Break current transformer paradigms to truly improve grid reliability

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An electrical grid's reliability is directly affected by transformer life. And, historical transformer design, loading, maintenance policy, and ambient conditions affect transformer life. Furthermore, new grid conditions, including distributed generation, may create additional disturbance to the interconnection element: the transformers.

In order to truly improve grid reliability, not only does it take a good solution but it also requires some changes to how the industry usually approaches transformer management. Good news is that it does not have to be painful, and does not require a huge capital investment or lengthy installation.

In this paper, we will discuss how utilities, by incorporating Envirotemp™ FR3™ fluid into their transformer specifications, can realize significant cost savings, increase transformer fleet performance and improve grid reliability.

Main factors that impact grid reliability and maintenance costs

1. Age and management of transformer fleet
2. Variable power flow (loading) impacts life expectancy, risk of failures, and aging rate of the transformer fleet
3. Investment (or lack thereof) in new transformers

The transformer fleet in the US is aging faster than the investment in new transformers is occurring

The transformer fleet in the US is aging faster than the investment in new transformers is occurring, causing significant stress on reliability of the grid and likelihood of failure to increase. Transmission and substation transformers today now bear near nameplate loading conditions as the norm. In distribution, the addition of transient, distributed generation (solar and wind) and higher harmonic content is causing additional stress and is accelerating service-aged transformer failures on residential circuits. Consumers add even more demand to those already stressed transformers as more energy intensive devices (including electric cars, on demand digital devices, and LED TV's) are plugged in. Utilities have not been able to keep pace with this changing environment.

New DOE standards could force unintended consequences

Compounding the changing energy consumption environment, the US Department of Energy (DOE) has chosen to implement new efficiency requirements for distribution transformers through 2500kVA.

The first regulation took effect January 1, 2010, stipulating that "transformers through 2500kVA shall meet minimum efficiency requirements [1]" (transformers inherently have no load losses (NLL) associated with just being energized, and load losses (LL) associated with usage demand). A subsequent revision in transformer efficiencies is set to take effect January 1, 2016. As of the writing of this paper, the DOE expects "the lifetime savings for equipment purchased in a 30 year period that begins in the year of compliance with amended standards (2016-2045) amounts to 3.63 quads'[1]." 3.63 quads of energy savings eliminates the need for more than seven (10) 400MW power plants, and is expected to save more than 260 million metric tons of CO_2 production.

The intent is bold – improved efficiencies are always good. However, with these new regulations, potential unintended consequences surface:

- New efficiency mandates require more expensive and a heavier magnetic core for transformers
- Heavier transformers could cause incremental infrastructure replacement costs such as poles, trucks, and additional installation crews

[1] US Federal Registry, Vol 78, No. 75, Thursday April 18, 2013

Loading patterns prematurely age transformers and increase risk of transformer failures (reliability)

Based upon the historical capacity of transformers deployed for given loading patterns, utilities preordained the aging rate of their transformer fleet, and hence the reliability of the grid. Utilities regularly report their reliability metrics to FERC (Federal Energy Regulatory Commission). As this environment has evolved and variable loading patterns have increased, a more complex grid has emerged and as a result, new dielectric stress is accelerating the aging rate of the transformer fleet which threatens the long-term reliability of the grid.

Standard industry practices are limiting utility flexibility to meet demand changes

Utilities balance many variables when deciding which transformers to deploy to a particular circuit. Some decisions are based solely on utility practice such as supplying transformers from standardized inventories (in single phase distribution, it's typically 25kVA, 50kVA, or 75kVA transformers).

While standardization is a good best practice, supplying over-sized mineral oil filled transformers that are unnecessarily under-loaded inflates first cost and total ownership costs. We support the benefits of standardized inventories but suggest looking at which capacities are standardized and why.

A simple solution: Change the dielectric fluid and improve transformer designs

Three failure modes dominate transformer failures:

- Dielectric failure (either the solid insulation or the liquid insulation; the transformer industry tends to underestimate dielectric system failures by breaking out failures associated with lightning or line surges)
- Bushing failures
- Under oil switch failure

The transformer industry could delay bushing and under oil switch failures with improved maintenance programs. In transmission and substation class transformers, the fleet is more manageable and maintenance programs already exist. Improvements in condition-based maintenance are enabling the discovery of potential failures early enough to prevent catastrophic events.

