The pluggable transformer: flexibility for future grids

Fast installation, pretested components, reduced space requirements combined with highest system security using pluggable surge arresters

ABSTRACT

Transformers are becoming more and more space-saving, but they also need to be flexible, perhaps even mobile. All components must offer highest operational reliability, allowing quick installation as well as long-term flexibility.

This is the reason why separable connecting systems are the next step in connecting transformers. As they are making progress toward replacing conventional connection methods, the importance of an entire pluggable product portfolio is increasing. This portfolio includes pluggable surge arresters as they are a vital component for transformer safety. The dry-type pluggable surge arresters may highly reduce space requirements. A solution has now been developed for a rated voltage of up to 180 kV.

KEYWORDS

dry-type pluggable transformer, space-saving, surge arrester

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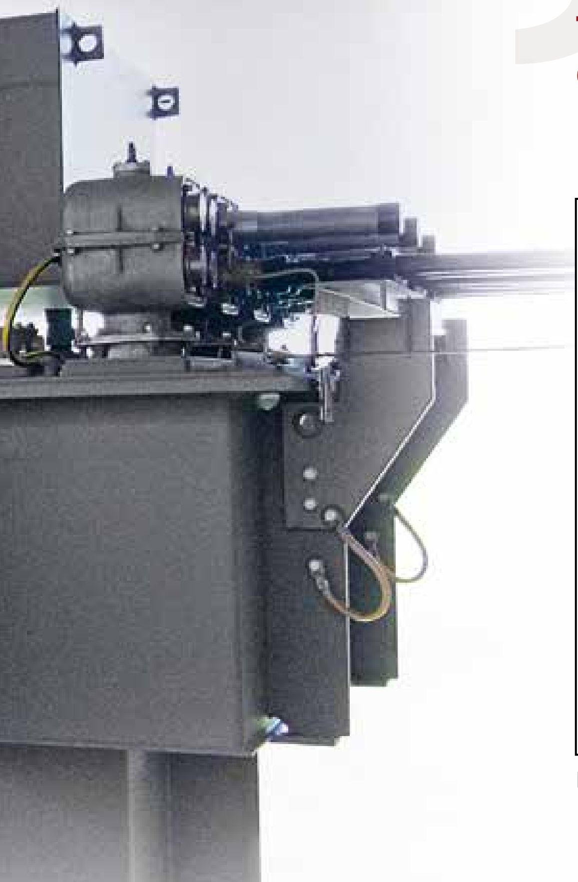

Dry-type separable connections make power transformers pluggable and thus flexible in their design, commissioning and use

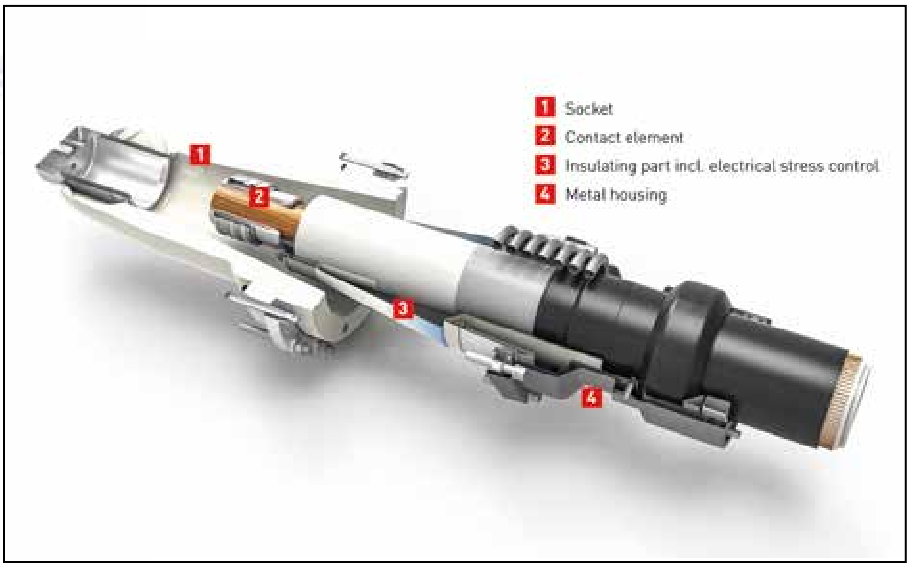

Figure 1. Separable connecting system, socket and connector

1. Introduction

Requirements on energy networks are continually changing dynamically and operators of power transformers are facing new challenges due to the reorganization of the load distribution. Substation size needs to be reduced and systems must be flexible, in special cases even mobile. Transformers in these applications must be quickly mounted and interchangeable, and they must offer outdoor and indoor use.

