Paper ID – 00437 Session 2022
A2 POWER TRANSFORMERS & REACTORS
BEYOND THE MINERAL OIL-IMMERSED TRANSFORMER AND REACTORS

EXPERIENCE ON DESIGN, MANUFACTURING & TYPE TESTING OF FIRST 420 KV CLASS ESTER FLUID FILLED SHUNT REACTOR

1. **Richik Manas DAS**
2. **Gunjan AGRAWAL***
3. **Rajil SRIVASTAVA**
4. **A K SINGHAL**
5. **Abhay CHOUDHARY**

Power Grid Corporation of India Ltd (A Govt. of India Enterprise)
INDIA
gunjan.agrawal@powergrid.in

SUMMARY

Mineral oil from petroleum crude is used in Transformers and Reactors since 1890s. Since inception, manufacture of mineral oil went through several stages of improvement during past 130 years. From the early refining method of distillation cum acid cleaning, today's highly refined oils are made by severe hydrocracking process and by gas to liquid technology in recent times.

The disadvantages of Transformer mineral oil are twofold: partial biodegradability and low fire point. It also raises safety issues with Transformer explosions and fires that can cause heavy catastrophic damage. Also, there are major concerns on the toxic effects of uncontained oil spills.

Ester based alternate fluids viz. synthetic esters and natural esters take over the disadvantages of conventional mineral oil in terms of partial biodegradability, low fire point and consequent safety issues with Transformer/Reactor explosions and fires that can cause catastrophic damages. Ester fluids can carry higher volumes of water compared to mineral oil at all temperatures as the water solubility in esters is very high compared to mineral oil, resulting in less water migration to insulating paper during stage of equilibrium, with consequent lesser ageing of paper.

The experience in India on using alternate environment friendly fluid is presently limited to distribution and medium voltage rating 66 kV class Transformers. World over experience with ester fluid is 400 kV for Transformers and 330 kV for Reactors. Power Grid Corporation of

India Limited (POWERGRID), a major Transmission utility in India took a pilot project of Natural Ester filled 420kV Shunt Reactor to gain field experience.

This paper discusses state-of-art of the natural ester, national and international standards dealing on various aspects of such fluids. In view of the inherent fluid properties, ester fluid Transformers and Reactors are different from mineral oil filled products and are treated differently. Philosophy behind selection of rating and finalisation of technical specifications for Reactor is covered in the paper. Due cares are taken during engineering, manufacturing and processing of ester filled Reactors to compensate the fluid properties. Paper has covered key design, manufacturing and processing experience gained during pilot project of the Reactor.

50 MVAr, 420 kV three phase shunt Reactor is successfully tested for all routine and type tests including temperature rise test. This is the first 420 kV three phase shunt Reactor in the world designed, manufactured and tested with ester fluid. Reactors filled with natural esters contributes altered performance in terms of moisture content, insulation resistance and power factor, thermal tests etc. while compared to conventional mineral oil filled Reactors. Test experience obtained in 420 kV shunt Reactor using such fluids is shared in the paper.

After successful factory testing, dismantling and packing of accessories also plays a vital role for natural ester fluid. Key precautions adopted during dismantling, packing and dispatch of the Reactor and accessories is covered in the paper.

Natural ester filled 420 kV shunt Reactor shall be installed in one of the key substations of POWERGRID. To gain maximum field experience a monitoring plan is prepared; such proposed field monitoring plan for coming years is covered in the paper.

KEYWORDS

Green Reactor, mineral oil, natural ester, synthetic ester, field monitoring.

1. MINERAL OIL – LAGS IN ENVIRONMENTAL REQUIREMENTS OF TODAY'S WORLD

The major role of dielectric liquids in Transformer is to provide cooling, dielectric medium and to assess the health of the Transformer/ Reactor on periodic basis. There are various type of Dielectric liquids used in Electric Equipment. However, Mineral oil has been a predominant choice for Transformers & Reactors since many years.

