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Be Prepared for the Unexpected: Design to Increase Personal Safety, Reduce Fire and Explosion Risk, and Mitigate Environmental Impact.

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SUMMARY

The search for safer and environmentally friendlier substations or power plants asks for setting of new standards. A modular innovation architecture allows a comprehensive fire safe substation concept. This modular concept can be implemented for use on any kind of transmission asset.

The raising demand for energy, as well as changing grid conditions, lead to substations operating closer to the design limits. This change in the mode of operation increases the risk for personal safety and for the environment.

This paper will address a modular innovation architecture with solutions that can help mitigate environmental impacts and reduce fire risks for new and existing substations.

For transformer tanks to have a rupture safe design, consideration of the highest possible system fault currents with verified and validated simulation methods to help demonstrate this rupture safety are necessary. The application of static and dynamic FEM simulations to evaluate and optimize tank withstand to internal arcs will be explained.

Ester fluids as an alternative to mineral oil liquid insulation, and transformer tanks with an adequate rupture resistance, mitigate fire and rupture risk for new transformers. This enhanced safety can be enabled by the use of an FM-global approved K-class liquid which significantly reduces the risk of insulation catching fire because of the higher flash and fire points and because of the lower gas generation rate it has compared to traditional mineral oil. That lower gas generation can increase the tank rupture withstand by about 20%. With a proper selection of components such as non-porcelain bushings and vacuum tap changers, an extended fire safety of the whole transformer can additionally be achieved.

Besides the higher fire safety offered by ester insulating fluids which are FM Global approved less flammable fluids, the environmental impact will also be discussed in the paper. Esters are an environmentally friendlier alternative over traditional mineral oils. Ester fluids are readily biodegradable and should spills occur, the environment would be better safeguarded. Tests have been conducted to demonstrate the biodegradation of different insulating liquids. As an example, a 28-day biodegradation test shows that esters have a biodegradation of 89% or higher compared to mineral oil with a biodegradation of less than 10%.

Even after all available preventative measures have been implemented, the unexpected may still happen. Mobile resilience, multi-ratio flexible transformers can significantly reduce the impact of failures on the reliability and availability of the power grid helping react quickly when rapid replacement is needed. In addition to these topics, the paper addresses the incorporation of the transformer in the world of IoT, which enables indication of abnormalities and optimization of the operation.

The paper will show how the optimized total cost of ownership for utilities and for the society can only be achieved with the safest and newest standards in environment, health and safety for substations. Even though state-of-the-art technology presented in this article goes beyond requirements of our industry standards, personal safety and environmental protection should always be evaluated considering the best possible available solution. Every day, anywhere transformers are catching fire – this could be greatly avoided in future.

KEYWORDS

Environment health and safety (EHS), tank rupture prevention, less flammable fluids, biodegradation, mobile resilience transformer, internet of things (IoT), digital twin, static & dynamic FEM calculation, ester, plug-in-bushings, fire safe substation.

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1. Introduction

Effects of weather and climate changes as well as operational issues bring new challenges. Such risks can lead to malfunctions and blackouts thus having a huge impact on our society which depends on electrical energy.

Setting new standards in environment, health and safety for substations by designing the world's first fire safe substation. The concept defines three new performance levels in a modular innovative architecture. It starts with a tank rupture and fire safe design for personal safety continuing with increased environmental safety and highest availability by exceeding industry standards. Finally, the concept can be enhanced with digital twin and IoT technology resulting in an optimized total cost of ownership (TCO).

The combination of proven technologies and new innovations unlocks new potential and by innovating solutions beyond existing standards, substations become more resilient, creates higher value for the society and minimizes the impact to the environment and human beings.

A new fire safe substation concept in modular innovation architecture offers: a) Maximized personal safety due to fire- and explosion safe design b) Increased environmental safety by utilizing alternative insulation and switching technologies c) The highest level of availability by exceeding industry standards with digital twins d) Optimized TCO. Setting new standards in environment, health and safety by defining three new performance levels with a customized modular design for an overall optimum is the base for any further component development in Siemens Energy Transmission.