A separable connection system is used to connect a Cross-Linked Polyethylene (XLPE) or Ethylene Propylene Rubber (EPR) insulated cable to electrical equipment such as oil insulated transformers. Such a connecting system consists of two main parts – the socket and the connector, as shown in Figure 1. The separable connector is a male component that is plugged into the socket. It consists of the contact element, an insulating part including the electrical stress control, and a metallic housing.

The socket is fitted into the transformer, enclosing the equipment and ensuring its tightness. Installation of the socket offers the greatest advantage if installed during transformer manufacturing. The system offers the possibility to completely enclose and test the transformer at the manufacturing site, ship it on-site and connect it by a plug-in process. This not only makes handling easier, but it also clearly defines the point of responsibility and saves money. The dry-type plug-in cable termination also offers a more compact design for high-voltage transformers (>52 kV) compared to conventional systems. The length difference based on standard EN 50299-1 and EN 50299-2 between the conventional oil-filled and dry-type plug-in systems is exemplarily shown in Figure 2 for a voltage level of up to 245 kV.

The socket makes power transformers pluggable and thus flexible in their design, commissioning and use. For cable or overhead line connection as well as for pluggable surge arrester, the same socket and therefore the same interface can be used. The installation can be made in a very short time span, thanks to the plug-in principle with standardized connection interfaces. Fast maintenance and replacements at a later date are possible over the whole transformer lifetime. Different options are available for the socket: either connecting to an overhead line using a pluggable bushing, connecting an XLPE cable using a connector, or protecting the transformer with connection of a pluggable surge arrester; the possibilities are shown in Figure 3. For each component,

Requirements on energy networks are continually changing, forcing operators of power transformers to be able to quickly mount and interchange transformers in both outdoor and indoor applications

Compact dry-type plug-in cable connection reduces the installation length in the transformer tank by up to 50 %

one socket has to be installed. In case a socket is not used, a voltage-proof closing by a dummy plug can be installed. Thus later changes become possible.

Surge arresters are a main component in securing the key elements such as transformers in a high-voltage network. There are three types of overvoltage that can occur [1]. Lightning overvoltage can reach very high values endangering the system safety. Switching overvoltage occurs during switching procedures and consist mostly of heavily damped oscillations with frequencies of up to several kHz. Voltage swells may occur during load rejection or earth connection faults. The duration of voltage swells lies between 0.1 seconds and several hours. In general, the surge is of no danger to the network operation; however, it is important information when dimensioning the arrester. Lightning and switching overvoltage can be limited by surge arresters as it can be seen in Figure 4.

In order to minimize these risks damaging the key network elements, surge arresters are widely used. As there is a major change in replacing air insulated systems by cable systems, mainly in urban areas, compact surge arrester design becomes more important. For places with little space and areas with high levels of security, surge arresters should fulfil the same expectation when it comes to reliability, lifespan and securing aspects. This was why the compact, pluggable, encapsulated surge arresters have been developed, tested and are available for service up to a rated voltage of 180 kV.

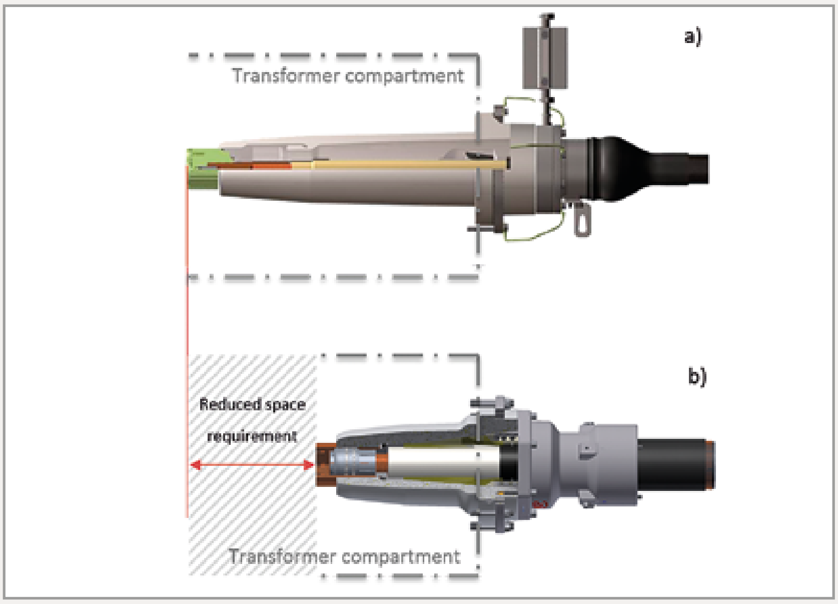

Figure 2. Compact dry-type plug-in cable connection reduces the installation length in the compartment by up to 50 %
(a. Oil-filled cable termination; b. Dry-type plug-in cable termination CONNEX)

