

Bypassing GSU transformers in case of emergencies or maintenance

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SUMMARY

A forced outage of a Generator-Step-Up (GSU) transformer in any power plant is a nightmare for everyone involved, not only because of possible power outages on industry and communities but also because they can quickly evolve into financially critical situations that could even lead to bankruptcy of different stakeholders, including producers, consumers and retailers of electricity.

Beside the conventional practice of having for each of the stations a spare transformer, more advanced solutions are also now available for conventional generating power plants as well as for renewable generating facilities which will be presented in this paper.

Resiliency GSU's are designed and constructed to be mobile, meaning they can easily be transported to anywhere in North America. They also can be installed and energized in industry-benchmark short times. Applying state of the art design tools the most compact transformers can be manufactured. High temperature materials like NOMEX® in combination with the use of synthetic ester insulating fluid MIDEL® 7131 consequently ease the transport and enable higher power ratings compared with a conventional design. Through the incorporation in the solution of plug-in bushings and cables, the installation and commissioning time is reduced dramatically. By monitoring the key performance data including for example a direct hot spot measurement the units can be pushed to the limit with the reassurance of a safe and reliable operation.

Mobile resilience Generator Step-Up transformers contribute in a new way to enhance grid resilience.

While the resilience transformer concept is a known state of the art solution used in step-down substations, newest developments in the area of Mobile Resilience Generator Step-Up transformers are significant and have proven versatile and able to replace many different types of units in a wide variety of configurations. The coverage of various generator and transmissions voltages guarantee highest flexibility in operation. Reliable and proven transformer technologies recombined to maximum added value for securing power supply by means of fast exchangeability transformers.

The new concept provides additional reliability and peace of mind to the owners and operators of any kind of generating plants."

KEYWORDS

Resilience, reliability, GSU, transformers, plug-in-bushings, plug & play transformers, ester, environmentally friendly, mobile, rapid response, bypassing.

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INTRODUCTION

Development of alternatives to increase resiliency of the grid is not only a task that should be tackled by a few, but really should be embraced by a broader group of stakeholders. In recent years, governments through their regulatory and reliability agencies, together with users (power generation as well as transmission and distribution companies) as well as OEMs (manufacturers of products and suppliers of systems and solutions) have been engaged in the development of alternatives that have already been proven pivotal to enhance availability of power systems.

Of the different equipment needed for the transmission and distribution of energy, power transformers as the ones that are most difficult and costly to replace in case of failures. Usual sourcing times for new power transformers are of the order of eight to twelve months, not considering transportation to the final site which together with installation and commissioning can require several additional weeks.

This paper compares state of the art resiliency power transformers that have been manufactured to address the needs of Generation as well as Transmission and Distribution companies in North America and were designed and built so that deployment as well as installation and commissioning can be made in extremely short times which are currently benchmark in the industry.

PREVENTION, PROTECTION AND REACTION

Because of the ample nature of grid resiliency requirements, an integral approach is necessary to cover the different required fields of action. The PRETACT[®] concept, which consists of a toolbox around three pillars: prevent, protect and react helps evaluate risk factors and challenges and define solutions to address them.

Prevention

The risk of an operational outage can be reduced by a range of effective preventive measures for transformers. Some selected examples are as follows:

- Transformer Lifecycle Management to keep the equipment healthy.
- The use of voltage regulators to help regulate low- and medium-voltage grids and remain within the permissible voltage range, increasing the network stability.
- High quality design of distribution transformers to cope with switching stress loads of wind power generation.
- Consideration of potential stresses in the design phase and use of sophisticated and state-of-the-art design tools.

Protection

Transformers can be stressed by impacts which occur during operation. Some of these stresses might not damage the equipment immediately or there might be work arounds. But these impacts might lead to a damage of the transformer. A way to avoid uncertainties is to consider risk prevention about grid resiliency at the early beginning of a project.

Protective measures can safeguard against forced outages caused by exposure to the natural environment or human impacts, as well as increasing the overall safety of the transformer, i.e.:

- Ester insulation fluids, which reduce the risk of fire or explosion, can be used in all kind of transformers as well as reactors. Ester fluids can also protect the environment as they are fully biodegradable.
- Asset designed to withstand Geo-magnetically induced currents (GIC) caused by sun storms.
- Mechanical design: Bullet-resistant transformers and tank-rupture-safe design.
- Flame-resistant cast-resin transformers.