2. Tank rupture prevention

With respect to tank rupture simulations, two different methodologies shall be followed:

- static methodology
- dynamic methodology

2.1. Static methodology

To fulfill the requirements of the standard "PC57.156-2016 – IEEE Guide for Tank Rupture Mitigation of Liquid-immersed Power Transformers and Reactors" a static methodology has to be used. For this simulation and optimization of the tank, we use the electric energy. Also, the full hydrostatic pressure of the tank (from base plate to oil level in the conservator) and the weight of the active part is considered. For those simulations we use a FEM program.

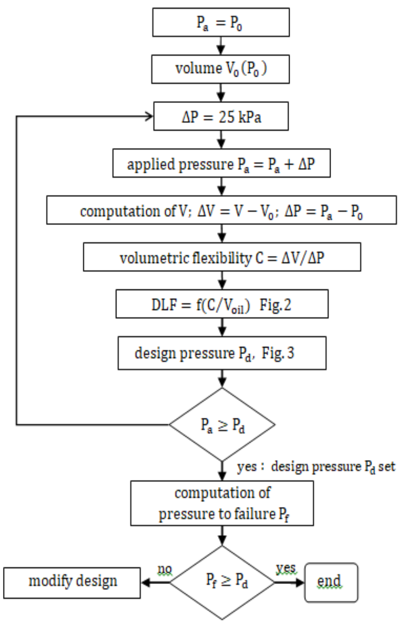


Figure 1: Schematic presentation of the static tank rupture methodology [10]

2.2. Additional Safety Feature

Siemens design considers a predetermined breaking point in the weld between tank cover and tank wall which means, if the electrical energy would be considerably higher than expected and; consequently; a rupture with a leakage would occur, then it will happen at the highest point of the tank with only a small amount of oil spill to be expected.

2.3. Dynamic Methodology

For special investigations, like e.g. the behavior of HV chimneys (bushing turrets) under stress conditions, we use the dynamic methodology. We developed and executed it based on real transformer projects. Moreover, dozens of real tank rupture tests with an artificial internal arc were performed on transformers up to 15 MVA and we incorporated related test results in our model.

Further to those tests we realized that for the dynamic investigation we can only use a certain portion of the electrical energy as mechanical energy.

The majority of electrical energy transfers into heat, enabling the phase transformation from fluid to gas and cracking of the molecular chains in the oil.

2.4. Tank flexibility

Given that the tank of the transformer is allowed to exceed the elastic limit of the material in the event of an internal arc, its deformation behavior will be dependent on the value of the resulting internal pressure.

Initially, the whole tank works within the elastic range of the material, being its deformation (and, consequently, its change of internal volume) directly related to the material's modulus of elasticity E.

As the internal pressure increases, gradually the structure of the tank starts presenting plastic behavior, increasing its rate of deformation with respect to the internal pressure.

3. Less flammable fluids (ester fluids)

Ester fluids as an alternative to mineral oil liquid insulation, and transformer tanks with an adequate rupture resistance, mitigate fire and rupture risk for new transformers. This enhanced safety can be enabled by the use of an FM-global approved K-class liquid which significantly reduces the risk of insulation catching fire because of the higher flash and fire points and because of the lower gas generation rate it has compared to traditional mineral oil. That lower gas generation can increase the tank rupture withstand by about 20%.

3.1. Enhanced Fire Safety

During operation, transformers are exposed to overloading or overvoltages associated with contingencies or emergency operation conditions, are exposed to short circuit currents and to tough environment conditions like earthquakes, geomagnetic induced currents or overvoltages like lightning.

Besides normal wear and tear and associated life consumption, special operating conditions, as described above, can cause transformers to fail. Synthetic esters have a much higher fire point than mineral oil, so their use as insulating fluid can increase fire safety significantly, thus reducing the risks associated with a transformer failure [1, 3].

ASTM D92 / ISO2592	Mineral Oil	Natural Ester	Synthetic Ester
Fire point	170°C	350°C	>316°C

Figure 2: Summary of fire points of different insulating liquids [1, 3]

Installation and operation of transformers with enhanced fire safety can be cost effective because of the following:

- Reduced fire risks allow users to decrease investments needed to protect power plants, adjacent power equipment and buildings.
- Investments in fire walls, fire pits, fire prevention systems, like deluge sprinklers, can be reduced or eventually be fully eliminated.
- Traditional fire safety clearances can be reduced, optimizing the installation area footprint.