2. Electrical stress control in different applications

The cable's electrical field is controlled by semi-conductive layers applied cylindrically under and over the cable's insulation. The outer semi-conductive layer has to be connected and stress control needs to be applied. In order to keep the system compact, a geometrical field control was chosen.

The field control element (earth deflector) is placed at ground potential opening the cylindrical cable geometry and decreasing the electrical field to a value controllable by the electrical strength of silicone

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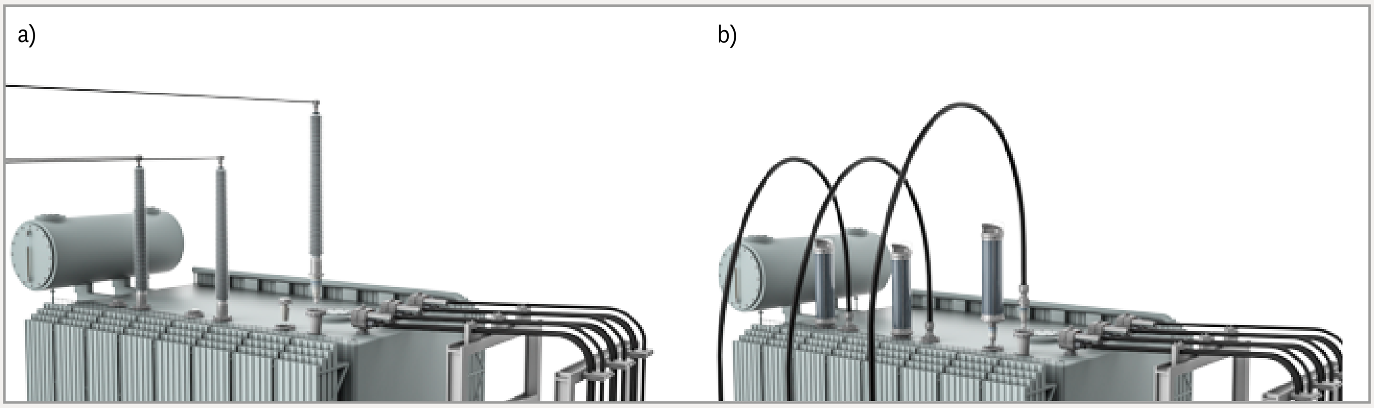

Figure 3. Left: Pluggable solution for connecting overhead lines to transformers with socket and pluggable bushing; optionally a socket with dummy plugs for later changes is installed. Right: Pluggable solution for connecting cables to transformers and ensuring operation security with pluggable surge arresters

