the same reasons (also including the waiting time prior to energization after vacuum filling the transformer). This closed loop oil reclaiming has usually been done while the transformer is not in service (called "offline reclaiming" in this paper) but can also be done while the transformer is energized (called "online reclaiming" in this paper).

Reclaiming for the purposes of removing contaminants like DBDS is a special type of reclaiming, but the process is essentially the same. There can be several types of corrosive sulfur compounds in transformer oil, but DBDS is generally the dominant corrosive sulfur compound. The online oil reclamation process can remove DBDS and all other corrosive sulfur compounds from the transformer oil but will also effectively clean corrosive sulfur & DBDS contaminants from the winding insulation paper & the core. As will be shown in this paper, the online process is effective due to the help of heat from winding losses, high thermodynamic oil velocity through the windings, electrical humming, mechanical vibration (core magnetostriction) and thermal diffusion stresses.

III. OIL RECLAMATION RESULTS

The 6 transformers had 6 oil passes (i.e., the transformers were processed for 6 times the transformer oil quantity in Table 1) of reclamation process performed. The DBDS was removed (5 ppm or lower) and the oil become completely non-corrosive – see **Table 2** below. After the final reclamation pass, additives (DBPC & passivator) were added to the oil to prevent oil oxidation and further formation of copper sulphide in the transformer. The passivator was diluted into the oil to a concentration of around 100 ppm, where it then reacts with the copper conductors to form a complex layer around the copper to prevent further forming copper/silver sulphide due to the residual sulphur elements & DBDS compounds present in the transformer oil.

Units 1 and 2 were remeasured for corrosive sulphur after 6 months, and they have remained non-corrosive. This shows that the reclaiming effort to remove the DBDS is effective and long lasting. The other 4 units will also have measurements done after 6 months.

Units 3 and 4 had the reclamation process done while offline and the rest of the units were done online. Both the offline and online did remove the DBDS and leave the units non-corrosive.

Table 2 – Overall Reclaiming Results

ID	Before		After Reclaiming		After 6 Months		Process
	ASTM 1275B Tarnish	DBDS [ppm]	ASTM 1275B Tarnish	DBDS [ppm]	ASTM 1275B Tarnish	DBDS [ppm]	
1	4b	37	2b	< 5	2b	< 5	Online
2	4b	33	1b	< 5	1b	< 5	Online
3	4b	53	2b	< 5			Offline
4	4b	55	2b	< 5			Offline
5	4b	52	1b	< 5			Online
6	4b	76	2b	<5			Online

Detailed reclaiming results are shown below transformer # 2 and is representative of all the transformers. The oil quality results are shown in **Table 3**. The interfacial tension improved from 34 to 45 Dynes/cm, which is near new oil levels. The oil became non-corrosive after the 3rd pass and the DBDS was also fully removed by the 3rd pass. More passes (6 passes total) were done to be extra sure the DBDS was removed and to give more opportunity for cleaning of the windings.

The oil color improved from 1.5 to 0.5 as shown in **Figure 1** which shows small oil samples for each of the 6 oil passes. The oil is very clear after the final pass.

The oil corrosivity is compared to before and after reclaiming in **Figure 2**. This shows the gas chromatographic measurement of the sulfuric compounds and shows the removal of the DBDS.

The copper tarnish level is shown for each oil pass in **Figure 3**. As can be seen, the oil tarnish level decreased steadily with each oil pass for a final value of 1b.

Table 3 – Unit # 2 Detailed Oil Quality Results

Test	Unit	Method	Limit IEC 60422	Before	After 3rd Pass	After 6th Pass	Final	After 6 Months
Interfacial Tension	Dynes/cm	ASTM D971	> 22	33.45	44.42	42.94	44.9	43.6
Corrosive Sulfur		ASTM D1275B	Non Corrosive	Corrosive	Non Corrosive	Non Corrosive	Non Corrosive	Non Corrosive
		IEC 62535	Non Corrosive	Corrosive	Non Corrosive	Non Corrosive	Non Corrosive	Non Corrosive
Tarnish Level		ASTM D130	---	4b	3a	1b	1b	1b
DBDS	ppm	IEC 62697	---	33	2.9	1	1	3