- Users have reported reduction of insurance costs/ premiums because of demonstrated lower risk.

As an example of possible associated civil construction savings, FM-Global Property Loss Prevention Data Sheets [7] give guidance indicating that the minimum distance between a traditional large (with >38 m^3 of fluid) mineral oil filled transformer containment to a non-combustible main building wall should be 15.2 m, but if that transformer is instead filled with an FM approved ester, the distance can be reduced to 4.6 m. If the construction has 2-hour fire rated walls, the distance can be reduced from 7.6 m to 4.6 m when using an FM approved ester.
FM-Global also indicates that the distance between two transformers without fire barriers can be reduced from 15.2 m to 7.6 m (for liquid volumes >38 m^3) when using an FM approved fluid [7].

	Minimum Horizontal Distance from Containment to Exposed Building		Minimum Separation Distance Between Adjacent Transformers
	2-hour fire rated wall	Non-combustible wall	
FM Approved fluid (Ester)	4.6 m	4.6 m	7.6 m
Non-Approved fluid (Mineral oil)	7.6 m	15.2 m	15.2 m

Figure 3: Separation for Exposure Protection according to
FM-Global Property Loss Prevention Data Sheets 5-4, for liquid volumes >38 m^3 [7].

While ester filled transformers have in general a higher initial cost than traditional mineral oil filled units, all the above-mentioned benefits are in many cases offsetting the higher initial cost and typically reduce the total cost of ownership over the life of the transformer.

Fire safety regulations are different in every jurisdiction and users are so advised to communicate with the local authority having jurisdiction over local rules and regulations regarding use of less flammable fluids.

3.2. Performance during operation

Use of synthetic ester increases the stability and flexibility during operation.
While natural esters rapidly oxidize, solidifying or becoming gelatinous when in contact with oxygen, synthetic esters are highly stable and can be used in free-breathing transformers as well. Synthetic esters have extremely good behavior at very low temperatures. While the pour point of natural esters is in the range of -21 °C [4], synthetic ester has a pour point of -56 °C [2, 3] making it adequate for utilization in regions with extremely low ambient temperatures. Other benefits of synthetic esters include their high moisture tolerance. Esters can absorb far greater amounts of water than mineral oil without compromising its dielectric properties. It has been shown that even with ten times higher water content [ppm] of the ester fluid, the equilibrium water remaining in the cellulose insulation is less than half compared with mineral oil [6]. It means cellulose remains much dryer in a transformer filled with ester fluid, thus reducing its ageing and ultimately its risk of failure.

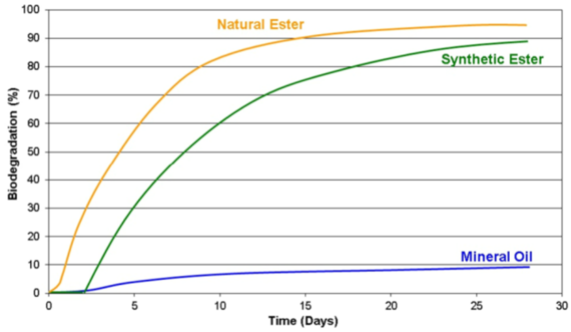
3.3. Design considerations

It should be noted that esters have different dielectric, physical, thermal and chemical properties from mineral oil and thus transformers shall be specifically designed for the type of fluid to be used. As an example of such differences, esters have a dielectric constant that is more than 45 % higher than the for mineral oil, meaning that the equipotential field distribution associated with an insulating structure design which is optimized for a type of fluid might become significantly distorted and inadequate for another fluid.
All other differences in the fluids mentioned above shall integrally be considered during the design and manufacturing to assure highest reliability and performance during operation.

3.4. Environmental impact

Esters are an environmentally friendlier alternative over traditional mineral oils. Ester fluids are readily biodegradable and should spills occur, the environment, including soil or water bodies would be better safeguarded.