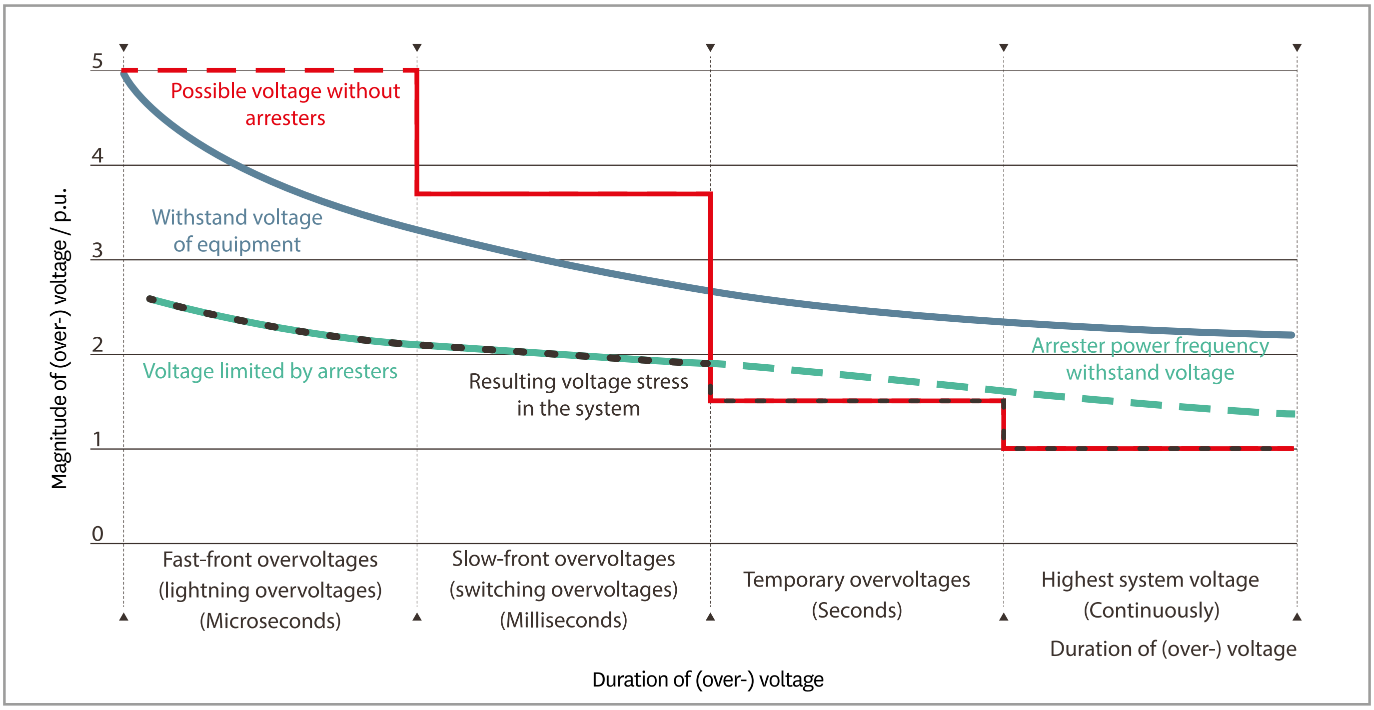

Figure 4. Schematic representation of the magnitude of voltages and overvoltages in a high-voltage electrical power system vs. duration of their appearance (1 p.u. = $\sqrt{2}\,U_s / \sqrt{3}$) [2]

as well as epoxy resin. The design of the stress control element is the core of the system. To shield the contact system on high-voltage (HV) side an HV field control element (HV deflector) is integrated to the socket.

Figure 5 shows a sample of the equipotential lines of a dry-type plug-in cable termination. This picture shows the electrically smooth transition from the small cable diameter to the equipment housing. The highest electrical load is along the earth deflector.

The integration of conventional overhead line connection bushings into the separable connecting sockets needs detailed coordination. The pluggable interface is adapted to the bushing as well as the capacitive field controlling of the bushing is adapted to the geometrical field controlling in the socket.

In a geometrical controlled set up, of course, the permittivity of the insulation oil is of note. Recent developments indicate using natural ester oil as a substitute to mineral oil is becoming common in fragile environmental applications. The use of ester is regaining relevance primarily due to its lower environmental impact as well as its high fire safety margin [3]. Nevertheless, the use of ester in

The use of ester in transformers places challenges when designing the connecting system