- Radiation-reduced systems for liquid-immersed distribution transformers and cast-resin transformers to protect the surrounding environment to ensure the electromagnetic compatibility (EMC).

Reaction

Different resiliency strategies are on the market, but none of them avoid failures on installed equipment from happening. One of the solutions are mobile resiliency units based on a plug-and-play-concept. Those are transformers that can be kept in a storage area and be transported to the needed location within a very short timeframe. Resiliency transformers have been used as well to optimize maintenance procedures, time and costs, keeping the grid fully enabled also during contingency situations.

Some enablers to react fast are: easy transport, flexible voltages and fast installation as outlined in Figure 1.

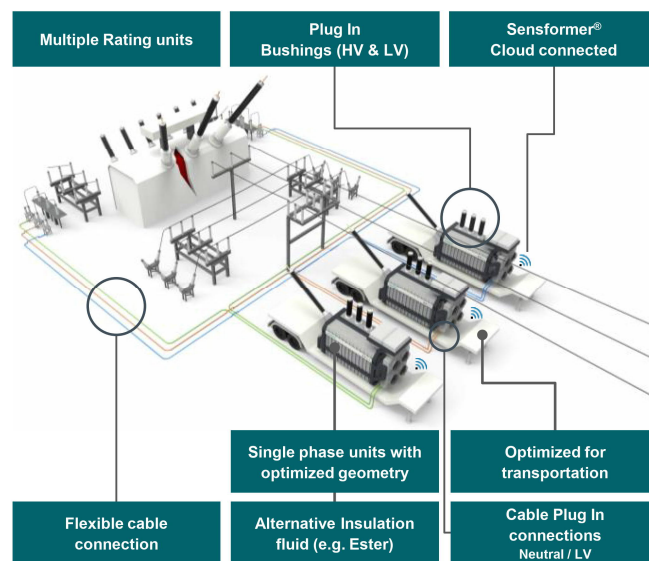


Figure 1. Schematic arrangement of Siemens' resilience concept [5]

A very lightweight and compact design by using of high temperature insulation material like NOMEX® and laid out as single-phase units to ease fast transportation.

Reduction of the installation and commissioning time can be achieved by transportation of the transformer fluid filled and the use of pluggable bushings and cable connection.

Versatile operation and flexibility for the use at different locations is another field to be considered. Multi ratio rating and flexibility on the types of high voltage and low voltage terminals and cables allows to replace more than only one type of transformer.

Taking substation layouts into account, it might not always be possible to connect the HV and the LV to the overhead bus bar. Therefore, the LV connection could be connected by a pluggable bushing or a pluggable cable connection. To consider different routes and distances the use of cable joints is a common practice. The connection from the cable to the LV bus bar or the overhead line can be done by connecting the cable via portable pothead stands. Cables are used for the delta connection of the single-phase transformers as well.

CASE STUDIES

Two transmission projects and one generation project have been developed to meet the requirements of different users.

While the transformers seem to look different, all the project designs follow a modular architecture. A plug and play concept allows maximum flexibility without jeopardizing the purpose of such transformers.

1) Case I - Autotransformer Transmission Project

Design key facts:

Six units of 100 MVA each – single phase – 60 Hz

- Operation mode I: $335 \text{ kV} \pm 16 \times 0.75\%$ / 136 kV / 13.8 kV @300 MVA (bank).
- Operation mode II: $136 \text{ kV} \pm 5 \times 1.84\%$ / 69 kV / 13.8 kV @150 MVA (bank).
- OLTC for voltage regulation and DETC switching between operating voltages.
- Plug-In bushings.
- LV (136 / 69 kV) with alternative plug-in cable connections or plug in bushing to grid.
- Full overload capability as per customer specification (e.g. 169 % for 1 hour @ 30°C ambient).
- Neutral with plug-in cable.
- Tertiary with plug-in cable.
- Noise level 70 dB(A) under no load, sound intensity.
- KDAF cooling – Insulating liquid Synthetic Ester – MIDEL[®] 7131.
- Common control cabinet with heavy duty plug multi connectors.

Low transport weights:

- Main tank without oil: 133,000 lb, 60 t.
- Total weight (assembled and oil filled): 216,000 lb, 98 t.