Use of esters can significantly reduce associated environmental impacts. In a 28-day test, biodegradation of synthetic ester reaches 89 %, while traditional mineral oil typically only degrades 9.7 %. Ester insulating fluids are classified as fully biodegradable (according IEC 61039) [5].



	Synthetic Ester	Natural Ester	Mineral Oil
28-day Biodegradation	89%	94%	9.7 %
OECD 301 status	Readily Biodegradable	Readily Biodegradable	Non-Biodegradable
IEC 61039	Fully Biodegradable	Fully Biodegradable	n/a

Figure 3: Biodegradation of different insulating liquids

Environmental regulations are different in every jurisdiction and users are so advised to communicate with the local authority on the application of local rules and regulations associated with spill control and clean-up of ester fluids.

4. Transformer components

4.1. Bushings

Traditional Oil Impregnated Paper (OIP) bushing failures accounts for almost 50 % of all catastrophic transformer failures that result in fires [11]. The insulation typically has a breakdown when an OIP bushing fails, resulting in an internal arc. This arcing then causes the oil to break down into gasses at a very fast rate, which in turn causes an extremely fast pressure build-up inside the bushing housing. This pressure build-up and the heat from arcing plasma cause the bushing enclosure/housing to rupture, which results in an explosion that discharges bushing material shrapnel (pieces of porcelain or fibreglass) and oil at high velocity. This explosion usually causes the bushing bottom end to disintegrate and leads to the collapse of the remainder of the bushing into the transformer tank. This typically occurs while arcing is still ongoing and result in internal arcing and an oil fire due to the heat and combustible gasses formed during the bushing failure incident.

This risk can be reduced by eliminating the oil content of the bushing by replacing it with a dry type (non-oil-containing) bushing, i.e. Resin Impregnated Paper or Resin Impregnated Synthetic bushing.

4.2. Resin Impregnated Paper (RIP) Bushings

The insulating condensers of RIP bushings are made of special paper and conductive layers (either foil or carbon prints) that is vacuum impregnated with epoxy resin. Due to the excellent conductive properties of the condenser design, optimum voltage distribution is guaranteed, even in cases of rapid voltage changes.

The condenser body is wound onto the central tube (for the centre bushing conductor), then impregnated under a tightly controlled vacuum process with resin and then hardened. The condenser is then machined to its final shape - the condenser body acts as an oil-tight seal to the transformer at the flange.

This results in a totally dry type bushing that has no transformer oil above the transformer main tank and thus reducing the risk of exposing transformer oil to the atmosphere during a busing failure. The higher temperature class rating of RIP bushings provides for increased thermal stress withstand capability compared to OIP bushings. RIP bushings are also not limited by restrictions on the angle of installation that is a typical limitation for OIP bushings. The standard OIP bushing is designed for inclinations in a position 0-30° from the vertical.

The external insulation typically consists of a composite insulator housing with silicone skirts to increase creepage distance per the customer requirements. This external housing is vulcanized onto the tapered laminated fibre glass cylinder which will provide mechanical protection and support to the complete bushing assembly. Silicone is chosen as the preferred material for the external housing due to its exceptional dirt-repellent characteristics thanks to its hydrophobic surface and the property of hydrophobic transfer in contamination layers.

The fibre glass support tube has aluminium fittings at both ends that are joined together by using a special sealing technique to ensure a permanent and gas-tight seal at the joints.
The space between the fibre glass tube and the condenser body is filled under vacuum with polyurethane elastomer to ensure that there is no air in the system. This yields a bushing that has zero oil or air content.

RIP bushings offer an outstanding combination of mechanically strong, permanently elastic and good damping properties with the added benefit of high electrical strength. As a direct result of these benefits, RIP bushings are particularly well suited for applications where extreme mechanical stress withstand, such as seismic designs in accordance with IEEE ¬ 693, are required.