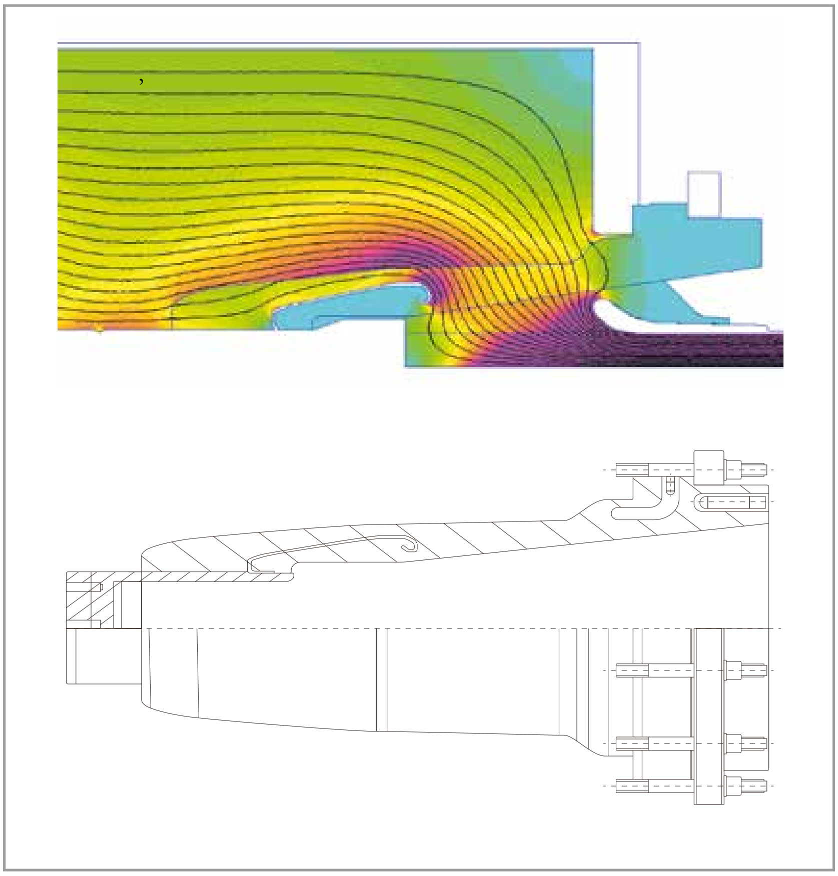

Figure 5. Top: Electric field at the HV-socket in transformer tank filled with mineral oil (rotationally symmetrical analysis). Bottom: Schematic view of the socket

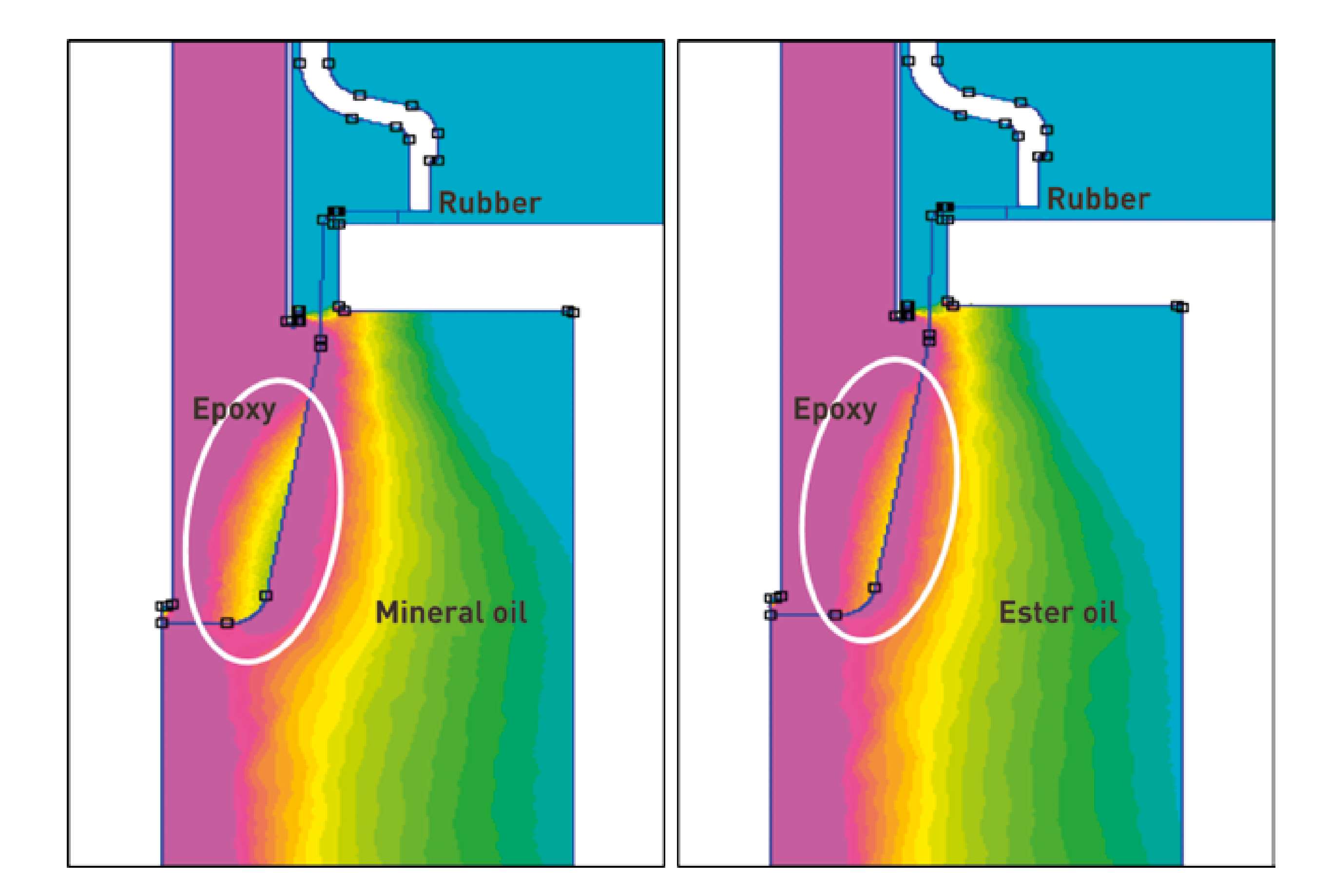

Figure 6. Comparison of electrical field in mineral oil (left) and ester oil (right) used as insulating material for a CONNEX multi-contact bushing

transformers places challenges when designing the connecting system.