Figure 2. Rapid recovery resilience transformers on site

2) Case II – Autotransformer Transmission Project

Design key facts:

Three units of 133 MVA each – single phase – 60 Hz

- Five operation modes:
 $345/230 \text{ kV}$, $345/138 \text{ kV}$, $345/115 \text{ kV}$, $230/138 \text{ kV}$ or $230/115 \text{ kV}$ @400 MVA (bank).
- Tertiary: 14.4 kV.
- Switching links utilized to change between operating voltages.
- Plug-In bushings.
- LV (138/115 kV) with alternative plug-in cable connections or plug in bushing to grid.
- Neutral and Tertiary with plug-in cable.
- Noise level 72.8 dB(A) under no load, sound pressure level.
- ODAF cooling – Insulating liquid Mineral oil.
- Common control cabinet with heavy duty plug multi connectors.

Low transport weights:

- Main tank without oil: 108,000 lb, 50 t.
- Total weight (assembled and oil filled) 167,000 lb, 75 t.



Figure 3. Resilience transformers at the final tests in the test lab

3) Case III – Generator Step up (GSU) Project Design key facts:

Three units of 83.3 MVA each – single phase – 60 Hz

- 41 operation modes:

Vector Group		d	d	y	d	y	d	y	d	y	d	y
LV Voltage [kV]		34.5	20	34.6	18	31.2	16	27.7	14	24.3	12	20.8
HV Voltage [kV]	400 ^{*)}	•	-	-	-	-	-	-	-	-	-	-
	345	-	•	•	•	•	•	•	•	•	•	•
	230	-	•	•	•	•	•	•	•	•	•	•
	138	-	•	•	•	•	•	•	•	•	•	•
	115	-	•	•	•	•	•	•	•	•	•	•

Tertiary 13.6kV *1400kV via adapter and BIL 900kV

Figure 4. Possible operation voltage of the resilience GSU

- Tertiary 13.6 kV (for stabilizing).
- Switching links utilized to change between operating voltages.
- HV Plug-In bushings up to 345kV.
- LV customer connection via oil/air GSU bushing,
LV interconnection via plug-in Cable connection.
- Neutral with plug-in cable.
- Tertiary with plug-in cable.
- Noise level 75 dB(A) under no load, sound pressure level.
- KDAF – Synthetic Ester – MIDEL[®] 7131

Low transport weights:

- Total weight (assembled and oil filled): 214,000 lb, 97 t.
- Transport weight (transformer) w/o oil: ~114,600 lb, 52 t.



Figure 5. Resilience GSU transformers at the final tests in the test lab

4) *Comparison of the three cases:*

Even some of the requirements differ, the main purpose of the resilience transformer is the common goal to be able to energize the transformers within the shortest possible time even under difficult and unpredictable conditions. Resiliency transformers are designed to be flexible and be able to operate in many locations and covering as many transformer types as possible under the consideration.

The plug-in type bushings, as well as the flexible cable connections make the units versatile, with the advantage that it is not necessary to open hand holes for bushing installation or any oil manipulation (Figure 2). Units are designed under the plug and play philosophy.

Use of Synthetic Ester (e.g. MIDE[®]L 7131) as insulating fluid in combination with aramid solid insulation (NOMEX[®]) enhances operating performance, keeping the transformer compact and lightweight for easier transport and installation.

Ester insulating fluids are fully biodegradable reducing environmental risks associated with transport and operation.

Some of the differences in the projects are as follows:

	Case I	Case II	Case III
Number of transformer types covered	2	5	80+
Voltage selection	LTC voltage regulation (HV)	Switching links	Switching links
Switching between configurations	DETC	Switching links	Switching links and connection box
Insulation material	Synthetic Ester MIDE [®] L 7131	Mineral oil	Synthetic Ester MIDE [®] L 7131
Power supply	From station	Built in the transformer	From station
Configuration during transport (bushings are not installed)	Fully assembled	Modular concepts per substation different weight limits	Modular concepts per substation different weight limits
Supported High Voltages	335kV & 136kV	345kV & 230kV	400kV, 345kV, 230kV, 138kV & 115kV
Supported Low Voltages	136kV & 69kV	230kV & 138kV & 115kV	<u>Delta</u> : 34.5kV & 20kV & 18kV & 16kV & 14kV & 12kV <u>Wye</u> : 34.6kV & 31.2kV & 27.7kV & 24.3kV & 20.8kV

	Case I	Case II	Case III
Connections	HV Wye LV Wye Tertiary - Delta	HV Wye LV Wye Tertiary - Delta	HV Wye LV Delta or Wye Tertiary - Delta*
Supported voltage combinations **)	2	5	41 (with LV Delta: 21 with LV Wye: 20)
Types of terminals	<u>HV</u> : plug-in bushing <u>LV</u> : plug-in bushing or cable <u>Ter</u> : plug-in cable	<u>HV</u> : plug-in bushing <u>LV</u> : plug-in bushing or cable <u>Ter</u> : plug-in cable	<u>HV</u> : 345kV plug-in bushing <u>LV</u> : LV customer connection via oil/air GSU bushing, LV interconnection via plug-in Cable connection <u>Ter</u> : plug-in cable

*) only applicable in Wye-Wye connection for stabilizing.