Other advantages of RIP bushings over OIP bushings include:

- Flame/fire retardant/resistant properties
- Can be used in more extreme temperatures
- More resistant to damage as a result of improper handling or vandalism
- Reduced stress on transformers and improved installation and maintenance handling due to lower weight
- Reduced collateral damage in the event of a bushing failure due to lower rate of projectile expulsion during failure

4.3. Resin Impregnated Synthetic (RIS) Bushings

RIP (Resin Impregnated Paper) type bushings include materials such as paper, vacuum impregnated with epoxy resin. Paper is a good insulator, but it is also hygroscopic, so it absorbs moisture from the surrounding atmosphere. This absorbed moisture will have a negative effect on the power dissipation and insulation aging of the bushings, thus increasing losses slightly and decreasing expected life of the condenser inside the bushing.

With Resin Impregnated Synthetic bushings this moisture absorption issue is mitigated by replacing the paper with synthetic materials – synthetic material web that has been evaluated through an intensive program of research, development and testing. These synthetic materials are non-hydroscopic (have very little moisture absorption) and reduce (close to eliminate) the issues associated with the moisture absorption of paper insulation systems.

RIS bushings are characterized by their highly stable dielectric properties, which is a direct result of keeping the insulation as dry as possible throughout the lifetime of the bushing.

A visual indicator for the new technology is the whiter color of the active component, compared to the brown shade of the active component with RIP technology.

Advantages over RIP bushings:

- Extremely stable dielectric characteristics
- Do not absorb moisture or is sensitive to moisture absorption during storage
- Longer expected service life and better aging performance
- Optimized production process
- Increased flame/fire retardant/resistant properties

4.4. Tap Changers

Traditional on-load tap-changers, which use diverter switches with in-oil arc quenching, poses some risk regarding catastrophic failures that can result in fire. These tap-changers can fail violently if there is a problem or failure on the tap mechanism that will cause the arc energy of the diverter to exceed its capability, i.e. the oil is contaminated by repeated switching and cannot quench the arc due to its lowered dielectric strength due to carbonization.

On-load tap-changers with vacuum diverter switches are reducing these risks due to their unmatched ruggedness, reliability and economical operation. They are effective, both in everyday normal use, as well as during overload operation of a transformer when sized properly. Most of the modern vacuum style tap-changers are rated for 300,000-plus tap-change operations without requiring maintenance or oil filtering. These vacuum style tap changers can also handle transients and higher voltages better than the traditional oil switched units. Most of the tap-changers on the market today, use vacuum diverter switches that can handle more than a million operations before needing replacement. This reliable operation is achieved through highly efficient arc quenching techniques used in the vacuum switch designs and result is a highly predictable and reliable switching operations.

Tap-changers with vacuum diverter switches are available for both types of commonly used tap-changers, i.e. reactor type tap-changers and resistive bridge type tap-changers.

Benefits of vacuum type tap-changers over oil type diverter switch tap-changers:
- Lower failure risk and thus reduced fire risk
- No oil carbonization
- Increased availability of the transformer due to reduced maintenance
- No replacement of contacts
- No need for oil filtering systems

5. Mobile resilience

In case that all the prevention measures the unexpected may still happen it is recommended to have a contingency plan prepared and ready. Such a detailed plan should include the steps which needs to be taken, like detail transportation plans, layout and work plans.
Together with mobile solutions this will reduce the outage time to a minimum. Such solutions are known as resilience concepts are state of the art for transmission power transformers and are available for Generator-Step-Up (GSU) power transformer as well.

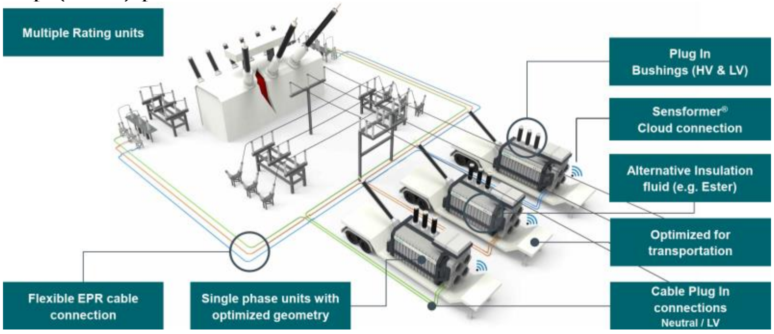


Figure 4: - Schematic arrangement of Siemens' resilience concept [8]

In order to facilitate a very rapid deployment, a reduced transport weight as well as small dimensions are crucial. Innovative solutions, like highly flexible cables and plug-in bushings are supporting a reduced installation time. Finally, by applying the recommended commissioning procedure, a transformer bank could be brought online within an extremely short period of time [9].