While the permittivity of mineral oil lays at around 2.2 – 2.5, ester oil is located at 3.2 – 3.5. The higher permittivity of ester oil changes the electrical field distribution in the oil as well as in the bushing. By using ester oils instead of mineral oils, some areas of the epoxy resin insulation are higher stressed, while other areas are relieved (see Figure 6). Furthermore, the electrical breakdown probability in synthetic ester oil has a more skewed distribution. These two reasons call for further steps in transformer design avoiding any failures by, for example, a spike.

Setup and function of dry-type, pluggable surge arrester

The dry-type surge arrester consists of a contact element relevant for low resistance connection to the socket, utilizing contact lamellas. This type of contact allows a reliable interconnection for the operating idle current of the surge arrestor as well as the high impulse current in case the surge arrestor has to secure against overvoltage. The insulating part of the plug-in system between high voltage and earthed parts is made of silicone.

The main part, regarding the function of a surge arrestor, is made of specific metal oxide (MO) resistor tablets. These MO-tablets are used as a non-linear component with a very low leakage current during operation. The tablets are connected to the male part of the plug-in system and are insulated by a silicone body. This insulating body includes geometric field controlling elements. The head armature includes a bursting disk for pressure relief and a turnable head for the re-direction of the gas outlet, in the event of a failure according to IEC 60099-4:2014 [4]. The housing is made of glass-fibre reinforced resin and allows mechanical strength in case of a short circuit as well as protection of the silicon body against environmental conditions. For a better overview all components are shown in Figure 7. The silicone body itself is protected and touch-proof designed with a conductive layer. A special arrangement of the earthing path allows connecting monitoring devices or discharge counters if desired. The cable at the head armature can be disconnected for this reason.

The arresters main insulation is pure silicone; there is no insulation liquid or gas such as oil or SF6 included.

In contrast to the conventional high-voltage (>52 kV) or medium-voltage surge arresters, there is no applicable standard for pluggable high-voltage surge arresters. To allow the possibility to replace conventional surge arresters by the pluggable one, all relevant mechanical and electrical

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requirements of IEC 60099-4:2014 [4] are fulfilled and type tested. This approach offers new possibilities in network configurations, space requirements and transformer designs.

Surge arrester for transformer application

Transformers are one of the key components of HV grids, which need to be secured against overvoltage. Conventional surge arresters are positioned at an air-insulated environment parallel to conventional bushings.

As space saving is becoming more important, and there are safety issues to consider, air-insulated switchyards are increasingly being substituted by encapsulated systems with cable connectors. In the event of an overvoltage impulse which is triggered by lightning, for instance, the impulse wave will travel along the high-voltage line. The amplitude of that signal will mainly be influenced by the intensity of the lightning as well as the distance between the position of the lightning stroke and the location of the transformer. Furthermore, every change of the surge impedance of the line, e.g. between the air insulated line and the underground cable, will cause reflections and phase inversions of the traveling wave. This could lead to interferences, causing increase in the amplitude. This wave, travelling along the cable conductor of a cable system, could hit into a transformer, causing damage if the insulating level of the transformer is below the amplitude of that wave. For example, a wave travelling at 800 kV/µs along a line where a surge arrester with a residual voltage of 800 kV is installed can lead to 16 00 kV at the transformer connection which is 300 m away.

One possibility of reducing risk is achieved by adding a surge arrester at the connecting point between the air-insulated line to the underground cable systems. This is a mandatory position to protect the underground cable line and a preferred position to limit the amplitude of the traveling wave in the cable line since the mismatch of the cable impedance to the transformers connections impedance usually doubles the amplitude of the incoming traveling wave.

This leads to additional effort in calculating the network and the specific surge arrester due to additional influences by cable impedance, cable length, transformer impedance, as well as external sources. The optimum would be to position a surge arrester directly at the transformer, possibly as near as possible to the transformer core. The pluggable solution offers this functionality: an additional socket is to be integrated in the transformer body and connected to the transformer core. The surge arrester is being assembled by a plug-in process and positioned directly at the so-called "hot spot".