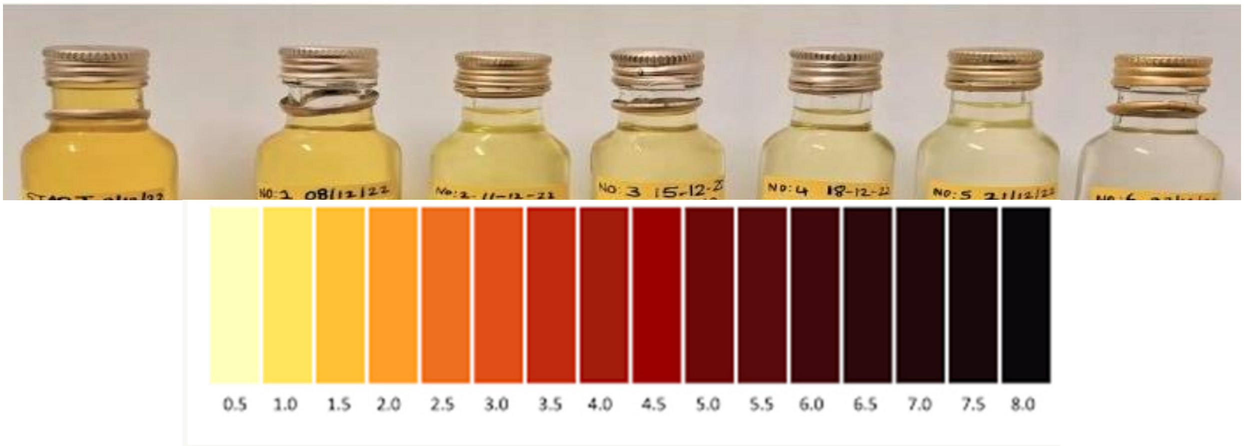

Figure 1 – Color Improvement (Left to Right = Cycle 1, 2, 3, 4, 5, 6) with ASTM 1500 Color Scale

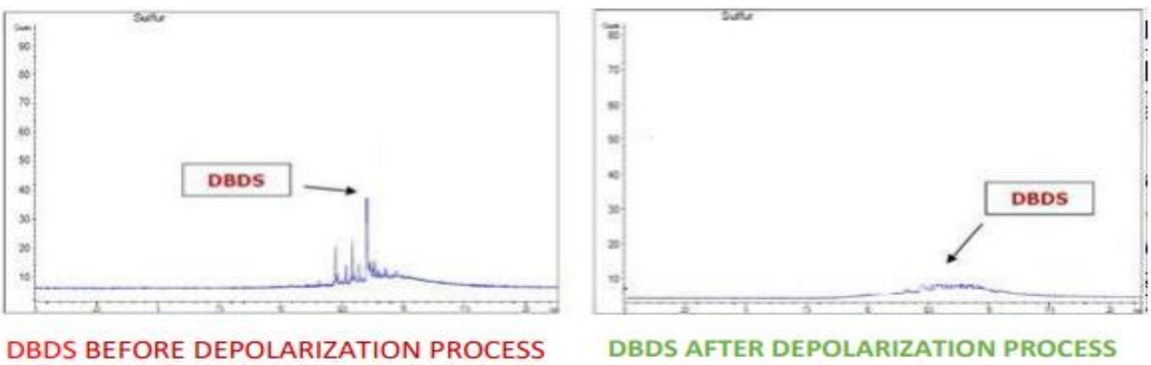

Figure 2 – Gas Chromatographic Corrosive Sulfur Measurement

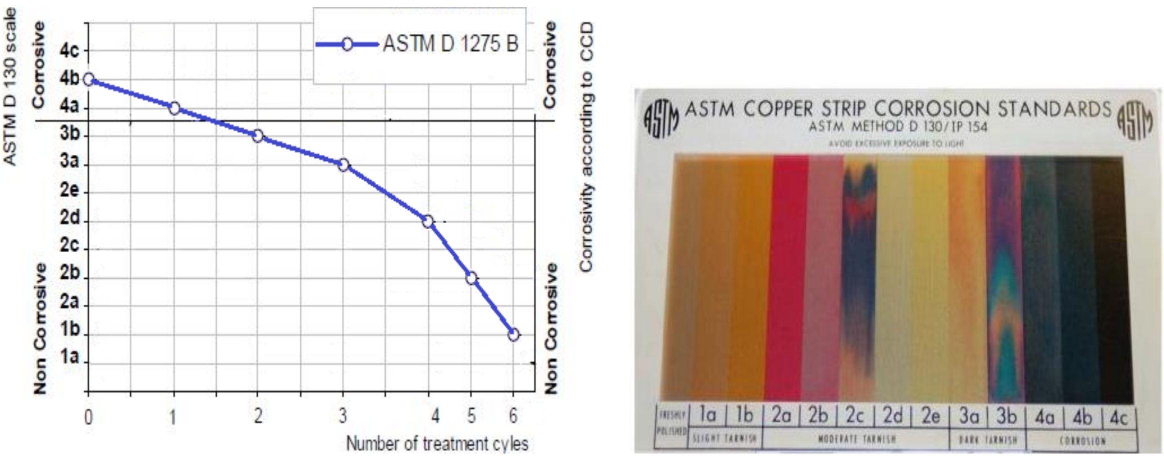

Figure 3 – Copper Tarnish Level Reduction During 6 Passes (with ASTM D130 Copper Strip Corrosion Chart)

In summary, the DBDS was fully removed by online oil reclamation and the oil quality results such as acidity, interfacial tension and color were very close to new oil parameters. The winding insulation was very well cleaned of DBDS and there was no disturbing of the transformer loading. The results are also long lasting as shown by the 6-month results. The reclamation process removed acidic/sludge contents, unsaturated hydrocarbons, corrosive sulphur, DBDS, furans in oil, and cleaned the entire transformer (core, winding, cooling).