Especially in case of a failure at a generation site it is essential to move on as fast as possible and replace such transformers within the shortest possible time. In case no spare transformers are in stock, lease models especially for GSU resilience transformers had been introduced.
Other applications which support the reduction of outage time are mobile plug & play concepts for reactors, power voltage transformers, GIS (Gas Insulated Switches), static synchronous compensators (STATCOM). In case there is an even more catastrophic event other portable power solutions could mitigate the outage time. These semi-permanent installations can be built as mobile unit on a trailer, skid-mounted or within a shelter as a so called "E-House".

6. Internet of things, digital twins

Transformers are positioned at each critical node in the energy grid, from power generation stations all the way down to the industrial and private consumers, yet they were only perceived as "voltage transforming devices". With digitalization the transformers can evolve into an info-hub.

Digitalization is typically done with a smart and robust IoT gateway securely transmitting the required information to a cloud-based storage and visualization platform. Operators get a comprehensive and quick overview of their assets and thus can improve their operations.

Benefits of Digitalization:

- Easy connectivity, by provision of a secure connection
- Enabling real time asset management
- A platform that is flexible and can be adapted to the customer's needs

The industry understands the ever-increasing cybersecurity requirements and therefore ensures that they comply with state-of-the-art security and encryption technologies to comply with regulations.

The basic versions of digitalization typically monitor the following: oil level, oil temperature and winding current plus indirect computing information like ambient temperature & humidity, weather warnings, etc. The advanced versions offer additional sensors, information and hence increased performance, while minimizing operational risks. Some advanced versions have a digital twin operation solution – as the status of a transformer is known at all times, from the moment of energizing onward, the digital twin provides a complete real time thermal image of the transformer, enabling accurate lifetime consumption simulation and performance prediction.

For example, load prediction for the transformer for the next few hours are determined by the targeted loss of life considered for a specified period.

Virtual sensors save cost and time while enabling more insights of the transformer's inner life and condition. This could include an extended temperature information system with advanced 3D visualization, selectable signals of different values and components as well as a virtual sensor notifier. This notifier can typically be parametrized to inform the operator of the status of the asset anywhere, anytime. Many more use cases are possible with advanced features: oil volume and analysis can be performed as well as integrating cooling based on current ambient conditions to gain greater insight or even control load conditions. Additionally, the functionality can be expanded by adding bushing and gas monitoring. The hardware is typically optimized to be robust, i.e. by minimizing handling of activities, reduction of number of sensors as well as avoidance of local analytics hardware.

Digitalization enables operators to optimize the quality and speed of operational decisions as well as to become more flexible, act faster and more efficiently in troubleshooting or to completely avoid it. Having more available information and reacting faster to potential issues is an effective way to reduce the risk of catastrophic failure and thus fire.

7. Special tests

There are many simulation possibilities available nowadays. Most of the commercial or open-source software have already included validation packages as well. However, without a sound verification of such simulations by real test you cannot improve your physical equipment. Therefore, many special tests have been conducted to verify those simulations.

As described before, more than a dozen real internal arc tests, confirming our detailed simulations, have been conducted. Finally, all those tests contributed to a tank rupture safe design.
But our efforts are not limited to verified tank rupture simulations. With regards to alternative insulation fluids and new innovative designs we performed cold start tests in a climate chamber, GIC/DC injection in high voltage test labs, seismic tests on vibrating table just to mention a few.

8. Conclusion

Power transformers contain large amounts of dielectric fluids and can be a significant risk factor regarding safety of personnel, equipment, the environment and fire and/or explosion risk. Operators have several options, as described above, to choose from to reduce these risks in order to align better with their specific risk aversions or requirements.

Reducing risk, however, does not mean that catastrophic or unexpected events will not happen. This will require contingency plans to allow for better response to such events on short notice to restore power to the customers. These contingency plans typically require the rapid deployment of spare or mobile equipment that can be installed and commissioned quickly and with enough flexibility to bypass the failed equipment.

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