Optimal protection of the transformer would be achieved by positioning a surge arrester directly at the transformer, possibly as near as possible to the transformer core

Technical data

Surge arresters are selected according to different aspects such as:

- highest system voltage U_s
- handling of neutral point (solid earth, Petersen coil, etc.)
- voltage swells and overvoltage
- nominal discharge current
- energy absorption
- safety factors

These factors lead to electrical definitions of the surge arrester suitable for the network.

The resulting residual voltages for different discharge currents are usually given by the manufacturer of the MO resistor stack. The typical values for the pluggable HV-CONNEX surge arresters are presented in Table 1.

Determination of Temporary Overvoltage Time Characteristic (TOV)

Due to networks setup and external influences, voltage swell as well as overvoltage might be unavoidable. As a result, thermal stress on the metal oxide resistor tablets may appear. A temporary overvoltage lays in the frequency range of 10 Hz < f < 500 Hz and has a typical duration higher than 0.02 s [6]. The maximum allowable limits regarding

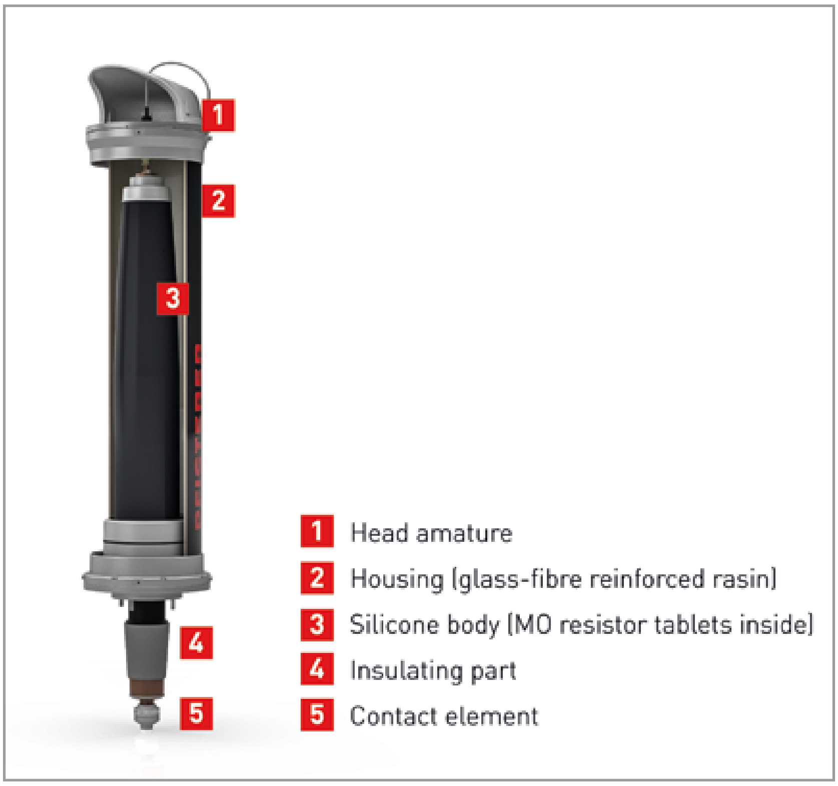

Figure 7. Main components of the HV-CONNEX pluggable surge arrester

Table 1. Temporary overvoltage capability and resulting residual voltages [5]

Connector Size	U_r	U_c	TOV capability		Max. residual voltages U_{res} with current wave				
			$U_{TOV(1s)}$	$U_{TOV(10s)}$	1/<20 µs	8/20 µs			30/60 µs
					10 kA	5 kA	10 kA	20 kA	500 A
	[kV]	[kV]	[kV]	[kV]	[kV]	[kV]	[kV]	[kV]	[kV]
Size 4	42.5	34.0	45.5	43.8	124.0	106.0	113.3	129.0	89.0
	45.0	36.0	48.2	46.4	132.0	112.0	119.9	136.0	94.0
	52.5	42.0	56.2	54.1	154.0	131.0	139.9	159.0	109.0
	61.3	49.0	65.6	63.1	179.0	152.0	163.2	185.0	127.0
	65.0	52.0	69.6	67.0	190.0	162.0	173.2	196.0	135.0
	72.5	58.0	77.6	74.7	212.0	180.0	193.2	219.0	151.0
Size 5 - S	78	62	86,6	81,1	215	183	200	220	159
	84	67	93,2	87,4	231	197	215	237	171
	90	72	99,9	93,6	247	211	230	254	184
	96	77	106,6	99,8	264	225	246	270	196
	108	86	119,9	112,3	298	254	277	305	221
	115	92	127,7	119,6	316	270	295	324	235
Size 6	120	96	135,6	126	305	270	279	305	233
	132	106	149,2	138,6	336	297	307	335	256
	144	115	162,7	151,2	366	324	335	366	279
	156	125	176,3	163,8	396	350	362	395	302
	168	134	189,8	176,4	427	377	390	426	325
	180	144	203,4	189,0	457	404	418	456	349

