COMPACT, SAFE AND ECO-FRIENDLY SUB-STATIONS FOR MUMBAI CITY

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ABSTRACT

Conventionally Distribution and Power transformers use mineral oil as the liquid insulating medium. The use of these insulating fluids is being re-evaluated based on the changing requirements to provide compact design to overcome the space constraints, increased life expectancy, reduce total owning costs from both economic and risk exposure perspectives as well as higher margins of safety and better environmental properties.

A totally different approach towards meeting these requirements is therefore called for. Tata Power is working towards developing solutions to address these needs collaboratively with the Standards Committees, Electricity Regulators, Transformers and Insulating Fluid manufacturers in India.

This paper highlights the approach adopted by Tata Power to explore possible solutions for distribution transformers in their distribution sub-stations taking care of above mentioned needs.

INTRODUCTION

For over one hundred years, petroleum based mineral oil, purified to “transformer oil grade”, has been used in liquid-filled transformers. Nowadays, over a million tons of transformer oil is annually produced and used worldwide. The success of mineral oil in transformer application has mainly been built on its availability and low cost associated to good dielectric and cooling performance.

Today’s escalation in power demands pushes often aging networks to their limits, causing unprecedentedly high failure rate of transformers. In these situations mineral oil as dielectric insulating fluid has its limitations. Explosion of mineral oil filled transformers can cause fire, leading to heavy collateral damages with major safety concerns. Also, there have been major environmental concerns over the toxic effects of uncontained mineral oil spills. This has given rise to a new class of alternative dielectric insulating fluid (ester) that has historically been developed to answer these specific concerns. Globally, many transformer manufacturers, has been manufacturing, for number of years, power and distribution transformers with these highly biodegradable ester fluids. These fluids have a typical fire point of >350 °C, much higher than that of Mineral oil (170-180 °C).

APPLICATION OF ESTER FLUIDS

As an alternate to mineral oil, esters are used as dielectrics and coolants. Esters have very high fire point that makes them safer with the added benefit of being readily biodegradable and thus more environment friendly. They have good tolerance to moisture and can increase lifetime of the asset along with allowing compact designs. Natural esters, with these benefits, form a suitable choice to be used in transformers.

Due to their inherent high fire point >350 °C, esters are classified as K Class Fluids. The various properties of natural esters and mineral oil, are tabulated below:

<table>
<thead>
<tr>
<th></th>
<th>O Class Fluids</th>
<th>K Class Fluids</th>
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</thead>
<tbody>
<tr>
<td>Mineral Oil</td>
<td>Fire Point</td>
<td>&gt;350 °C</td>
</tr>
<tr>
<td></td>
<td>170-180 °C</td>
<td></td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>Flash Point</td>
<td>&gt;250 °C</td>
</tr>
<tr>
<td></td>
<td>160-170 °C</td>
<td></td>
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<tr>
<td>Natural Esters</td>
<td>Biodegradability</td>
<td>Slow to biodegrade</td>
</tr>
<tr>
<td></td>
<td>Breakdown Voltage</td>
<td>70kV</td>
</tr>
<tr>
<td></td>
<td>Water saturation at ambient (ppm)</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Cellulose ageing/transformer life</td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td>Compact transformer Design</td>
<td>No</td>
</tr>
</tbody>
</table>

Table-1: Properties of natural esters (Source: CIGRE Guide – 436, Experiences in service with new insulating liquids, Working group A2.35, October 2010)

Tata Power Company is India’s largest Integrated Power Utility with presence across the value chain from Fuel, Fuel Logistics, Generation, Transmission, Distribution and Power Trading. The Power Distribution arm of Tata Power has its presence in the Metropolitan cities of Mumbai and Delhi. The challenges faced by Tata Power Mumbai Distribution are unique as it is serving the financial capital of India. Following factors have motivated Tata Power to explore a solution with natural ester filled transformers:

Safety considerations

Transformers /Package Substations are required to be
erected in densely populated areas. Traditionally Mineral Oil filled transformers with a fire and flash point of 170 °C and 160 °C respectively are used in such areas which increases the risk factor in case of fault leading to fire.

**Space constraints**
Availability of clear space in metropolitan cities like Mumbai is getting difficult as well as prohibitively expensive.

**Life expectancy of assets**
Cellulose or the insulating paper is a vital component deciding the life of a transformer. Mineral Oil is hydrophobic thus making the paper absorb most of the moisture that enters the oil thereby ageing the paper at a much faster rate. This ultimately reduces life of the transformer, fast enough, leading to frequent and costly replacement programs.

**Environmental concerns**
Increasing concerns in terms of disposal of mineral oil and its limited biodegradability.

**DEVELOPMENTS AT TATA POWER**

TATA Power has been collaboratively working with Original Equipment Manufacturer’s (OEMS’s) of transformers and manufacturers of insulating fluids towards a solution for distribution transformer which is compact, safe and ecofriendly by exploiting the inherent properties of natural esters.

Various design options were worked out by changing the temperature rises to check the reduction in foot print and volume of transformer, which are presented in table-2.

For the purpose of comparison a standard rating of distribution transformer (990kVA, 11000/433V), used by Tata Power, is considered. This transformer is having an impedance of 5%, with an off-circuit-tap-changer on HV side and a tap range of +/-10%. Limit of losses is set as 800W and 8500W respectively for no load and load losses.

First natural ester filled design option, Case-1 presented in the table-2, is with very low temperature rises (35/40/66, top oil rise, average winding rise and hot spot rise respectively). The same temperature rise limits are being followed by Tata Power as a standard for mineral oil filled transformers.