Since inception, lot of improvements have been taken place in the technical parameters of Mineral Oil making it more suitable for Transformer & Reactors insulations. From the early refining method of distillation cum acid cleaning, today's highly refined oils are made by severe hydrocracking process and also by gas to liquid technology. Considering the suitability and being a cost-effective liquid, mineral oil is primarily used in Transformer & Reactors for all voltage class.

However, there are certain disadvantages of mineral oil also. The main drawback of this oil is its partial Biodegradability and low Fire point. This raises safety issues with Transformer or Reactor explosions and fires that can cause heavy catastrophic damage. Also, there are major concerns on the toxic effects of uncontained oil spills. Further, due to limited resources of Mineral Oil, utilities would have to shift from these oils to alternative oil/ fluid in future.

2. ENVIRONMENT FRIENDLY LIQUIDS

Considering the above disadvantages of the mineral oil, lots of research work is going on since last two decades to cultivate the alternative liquids which could replace the existing mineral oil. Based on attempts to develop the alternative insulating liquids, different K class liquids (based on their fire behavior) have been developed and now widely used in Transformers & Reactors of all the ratings across the globe.

Natural & Synthetic Ester fluids are considered as best alternative to Mineral Oil and these fluids are gaining popularity among Utilities and Manufacturers. Both Natural and Synthetic Ester fluids have certain advantages/ disadvantages over one another. Utilities in India and across the globe have gained lot of experience in lower voltage class Transformers on using Natural and Synthetic Ester fluids. However, there has been limited experience available globally regarding use of Ester fluids for higher Voltage class (400kV & above) Transformers & Reactors.

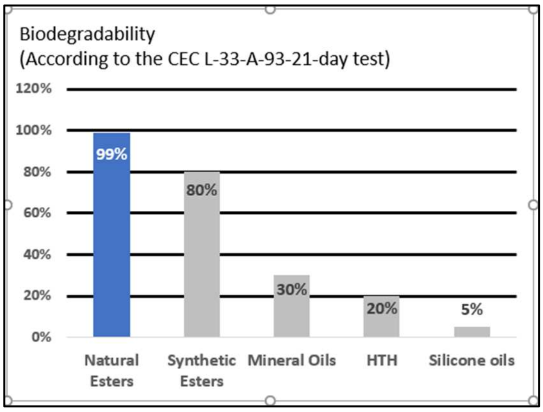


Fig.1. Comparison of biodegradability

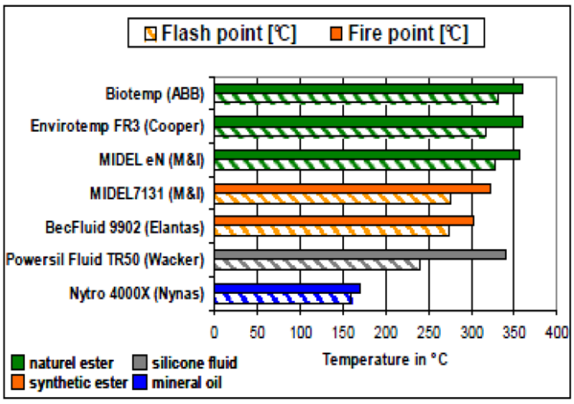


Fig.2. Comparison of fire points

Figure-1 shows comparison of biodegradability of various insulation liquids while Figure 2 shows comparison of flash and fire point of various insulating liquids.

3. POWERGRID INITIATIVE

To gain operational experience of Ester fluid in higher Voltage class Transformers & Reactors, POWERGRID India has taken up a pilot project in which one 400 kV Auto Transformer with Synthetic Ester Fluid and one Shunt Reactor of 420kV class is procured with Natural Ester Fluid. The Natural Ester filled 3-Phase Shunt Reactor has been manufactured and Type tested successfully by the manufacturer i.e. M/s Transformers & Rectifiers India Limited and commissioned at one of the Substations of POWERGRID.

The experience gained during design, various stages of manufacturing and Type testing of the above Reactor filled with Natural Ester is discussed in details in this paper.

4. REACTOR TECHNICAL DATA

The finalized Salient technical specification of the reactor designed for Natural ester fluid is tabulated in Table 1.