However, in distribution transformers the costs to implement an improved maintenance program outweigh the benefits. There are millions of service-aged distribution transformers operating today and no single event will trigger a significant grid outage.

We must also acknowledge the elephant in the room: there is no magic bullet for regenerating damaged solid insulation to prevent dielectric failures. Lightning and line surges cannot be predicted and with each surge, the insulation system is damaged. Eventually, even with the best maintenance programs, the transformer fleet will degrade to the point of failure.

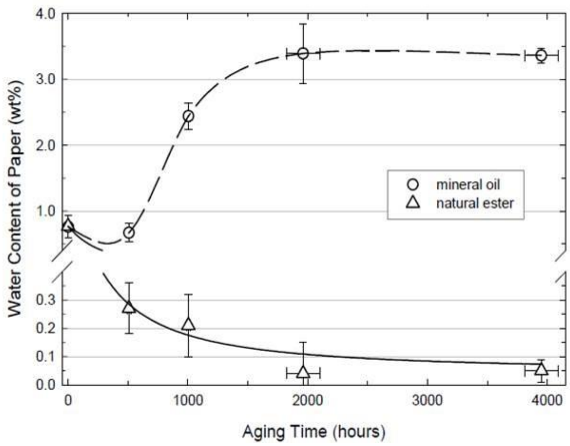
Installing FR3™ fluid filled transformers and retrofilling existing transformers are cost effective methods to address and delay dielectric failure in distribution, transmission and substation class transformers.

A. *Specify FR3™ fluid to protect the insulation paper and slow the rate of aging in order to reduce risk of failures*

FR3 fluid should delay dielectric failure in most transformer applications (even in serviced aged transformers), as the insulating paper stays stronger longer, even at elevated operating temperatures (up to 20°C). To understand how FR3 fluid can improve transformers, it is useful to understand a couple of relevant aspects of solid-liquid insulation systems and identify the most crucial parameter: moisture content.

Moisture content affects both aspects of dielectric capacity deterioration- it has a catalytic effect on the paper aging process and reduces the withstand capacity of the insulation system. When discussing the insulation system dielectric withstand, two aspects must be considered: the reduction of dielectric capacity when solid insulation is wet and the very critical risk of failure due to bubbling when submitted to cyclic loading and, especially, overloading.

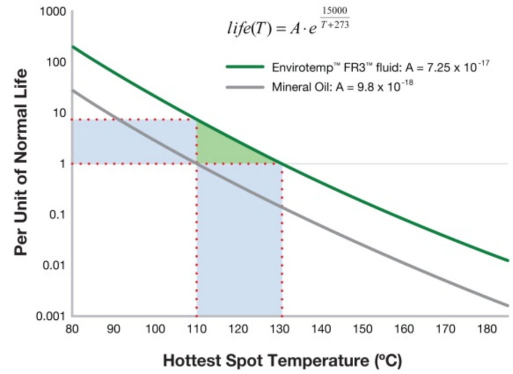
Laboratory studies and accelerated aging tests with real transformers confirmed the capacity of FR3 fluid to scavenge moisture from the cellulose based materials. As an example, two paper samples, having the same initial moisture content, have been aged in mineral oil and in FR3 fluid. The next chart presents moisture content along the aging time:



Installing transformers filled with FR3™ fluid will improve two essential aspects of a transformer's life expectancy: extending the life of its insulating materials and reducing the insulation related premature failures. This means improving transformer reliability, and in the long run, a utility's grid reliability.

B. Change transformer design with FR3™ fluid to handle load variability without sacrificing reliability or asset life

Today, several standards exist that define maximum operating temperatures for insulation systems comprised of typical insulation components, all focused on long term life expectation.



As noted above, transformer insulation systems based on FR3 fluid can be designed with 20°C increase in temperature and still meet the standard aging rate as mineral oil-based insulation systems.