**) not considered tertiary system.

Figure 6. Comparison of the three power transformers

TECHNICAL CHALLENGES FOR GENERATOR STEP-UP RESILIENCY TRANSFORMER

The resilience GSU (Figure 4,5,6, 9) was designed to be flexible to cover most specification variations of Siemens' existing fleet in North America (US, Canada and Mexico) up to 400 kV considering as well:

- Vector group = Yd and Yy(d).
- Power rating from 50 to 250 MVA for one bank.
- High voltage (HV) = 115kV, 138kV, 230kV, 345 kV & 400kV.
- Low voltage (LV) = between 12kV and 20kV, as well as 34kV.
- Have a delta connected stabilizing winding (for Yy transformers).
- The transformer(s) shall be able to be transported and be ready for service in a short period of time. Weight restrictions for transit considered to avoid idle time due to transit permits.
- Installation time: within the shortest possible time (e.g. using as benchmark Case I in this paper: 30 working hours within three day working period).
- Accessories delivered and stored in containers.
- Cost efficient solutions for planned and forced outages for bypass solutions.
- The LV connection between the GSU and the existing bus bar is done via high flexible cables with plug in connections and can be connected as delta or as wye. (Figure 7, 8).

TECHNICAL SOLUTIONS:

The aim is to address all changings with an adequate technical solution.

- **Vector group:** The high voltage is always with wye connection by on the low voltage side y-connection is in rare cases applied. In Wye-Wye connection an asymmetrical load must be handled additionally, thus a buried tertiary is state of the art. Connection chambers providing the customer connection points for low side and guarantee the necessary connection of the individual transformers and their windings (Figure 7, 8).

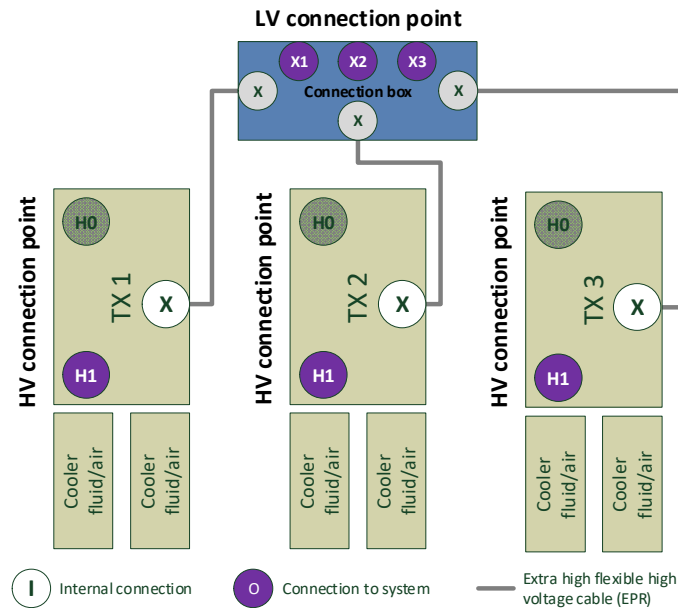


Figure 7. Connection diagram - Combination of single phase transformers to bank for GSU application

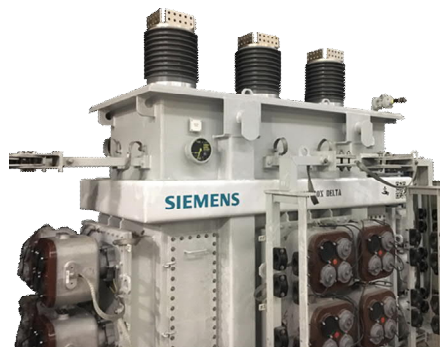


Figure 8. External connection box to connect the single phase transformers to bank configuration