Table 1: Technical parameters of Reactor filled with Natural ester fluid

Rated Reactive Power	50 MVAr, Three Phase Shunt Reactor
Voltage Rating	420 kV
Rated Frequency	50 Hz
Cooling Type	ONAN
Temperature Rise ºC	40 for Oil, 45 for Winding
Maximum Noise Level at rated voltage & frequency	80 dBA
BIL LI (kVp) SI (kVp) 1 min. Power Frequency withstand voltage Maximum PD level	 HV- 1300, HVN- 550 HV- 1050 HVN – 230 kVrms < 100 pC at 1.58 x Ur/√3 p.u.

5. EXPERIENCE AND CHALLENGES FACED IN DESIGN

The chemical composition of the Natural Ester is considerably different from mineral oils. Therefore, many of the design, manufacturing, handling and maintenance practices used for mineral oil cannot be directly applicable for the Natural ester fluids. Accordingly, the impact of difference in properties of Ester compared to Mineral oil on the design of Reactor was thoroughly studied and necessary changes were incorporated suitably in the Design of above Natural ester filled Reactor. The various areas of improvement/ changes are as under:

5.1. Thermal Design

(i) The thermal design of above Reactor with Natural Ester was a major concern considering the difference in various properties of Natural Ester compared to Mineral Oil. The above Reactor cooling is ONAN type. Therefore, oil flow inside the Reactor winding is governed by the temperature difference of Top and bottom and the oil passage provided in winding section. Comparing the viscosity of the dielectric liquids at 40°C, mineral oil has 9 mm^2/s (cSt) while Natural Ester fluid have 33 mm^2/s [3]. Due to higher viscosity, oil flow is lower than the mineral oil.

Therefore, considering the higher viscosity, Cooling of about 10-15% enhanced during design stage and radiator pipes of higher diameter (100 NB in comparison to 80 NB used in mineral oil) used to allow more fluid flow through radiators.

(ii) Transformer and Reactor thermal performance is also governed by the heat transfer coefficient of insulating liquid, which in turn depends upon thermal conductivity, kinematic viscosity, specific heat, density, and coefficient of thermal expansion. The thermally better liquid possess high thermal conductivity and specific heat; and smaller viscosity, density, and thermal expansion coefficient. The thermal conductivity @ 20ºC of Ester is 0.1644 Watt/mK whereas for Mineral Oil is 0.126 Watt/ mK, thus for Ester it is higher than the Mineral oil, which improves the cooling performance. Though, the cooler requirement may be slightly reduced for this aspect, the higher cooling was retained, as it is a pilot project being implemented first time.

The same Ester filled Reactor design was compared with Mineral oil (without changing physical parameters) through software-based analysis and comparison of thermal performance both the liquids is tabulated in Table 2 for reference.

Table 2: Thermal Performance comparison

Thermal Parameters	Natural Ester Fluid (°K)	Mineral oil (°K)
Top oil Rise	33.7	29.5
Winding Rise	36.9	30.2
Winding Gradient	10.0	7.4
Hot Spot Rise	47.0	41.3

From above, it is inferred that the temperature rise for Natural ester is higher than the Mineral oil for the same design with same cooling. Thus, the cooling was enhanced to maintain the similar Temperature rise as in mineral oil.

5.2. Dielectric Design

Dielectric Design is another critical aspect while designing Reactor filled with Ester considering various properties of Natural Ester varying from Mineral Oil. Like conventional design practice, Reactor Dielectric design was also thoroughly analyzed using 2D FEM softwares for various voltages (i.e. LI, LIC, SI, PF, LTAC etc.) considering the impact of Natural Ester properties i.e. Permittivity, effect of non-homogeneous field, Larger Oil Gaps etc.

Electric field distribution in EHVAC equipment is largely dependent on permittivity of various insulating mediums. Reactor internal dielectric withstand design is a combination of Oil gap and solid insulation, having different permittivity. Table 3 gives a typical comparison between permittivity of mineral oil and Natural ester at 20 °C.