The pluggable system offers the possibility to completely enclose and test the transformer at the manufacturing site, ship it on-site and connect it by a plug-in process

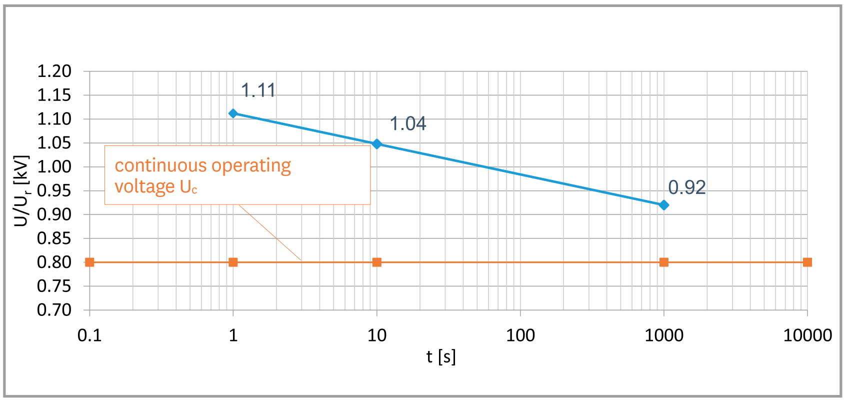

Figure 8. Power frequency voltage versus time characteristic (TOV) (initial temperature +60°C) [5]

time and overvoltage can be determined according to the so-called TOV chart (Figure 8). This information is crucial for network operators to know the allowed limits for safe network operation. This measurement is therefore obligatory to pass a type test according to IEC 60099-4:2014 [4]. The measurement is performed on a thermal equivalent consisting of a single tablet in its original configuration. This test configuration is thermally insulated at the top and the bottom to guarantee a thermal behaviour, which is equivalent to or worse than the original configuration in the surge arrester.

In operation an overvoltage can occur in the state of a maximum nominal thermal stress. Therefore, pre-stress is part of the actual TOV measurement. The samples are preheated to 60 °C. After preheating, two long duration current impulses are

Table 2. Advantages of pluggable components and pluggable transformer system

	Advantages of the pluggable principle to conventional systems
Socket	Reduced space requirement inside transformer; always the same interface for bushing, cable connection, surge arrester and testing equipment; no oil handling onside
Cable connector	Fast plug in process; Maintenance or later changes possible without oil handling
Bushing	Reduced space requirements compared to air insulated bushing
Surge arrester	Reduced space requirement; better protection due to position directly at the transformer

applied to reach the required energy according to IEC 60099-4. The time interval between the two impulses has to be between 50 s and 60 s. Within less than 0.1 s after the application of the second impulse, the temporary power-frequency overvoltage U_{TOV} has to be applied for the duration t_{TOV}. Then the elevated continuous operating voltage according to IEC 60099-4 has to be applied to prove the thermal stability. Power dissipation of the thermal equivalent must decrease or stay stable during application.

This measurement is to be repeated with several pairs of U_{TOV} and t_{TOV}. As these values should be as high as possible, the aim is to get the values as near as possible to the physical limits without thermal runaway.

To determine the overall power dissipation of the arrester during pre-stress, the energy level is monitored and calculated. Reference voltage U_{ref} is measured before and after each measurement block to ensure there is no physical damage of thermal equivalent. With several measurement pairs of U_{TOV} and t_{TOV} the chart in Fig. 8 is determined.

Table 2 outlines the main advantages of the pluggable principle in comparison to conventional systems.

Conclusion

The pluggable system is well known and has been used for many years of operation service in GIS and transformer applications. Nonetheless, the usage is limited if there is a lack of components required for all operation scenarios, such as voltage-proof enclosure, test equipment, connection to an overhead line and pluggable joints. Furthermore, the next evolutionary step was the implementation of surge protection into the pluggable portfolio.

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