- **Power rating:** The large variety of power plants with ratings from a few MVA up to GVA must be divided in several groups. To address the majority of medium size power plants a focus on a range of 50-250MVA is feasible. The solution was to concentrate on the top rating with enhanced cooling and the usage of upgraded insulation system materials (e.g. NOMEX®) in the most stressed areas. It is always a compromise of size and weight, top rating and flexibility in voltages classes, which define the applicable solutions. In case of an emergency the positioning of cooler and transformer is very important, thus a simple solution for connecting of transformers to the cooling equipment and the interconnection of transformers to the bank is significantly for a successful implementation. Flexibility could be granted by interconnection with cables and flexible tubes.
- **HV from 115 up to 400kV:** Based on optimized winding arrangement on the core and intelligent separation of windings the time and effort for reconnection could be reduced. The plug-in bushing supports the voltages up to 345kV, for the 400kV application an 400kV RIS bushing will be the connection to the utility network on the high voltage side.
- **LV from 12 up to 34kV:** A combination of a clever regulation principle and an optimized winding arrangement the time and effort for adopting the low voltage level to the generator specific voltage could be reduced.
- **Transport:** To guarantee a fast transport to the power plant a low weight and minimized size is key. With the application of state-of-the-art technologies, like NOMEX® high temperature

insulation materials in combination with thermally upgraded material and a high efficient cooling system this is achieved.

- **Safety:** Use of synthetic ester MIDEL[®] 7131 as insulating fluid, increases significantly fire safety. Synthetic esters have a much higher fire point (>316°C) and flash point (275°C) than mineral oil (fire:170°C, flash: 160°C) reducing fire risks [1, 7].
- **Insulating fluid stability:** Use of synthetic ester increases the stability and flexibility of operation. While Natural Esters rapidly oxidize (becoming solid) when in contact with oxygen, synthetic esters are highly stable (synthetic esters have higher oxidation stability performance as traditional mineral oil).
- **Low ambient temperature:** Synthetic esters have extremely good behavior at very low temperatures. While the pour point of natural esters is in the range of -21°C [8], MIDEL[®] 7131 synthetic ester has a pour point of -56°C [2, 7] making it adequate for utilization in regions with extreme low ambient temperatures.
- **Sustainability:** The application of MIDEL[®] 7131 show the focus on an environmentally safe solution. While after a 28-day test, biodegradation of synthetic ester reaches 89%, traditional mineral oil only has degraded 9.7%. Ester insulating fluids are fully biodegradable (according IEC 61039) [9].



Figure 9. Assembled Resilience GSU transformers

Info-hub and robust and secure IoT gateway with analytics

To go one step further the transformer is evolving into an info-hub. The Resilience GSUs is part of the Siemens Sensformer[®] family and through a smart and robust IoT gateway is securely able to transmit information to a cloud-based storage, analytics and visualization platform enabled to optimize the operation.

Key features:

- Easy connectivity, via ethernet or by provision of a secure GSM connection which is easy to set-up and does not require secondary IT infrastructure.
- Reduced vulnerability, by limiting actual physical measurements & avoiding unnecessary IT equipment at site (e.g. no local analytics). Designed with state-of-the-art security and encryption technologies such as ISO / IEC 27001, with end-to-end encryption and a device's private key for client authentication.[4]
- Enables real time asset management using a standard and open cloud solution for easy and quick insights to all connected assets and enhanced operational decisions.
- A platform for the future, enabling customer-centric cocreation of applications and offering value to all operations.
- A mobile app enhances asset management and offers a secure mobile connectivity to gain real-time data and overview about asset status, providing key KPIs and push messages in case of alarms.

- Preconfigured IoT gateway.
- The following measurement signals and data are available in the cloud platform and app:
Top oil temperature, oil level, winding current, GPS location and ambient temperature and humidity provided by could computed information based on the location provided by the GPS.

CONSIDERATIONS FOR INSTALLATION PROCEDURE

In January 2017, the design of Case I was successfully proofed at a trial run where it took only 30 hours within 3 working days to install and successfully put in to operation the 300 MVA transformer bank [3].

Storage of accessories

The challenges include the need for storage planning and optimized procedures. Conventionally the accessories are stored and delivered in wooden crates.

Containerization allows easy storage and fast deployment and allow for maximum flexibility of setup depending on the specific location where the transformers are needed.