Table 3: Relative Permittivity of different Insulating materials

Material	The relative permittivity of different insulating materials	The relative permittivity of solid insulation impregnated with	
		Mineral Oil	Natural Ester
Mineral Oil	2.2	-	-
Natural Ester	3.1	-	-
Kraft paper	2.3	4.3	4.8
High-density pressboard	4.0	4.4	4.8

From Table 3 above, the relative permittivity of ester liquids is relatively higher than mineral oil, but relative permittivity of liquid impregnated paper and pressboard are nearly matching. In case of mineral oil, maximum electric field strength is experienced by oil and solid insulation (pressboard and paper) receives less stress. However, in case of Natural ester, solid insulation gets higher stress compared to solid insulation in mineral oil. The dielectric strength of solid insulation is higher; thus, higher field strength does not have any negative impact on insulation.

Field calculations have shown that the field stress in the liquid duct is around 8% lower for Natural esters. Only in case of inhomogeneous the higher field strength experienced by the paper insulation may become critical. For above Reactor, there was a possibility to reduce Dielectric clearances (uniform gaps). However, a lower gap may impact the cooling performance due to higher viscosity of Natural ester. Hence, no reduction in uniform gaps were considered due to above aspect.

For non-homogeneous insulation arrangements with thick paper insulation, the higher field strength in the paper insulation may become critical. To take care of high stress on paper and to maintain adequate design margin, more oil gap provided between winding and Yoke (Top and bottom). 2D FEM based study was performed to estimate maximum electric stress in solid insulations and various oil gaps. Some of the result of this study shown in Fig.3 & 4 below:

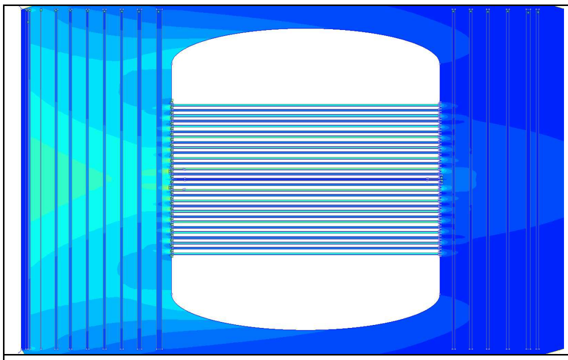


Fig. 3: Max. stress distribution between winding and shield during LI test of 1300 kVp

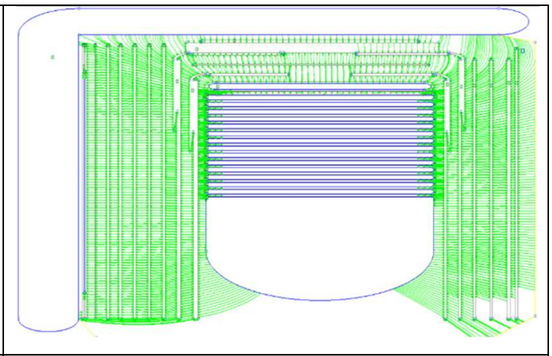


Fig.4: Safety margin in Oil ducts for non-uniform gaps during Power Frequency (230kV rms)

For an identical design employing Natural ester fluid there is an increase in the voltage stress in the paper conductor insulation, decreasing the stress voltage in the oil, i.e., if the same design is considered, the stress in the oil is reduced by the use of Natural ester fluid due to the relation between materials dielectric constant values. Considering this, Impulse analysis was performed through software and proper shielding is envisaged in the winding to have very smooth distribution of the impulse voltages. Further, modified shielding arrangement is used to improve voltage distribution within winding.

Figure 5 show the distribution of the voltage along the height of the winding and as discussed by providing better shielding arrangement very smooth Impulse distribution is obtained. Fig.6 shows the safety margin along the winding during application of impulse voltage.