Case-1, with natural ester and low temperature rise limits, is considered as the base design option. Keeping the same active part with increase in temperature rises, cooler size is reduced for case-2. This resulted in change of foot print area and volume to 58% comparison to case-1. Here, it is important to mention about case-2 that temperature rise limit of 50/55/66 is the maximum allowed temperature rise limit for a mineral oil filled transformer with Kraft paper insulation, considering ambient temperature conditions in India. Hence these temperature rises can be used safely for natural ester filled transformer.

Hermetically sealed, corrugated tank design without nitrogen cushion is considered for cases-1 and 2.

### Table-2: Various options for 990kVA transformer with natural ester

<table>
<thead>
<tr>
<th>Options with higher temperatures</th>
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</thead>
<tbody>
<tr>
<td>Temperature rises are further increased and case-3 is worked out. While working this case, cellulose insulation immersed in ester oil is considered as “high temperature class insulation” in line with clause 5.2 and 5.3 of IEC60076-14. These clauses mention that if it is agreed between manufacturer and purchaser, Kraft paper, thermally upgraded paper and cellulose insulation in combination with ester fluids can be considered as “high temperature class” insulation. In line with the suggestions given in table-C.3 of IEC60076-14 we may set higher temperature limits for such combinations.</td>
</tr>
</tbody>
</table>
temperature rise limits as indicated in case-3 of table-2 by providing thermally upgraded paper on winding conductors and cellulose insulation for other parts immersed in natural ester.

To arrive temperature rise limits indicated in table-3, a reduction of 10 °C is considered in top oil rise as well as in average winding rise and a reduction of 12 °C is considered in hot spot rise considering Indian ambient temperature conditions over to ambient temperature conditions specified in IEC60076. Further the temperature rises are reduced by 5°C to allow extra margin.

<table>
<thead>
<tr>
<th></th>
<th>As mentioned in table C.3 of IEC60076-14 for thermally upgraded paper</th>
<th>Suggested maximum temperature rises considering Indian ambient conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top oil rise</td>
<td>90</td>
<td>75</td>
</tr>
<tr>
<td>Average winding rise</td>
<td>95</td>
<td>80</td>
</tr>
<tr>
<td>Hot spot rise</td>
<td>110</td>
<td>93</td>
</tr>
</tbody>
</table>

Table-3: Suggested temperature rises in line with table C.3 of IEC60076-14, considering Indian ambient conditions

It can be observed in table-2 that with the highest temperature rise, change in footprint area and volume can be up to 42% and 46% respectively in comparison to case-1.

**Increase in load losses at high temperature**

Whenever it is required to compare the transformers specified with different average winding temperature rise limits, it is necessary to compare the losses at reference temperature determined in line with clause 11.1.1(b) of IEC60076-1 so that TOC (Total Ownership Cost) can be compared considering the increase in load losses due to higher average winding temperatures.

Here, reference temperature is rated average winding temperature rise + 20 °C, or rated average winding temperature rise + yearly external cooling medium average temperature, whichever is higher. In India, yearly external average cooling medium temperature is 32 °C hence later part of this clause will apply. For example in case-3, reference temperature is calculated as 80+32 = 112°C. For all the cases, reference temperatures and corresponding load losses are calculated and indicated in the table-2.

Total ownership cost (TOC) is calculated by the formulae: 

\[ TOC = C_t + A \times P_o + B \times P_L \]

Where \( C_t \) is the initial cost of transformer and \( (A \times P_o + B \times P_L) \) accounts for the cost incurred during operation of transformer due to loss of energy. \( P_o \) is no load losses and \( P_L \) is the load losses. Factors A and B are capitalization rates for no load and load loss respectively.

Comparison of TOC with consideration of losses at higher temperatures, indicates that case-2 offers the least TOC. There is a slight increase in TOC for case-3, still this case, or possible cases with slightly lower temperature rises, may be worth considering as they provide reduction in footprint and volume which may probably compensate for slight increase in TOC.

**ESTER FILLED TRANSFORMER AT TATA POWER**

A pioneer in providing reliable and uninterrupted power to the city of Mumbai, Tata Power caters to over 500,000 residential, commercial and industrial customers. Tata Power is committed to being a lead adopter of technology with a spirit of risk taking. Leadership through care is the company’s thrust area towards achieving sustainability, Safety is one of the core values of the company. With the introduction of Natural Ester filled distribution transformers, the company has made a significant progress in achieving the Company’s goals.

In June-2014 Tata Power announced the introduction of Natural Ester filled distribution transformers across the Mumbai distribution area. The objective of introducing these green and fire safe installations is to ensure safe and sustainable distribution of electricity.

As a first step Tata Power installed 990kVA, 11000/433V, Distribution Transformer with temperature rises of 35/40/66 °C, very similar to the case-1 of table-1. As a step forward, they decided to specify the temperature rises in line with case-2 for their next purchases. After having sufficient experience with these transformers Tata Power may decide to go for the option with higher temperature rise, step by, step up to case-3, to get advantage of reduced footprint and volume.

**CONCLUSION**

In recent times esters are becoming preferred alternative to replace mineral oil, in order to improve fire safety and reduced environmental impact. It also enhances performance with reduced footprint at higher temperatures with high temp class insulations.

Ester filled solution with high temperatures limits, considering thermally upgraded paper immersed in natural esters as high temperature class insulation, by mutual agreement between utility and manufacturer, may be an interesting option as it offers reduced foot print with nominal increase in TOC in comparison to the option of ester filled transformer with conventional temperature rises.
Indian utilities installing transformers in densely populated cities, near to residential areas can be benefitted by the ester filled transformer solution. Utilities may opt the best design solutions depending on their requirement. With the experience of Tata Power, it is expected that acceptance of ester filled alternative will grow and utilities in India may like to exploit the advantages of this solution.

REFERENCES