As mentioned earlier, many distribution utilities have limited their inventory of single phase transformers to two or three capacities, 25kVA, 50kVA, or 75kVA are most common. By specifying transformers optimized to the new standardized high temperature capabilities, utilities could be purchasing smaller transformers based on incremental temperature increases up to 20°C. This new transformer should:

- Meet the ever changing capacity requirements
- Achieve slower aging rate of insulation when compared with traditional mineral oil based aging, resulting in a longer lasting solid insulation (Regulatory: Reliability)
- Have lower no load losses than the traditional mineral oil solution (DOE: Efficiency)
- Require less resources (copper, electrical grade steel, paper, etc.) to support sustainable supply chain initiatives
- Additional benefits include
  - Be safer for material handlers (EHS) as FR3 fluid is biodegradable and non-toxic and non-hazardous in soil and water
  - Mitigate risk of fires and explosions (RISK) as FR3 fluid has a 300°C fire point

Another way to leverage the thermal capability of the insulation system may be to specify a similar sized transformer, but allow the operational temperature to increase 10-20°C in order to provide more flexibility in managing peeks in demands.

This increase in operating temperature opens the door to making significant impacts on how load capacity is optimally managed.

Economic benefit to transformer redesign: lower initial cost or improved NPV over life of asset

Beyond load capacity, the utility may weigh variables including cost of capital, expected growth in demand over the life expectancy of a transformer, space limitations, or other special circumstances when deciding what capacity transformer will be installed.

A study, conducted by Cargill, Incorporated, compared a 100MVA, 230kV-69kV transformer designed with mineral oil against the same transformer designed with FR3™ fluid and high temperature insulation.

Compared to a traditional mineral oil transformer, our study showed that the new FR3 fluid filled transformer:

- Met the capacity requirements
- Achieved slower aging rate of insulation (up to the 20°C increase in design temperature)
- Had similar or lower first cost
- Required less resources – it contained 9% less fluid and 13.5% less copper by weight
- Weighed 8.5% less which could reduce transportation costs
- Maintained superior dielectric performance due to continuous dry-out effect of the paper
- Mitigated the risk of failure due to bubbling during overloads / changes in temperature.

Example	Cost Comparison
Mineral Oil at 65K (base)	Nominal
FR3™ fluid at 65K	More than base example
FR3™ fluid at 75K	Comparable cost to base example
FR3™ fluid at 85K	Lower cost than base example

If managing the longer term asset life (rather the initial cost) is the primary driver, transformers filled with FR3 fluid will have longer life expectancy, thus reducing replacement cycles which can significantly impact the long-term NPV return, all while improving the long term reliability of the electrical grid.

Advantages are achievable today – It just takes a change in behavior

Improving the electrical grid's reliability is in the best interest of all stakeholders. Additionally, the DOE has mandated that our electric grid be more efficient. Since every utility operates an aging transformer fleet with a known capacity and documented failure rate, and given that the traditional loading profiles are evolving, changing a few behaviors (adopting high temperature capabilities, re-evaluating load patterns in relation to capacity required, and lowering failure risk) will ultimately increase the transformer fleet's performance.

Transformer manufacturers are designing FR3 fluid-filled transformers that meet the DOE mandates, and that operate within the temperature limitations outlined in IEEE while providing access to the thermal capabilities FR3 fluid enables. Utilities are improving their performance by adopting FR3 fluid and changing their usage profiles.

Significant advantages outlined in this paper are achievable today. By requesting new configurations, including multiple capacities (i.e. 65/75/85 C AWR ratings), and changing how those assets are applied, the transformer industry will transform the electric grid into a more reliable distribution system.

The concepts outlined in this paper apply to all ranges of capacity, at all rated voltages. The transformer industry has the tools to efficiently analyze the different scenarios that exist within individual utilities. Adopting FR3 fluid filled transformers enables utilities the opportunity to meet all of the following obligations: reliability, efficiency, use less resources, EHS, and RISK management.

To learn more, contact Cargill's Dielectric Fluids group at fr3fluid@cargill.com or visit envirotempfluids.com

Cargill's dielectric fluids group has been collaborating with utilities and their transformer manufacturer partners for years to create and implement solutions to improve transformer performance, increase grid reliability and achieve cost efficiencies.

NOTE: The views expressed in this document are based on Cargill's extensive testing of FR3 fluid and third party validation as of the publication date. We cannot guarantee that test results and/or third party standards will not change. Transformer design parameters are dependent on individual specifications, utility practices, conditions in which a transformer will be used and applicable laws, regulations and codes. The study described herein outlines potential cost savings identified by Cargill that users of FR3 fluid could realize. However, results will vary and Cargill makes no representations or warranties whether express or implied, with respect to use of the information included herein or any cost savings users may or may not realize.

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