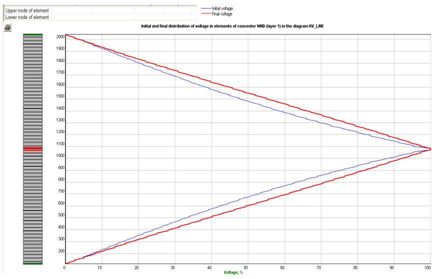


Figure 5: Impulse Voltage distribution in the winding

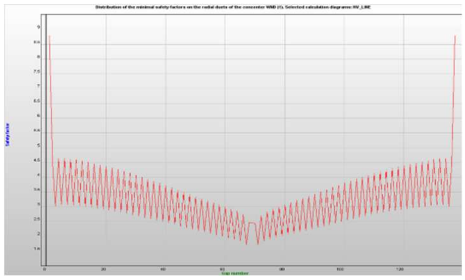


Fig.6: Safety factor for impulse voltage application

A technical comparison of dielectric design with Natural Ester fluid and Mineral oil for various critical locations is given in Table 4 for reference.

Table 4: Summary of Dielectric Insulation study

Location in the winding assembly	Maximum Electric Field Strength on Copper (kVp/mm)		Maximum Electric Field Strength at oil paper interface (kVp/mm)		Safety Factor	
	Mineral oil	Natural Ester	Mineral oil	Natural Ester	Mineral oil	Natural Ester
Middle Insulation	27.21	34.88	24.78	23.38	1.15	1.18
Top Insulation	4.64	5.06	6.31	5.95	1.45	1.50
Bottom Insulation	3.77	4.83	6.34	5.98	1.30	1.39

From above, it is observed that dielectric strength in gap (oil is higher compared to mineral oil filled gap.

5.3. Compatibility with materials

When changing type of fluid, it becomes very essential to check the compatibility of new type of fluid with the different types of component materials used and surrounded by oil. Materials found compatible with mineral oil found also suitable while using with Natural ester in general.

Thorough studies were done for material compatibility tests on gaskets, ceramic spacers, etc. in 420kV class reactor and only those material were used which was found meeting the requirements.

All the components used in the reactors like, Buchholz relay, aircell, bushings etc. are also reviewed for their compatibility with natural ester fluid, concerns discussed with component manufacturers and confirmations were taken at design stage before procurement and its application to reactor.

6. EXPERIENCE AND CHALLENGES FACED IN MANUFACTURING

During manufacturing process of the Natural Ester filled shunt reactor, Core building, Winding, Core & Winding assembly and Drying process were followed in line with the mineral oil filled Reactor. However, due to change of fluid, certain challenges were faced during post drying to testing activities. Though certain amount of miscibility of Natural Ester and Mineral Oil is acceptable, arrangements were made to avoid mixing of these two fluids as it may compromise the fire point of Natural Ester and other properties. The details of such challenges and actions taken to meet them are described as below:

6.1. Lower Oxidation Stability of Natural Ester:

Generally, the Oil for new Transformer/ Reactor is sent directly to site and testing at works is carried out with the test oil available at works meeting the Technical requirements. However, in case of above Reactor, impregnation, filling and testing at works was to be carried out with the new oil and same oil had to be sent to site. Considering multiple handling and lower oxidation stability of Natural Ester, various steps were taken to retain the properties of Ester fluid.

During manufacturing, Ester fluid for reactor was procured in tanker (for quantity equivalent to tank volume) and drums (balance quantity for headers, radiators etc.) to reduce fluid handling activities. Storage tanks used were first cleaned with new Ester fluid and their gaskets were replaced. New set of fluid handling hoses were used. For oil filter machine, old gaskets and filter units were replaced with new sets and proper flushing with ester fluid was done multiple times before usage to ensure no mineral oil should mix with Ester fluid.

Unlike reactor assemblies impregnated with mineral oil, hot air drying is not an acceptable process for drying out. For additional drying of Natural ester impregnated assemblies, it is required to use methods of drying that do not expose the impregnated insulation to air to avoid polymerization of the dielectric fluid. For active part drying of 50 MVAr Reactor, Vapor phase drying method was adopted. After necessary post VPD treatment and clamping fluid filling in the reactor was done under fine vacuum.