IV. BENEFITS OF DBDS REMOVAL BY RECLAMATION

The presence of corrosive sulfur in a transformer increases the risk of transformer failure and it is an important transformer life management action to eliminate this concern from the transformer. As shown in this paper, oil reclaiming is very effective at removing the corrosive sulfur compounds, so that the transformers became non-corrosive. The other options for addressing the DBDS are replacing the transformer or replacing the oil.

Obviously replacing the transformer is rather extreme but this would for sure solve the DBDS problem. This would be a very high cost compared to online reclaiming or oil replacement and have a very high carbon footprint (new transformer manufacturing, new raw metal materials, transport of transformer to site, disposal of old transformer etc.).

Oil replacement requires the old oil to be drained (and disposed of), during which time the windings are exposed. Vacuum filling may not be good for very aged transformer winding insulation due to weak paper insulation mechanical strength. The vacuum might peel/break the weak paper insulation inside transformer winding unknowingly. The oil flushing during oil replacement only helps to clean/remove sludge in the outer layer of HV winding insulation and flushing may damage weak paper insulation in the HV side outer layer. Around 20 - 25% of the old oil sludge, corrosive sulphur & DBDS content may stay embedded in the transformer active part. Thus, the acidity will increase rapidly after the oil change and cause cross contamination from the residual oil sludge, corrosive sulphur & DBDS left in the core and winding insulation (mainly from the LV winding). In a short duration after the transformer is returned to service, the contaminants left inside will mix with the new oil and start to deteriorate the oil faster. The root problem of DBDS in the winding insulation is not solved. In fact, the oil may need to be replaced more than once to fully remove the DBDS from the transformer. Oil replacement requires a long down time for the transformer (high production cost loss) and has the cost of the new oil. The scrapping of the old oil is not environmentally friendly since it will need to be disposed of in some manner. There is a higher carbon footprint (less than transformer replacement) and use of new resources for oil replacement.

The online reclamation process in contrast has a low carbon footprint and does a far more effective job of DBDS removal than oil replacement. During the online process, heat from winding load losses and core vibration improves winding oil circulation – this causes the acids, sludge and sulfur elements in the outer winding (typically the HV winding with less paper area) and inner winding (typically the LV winding with a bigger paper area) to be removed in the oil circulation. The online process overall cleans the transformer tank, radiators, core & windings. Although there is much more oil processing to do (there were 6 oil passes performed for this paper), the reduced amount of equipment (do not need oil storage tanks) and not having to perform draining, vacuum and oil filling makes the oil reclamation more competitive. After the oil reclamation is performed, added oil additives (DBPC & Irgamet 39) will last longer and protect transformer from oxidation and formation of copper sulphide.

The online reclamation process is expected to be more efficient than offline reclamation process and have better long-term results. It is anticipated that online process oil results will be effective longer (10-15 years) than offline process (4 - 6 years). During the offline process, it does not have the advantage of the winding losses and core vibration to clean the windings so it will take longer offline processing to achieve the same DBDS removal in the windings as with online processing. It will be interesting to compare the oil results of units #3 and #4 (offline units) after several years with the other units (online units) to confirm.

V. CONCLUSIONS

The online reclamation to remove copper sulphides from the transformer oil was highly effective. The corrosive level was improved from “corrosive” to “non-corrosive level” up to tarnish level 1b. The DBDS was fully removed, and the oil quality results such as acidity, interfacial tension and color were very close to new oil parameters. The winding insulation was very well cleaned of DBDS and the transformers had no service interruption during the oil reclamation. The results are also long lasting as shown by the 6-month results. The reclamation process removed acidic/sludge contents, unsaturated hydrocarbons, corrosive sulphur, DBDS, furans in oil, and cleaned the entire transformer (core, winding, cooling).

The oil reclamation process has effectively extended the transformer useful life – this has significant environmental benefit compared to prematurely replacing the transformers, and for the re-use of the oil (versus replacing the oil).

Oil reclamation for the removal of copper sulphides can be an important asset management mitigation action.

VI. REFERENCES

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