Figure 10. Accessories storage in containers [6]

Installation procedure and storage for transformers – The conventional procedure

Conventionally large power transformers are transported disassembled (without any accessories or components) and without oil to the site. Upon arrival checks are conducted to assure integrity of seals and to make sure no moisture has entered the main tank. An insulation resistance measurement is performed with a test voltage of around 1kV. It is necessary to open the main tank via hand holes to assemble the bushings exposing the active part and high voltage insulation system to the environment [6].

During installation all accessories and components have to be assembled according the manufactures instructions, e.g. cooling system, bushings, conservator, pipework and motor drive for OLTC. All accessories need to be wired/ connected and control cabinet operation needs to be tested.

After completion of assembling, the transformer is prepared for the evacuation and oil filling. Depending on the transformer size, the evacuation time is around 48 hours. Then the transformer can be oil filled with consideration of filling rate, so that the vacuum does not exceed a specific value. Such a procedure varies with the transformer size and site conditions, but could take up to two weeks, or even longer for large units.

Before commissioning, various checks and tests are to be performed, e.g. visual-, leakage-, wiring and grounding checks as well as dielectric tests to verify insulation integrity has not be compromised.

To sum up, the whole installation, commissioning and testing procedure may take some working weeks (2-4 working weeks) for a large power transformer or even longer if the ambient conditions are not favourable (e.g. rain, snowfall).

New test approaches to achieve a very short installation time

The goal is to react rapidly in emergency cases, but also at planned outages for maintenance. Quick transportation, installation and commissioning are the key factors for a resiliency transformer.

Because the resilience transformers can be delivered to the site fully assembled, and even oil filled, the required site installation work is significant less compared to a conventional transformer. Bushing installation is greatly simplified when using plug-in bushing or cables and most importantly, as there is no need to open the tank in the field, the internal insulation does not get exposed to the environment assuring integrity of the unit.

A new site and commissioning tests procedure has been agreed between manufacturer and customer, to achieve the objectives for these transformers in this new application field.

Commissioning test procedures, considering the reduced risks a resiliency transformer is exposed to, have been simplified as follows:

- If resiliency transformers was stored for a long time:
 - Dissipation factor ($\tan\delta$).
 - TTR (Transformer Turns Ratio).
 - Insulation resistance measurement.
- If resiliency transformer was stored for a short time (~3 months):
 - TTR (Transformer Turns Ratio).

Optional: SFRA (Sweep Frequency Response Analysis) measurement if unit was moved.

Visual checks are always recommended, but they are normally not time consuming. The performance of the insulation fluid can be checked periodically at storage condition or when energized, because the units are always filled and ready for service. Special tests on cables can also be done periodically when the cables are at the storage location.

With these solutions, site test can be reduced to a minimum; the special design guarantees also a short installation assembly time.

Logistics and preparedness for emergencies and maintenance

Having a well developed deployment plan in place is one last but key aspect which should be given the sufficient importance. A well studied and documented plan will ensure highest response effectiveness. Users should develop a plan that includes:

- Step by step and fully documented procedures.
- Procedure variations might be needed for different substations. In case of an emergency the operator in charge shall have easy access to the applicable plan for each site.
- Continuous maintenance plan of resiliency transformer during storage to assure readiness for fast deployment.
- Transportation logistics and access roads (including upfront road surveys for each location).
- Logistics and equipment movement inside each substation and/or power plant.
- Manpower resources and installation equipment (cranes, forklifts, etc.).
- Space availability pre-evaluation for deployment of resiliency transformers (allowing space removal or scrapping of bypassed transformer).
- For each site, a connection plan including needed connection types and cable lengths.
- Environmental plan.

- Integration of protection and control signals of the resiliency transformer to the protection and control scheme of the substation.

CONCLUSION

State of the art solutions are currently available to address both step-down transformer as well as generator step-up transformer replacement or bypassing needs. A single resiliency transformer can be designed to be extremely flexible and be able to operate at a wide range of different conditions including different voltage levels or vector group connection requirements, as well as to be able to be installed using plug-in bushings or cables as alternatives in otherwise normally non-accessible places. Using state of the art design tools and materials a resiliency transformer can be made extremely compact and lightweight allowing manageable transportation, installation and commissioning. Use of environmentally friendly insulating fluids reduces risks during transport and operation.

Keeping purpose in mind, units can be designed so the total installation and commissioning time is reduced from several weeks, which is common on standard power transformers, to only a few days becoming so a valuable and proven option in the industry.

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