Due cares were also taken during post testing and dispatch activities. Nitrogen blanketing was done during dismantling activities to reduce exposure of active part to ambient air. Since nitrogen was used inside reactor tank, a self-contained breathing apparatus (SCBA) was used during dismantling of bushings and post FAT internal inspection. Figure 7 shows a typical SCBA used during post FAT internal inspection.

Fig. 7: Typical SCBA used post FAT internal inspection

Fig. 8: Reactor under dispatch

The Reactor was dispatched in ester fluid filled condition with pressurized nitrogen cushion at top. Fluid drums were refilled with nitrogen cushion at top and sealed. To reduce possibility of thin film formation, all the dismantled parts such as conservator, pipes and radiators were pressurized with nitrogen along with provision to check pressure at receipt. Before dispatching of the unit and accessories 48 hours monitoring was done to check for any pressure drop. Figure 8 shows the reactor under dispatch. All the cares were taken so that the properties of fluid should not be degraded.

6.2. Construction of Breathing System

It is recommended to restrict direct contact of Natural Ester with air to avoid deterioration of fluid properties on account of lower oxidation stability of Natural ester fluids. In this case, non-breathing (aircell type) arrangement is adopted along with protection relay (CPR) to reduce the chance of contamination of liquids by exposing them to direct air.

Couple of experiments performed show that volume of fluid relative to the surface exposed to ambient air significantly impacts the rate and degree of polymerization that occurs [4].

6.3. Higher viscosity

Higher viscosity may hamper the impregnation rate of the solid insulation hence in the case of Natural ester liquids; more impregnation time should be given for proper impregnation of the solid insulation. It is also preferred and recommended to fill Natural ester fluid only under vacuum. For 50 MVAr reactor, to improve the impregnation of the solid insulation, Natural ester fluid was filled under 0.1 torr vacuum. Transformers and Reactors with higher voltage class require more impregnation times (2 to 3 times) compared to mineral oil. For above Reactor, impregnation time of 72 Hours was given post processing as compared to 24 Hours for mineral oil.

Pump capacity used in handling and filtration activities of the Natural ester fluids need to be reconsidered as higher viscous Natural ester fluids require more power to maintain the same flow rate as of mineral oil. For the above said reactor, more filtration time was given considering the reduced efficiency of churning the fluid from tank using same capacity pump (existing facility).

Considering the higher viscosity and chance of higher bubble formation in the Natural Ester fluids, settling time before high voltage test increased to nearly three times.

6.4. Challenge of Stray gassing

Ester fluids have tendency to generate more stray gassing than mineral oils. Thus, at higher temperatures during filtration, Ester fluid may release fault gases which may mislead and indicate some fault inside the Reactor i.e. Partial Discharge, thermal fault etc. Therefore, to reduce this phenomenon, fluid filling was done at a relatively lower temperature. To increase the rate of impregnation in the insulation and to compensate

higher viscosity effect, long hour's oil filtration at 60-65 °C in the reactor was carried out.
It may be mentioned that as per WG32 of CIGRE, the analytical techniques and interpretation methods for dissolved gases used for mineral oils can be used with some adjustments for non-mineral oils [5].

7. TEST EXPERIENCES

The Reactor was fully assembled including Radiators, Marshalling Boxes and all other fittings before testing. RIP Bushings were specified and used for this Reactor. The above Reactor was subjected to all the Routine and Type tests as per IEC 60076. Few important measured test parameters are given below for reference. Figure 9 below shows fully assembled reactor under testing.

Figure 9: Fully assembled 50MVAr reactor under testing.

7.1. Insulation Power Factor and Insulation Resistance

Ester fluids are polar in nature and it was expected to have higher winding Insulation power factor for above reactor, however measured winding insulation power factor was 0.247 at 35 °C.

Significant decrease in insulation resistance is seen in above reactor as compared to other mineral oil filled reactors of similar rating. Measured Insulation resistance was 1.6 Giga Ohm (one minute).

Core-Frame-Tank insulation values were in the range of 0.24 to 0.70 Gega Ohm.

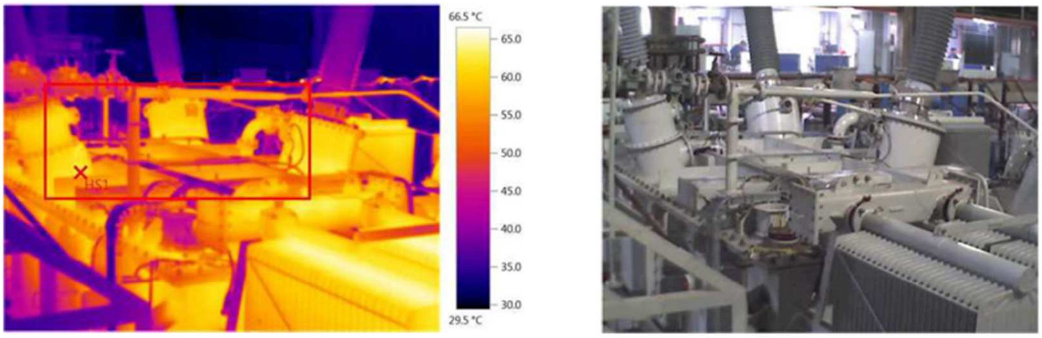
7.2. Dielectric Tests

The above Shunt reactor successfully passed all Dielectric tests (lightning, switching and applied voltage tests including Partial Discharge measurement) in first attempt. The Partial Discharge measured was ranging from 64pC to 77pC at 1.58Ur/√3 voltage against guaranteed value of 100pC.

7.3. Temperature rise Tests

The Temperature rise test was carried out as per IEC. Fiber optic sensors were embedded in the reactor windings to measure hot spot temperature during Temperature rise test.
Oil DGA was performed before and after temperature rise test and results were found in order. Thermal image of Reactor during Temperature rise test is given in Fig. 10 below:

Fig. 10 Thermal image during temperature rise test



Picture parameters:

Emissivity:	0.95
Refl. temp. [℃]:	20.0

Picture markings:

Measurement Objects	Temp. [℃]	Emiss.	Refl. temp. [℃]	Remarks
Hot spot 1	65.1	0.95	20.0	-

Table-5 compares the design and tested temperature rise parameters for the Natural Ester filled reactor.

Table 5: Comparison of Thermal parameters for Reactor

Parameters	Designed values	Measured values
Top oil Rise	33.7	30.5
Winding gradient	10.0	9.97
Winding rise	36.9	32.9
Winding hot spot rise (using FO sensor)	47.0	45.2

Test results confirms the Technical specification, IEC 60076-6 requirement and matched with the design parameters. The above reactor was successfully commissioned in August 2021.

8. CONCLUSION

Sufficient experience is now established in the world for use of Natural ester in distribution transformer and medium voltage transformers. There is a vast potential of this “K Class” liquid in Large Power Transformers and Reactors also as it is ecofriendly and available limited resources of Mineral Oil.

POWERGRID has acquired experience to use this fluid in 50 MVAr, 420 kV class Reactor, which incidentally is the largest rating Reactor tested with Natural Ester (Envirotemp FR3) fluid in the world. Further, one 400kV Transformer with Synthetic Ester is also under advance stage of manufacturing. Once sufficient experience is gained in this voltage class, more number of such Transformers & Reactors shall come in future with Natural Ester Environment friendly fluid.

A beginning has been made in India!

9. ACKNOWLEDGEMENT

The authors are grateful to POWERGRID management for granting their permission to write and present this paper. The views expressed in this paper are of the authors only and not of the management of POWERGRID.

BIBLIOGRAPHY

[1] Roberto Asano Jr. etc, “Reduced environmental impact and improved safety and performance of Power transformers with Natural ester dielectric insulating fluids”, IEEE transactions on industry applications, vol. 50, no. 1, January/February 2014

[2] Kausha M. Oza etc., “Environment Friendly Power Transformers”, TRAFOTECH 2014 - Ninth International Conference on Transformers

[3] Cigre brochure 436, “Experiences in service with new insulating liquids”.

[4] Cargill reference information R2080, “Thin film oxidation”

[5] Cigre brochure 443, “DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria”