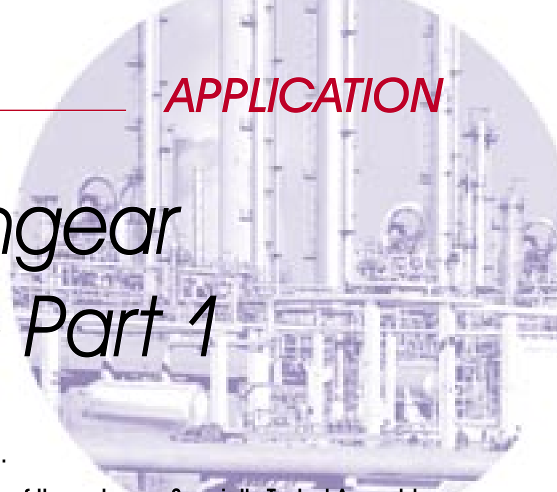

Safety of low voltage switchgear assemblies in South Africa - Part 1

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This article is Part 1 of a two part article. Part 2 will be published in the next issue of ENERGIZE.

A technical analysis was undertaken to investigate the safety implications of the introduction of the category Specially Tested Assembly (STA) into the South African standard SANS 1473-1:2003. The testing requirements specified for a Specially Tested Assembly (STA) are compared to the testing requirements specified for a Type-Tested Assembly (TTA), tested in accordance with standard IEC 60439-1:1999. The technical inadequacies and the potential safety risks associated with an assembly that is certified as a STA are exposed, and remedial measures proposed.

New manufacturing methods developed in industry in recent years have brought a notion of industrial dependability to light. This concept, which covers two different aspects, safety of persons and equipment, and availability of electrical power, shows when it is applied to complex processes, the critical points whose operation must be thoroughly mastered. The electrical switchgear and controlgear assembly is one of these critical points. Electrical switchgear is increasingly technical and requires a certain number of basic studies in order to master, in the design phase, the operating conditions of its components in a specific environment.

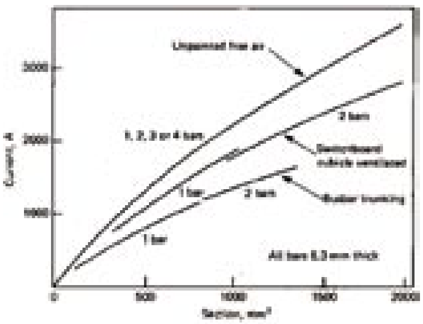

Fig. 1

Many South African switchgear and controlgear assembly manufacturers have historically been manufacturing low-voltage assemblies more by 'rule-of thumb' than by a technically calculated and tested manner. As unsafe conditions became more apparent, the South African Bureau of Standards decided to adopt the standard IEC 60439-1:1999 (Low Voltage Switchgear and Controlgear Assemblies: Part 1: Type-Tested and Partially Type-Tested Assemblies) [1] in 2001, as the official standard to which all low-voltage assemblies with a short-circuit withstand greater than 10 kA shall conform to. The South African Bureau of Standards (SABS) is a voting member of the International Electrotechnical Commission (IEC). SABS official policy is to adopt IEC standards either unchanged, or where deemed necessary, to adapt them to suite South African conditions by the introduction of a front-end standard detailing any deviations from the original IEC standard. The latest South African National Standard, SANS 1473-1:2003 (Low Voltage Switchgear and Controlgear Assemblies: Part 1: Type-Tested, Partially Type-Tested and Specially Tested Assemblies with rated short-circuit withstand strength above 10 kA) [2] has been included as a front-end specification to standard IEC 60439-1:1999 [1], which is renumbered as SANS 60439-1:1999. With this standard comes the introduction of the Specially Tested Assembly (STA) in addition to the Type-Tested (TTA) and Partially Type-Tested Assemblies (PTTA) specified in standard IEC 60439-1:1999[1]. Local standard SANS 1473-1:2003[2] is referenced in standard SANS 10142-1:2003 [3] and is therefore a compulsory safety standard according to the Occupational Health and Safety Act, 1993 (Act No. 85 of 1993) [4].

A precise knowledge of standards is the fundamental premise for a correct approach to the problems of the electrical plants, which shall be designed in order to guarantee that an acceptable safety level is achieved and maintained. The applicable standards establish the criteria for achieving the qualified status of the product being tested. This is done by establishing safe guidelines within which the product must operate. The guidelines are fundamentally physical limits determined by the operational voltage, rated continuous current and short-circuit current. The concerns for voltage are with regards to the suitability of the insulation material and its capability to withstand voltage gradients and potential differences. The concern for continuous current is with regards to the maximum operating temperature of the assembly switchgear components, while the switchgear assembly must be able to withstand the effects of the prospective short-circuit current.

A Specially Tested Assembly (STA), tested in accordance with standard SANS 1473-1:2003 [2], will at most, only require three of the seven type-tests specified in standard IEC 60439-1:1999 [1].

The exclusion of a number of the type-tests specified in standard IEC 60439-1:1999 [1], warrants closer inspection to determine if a specially tested assembly fulfills the safety and performance requirements of the IEC 60439-1:1999 [1] standard, particularly since it has been included for use in power systems with short-circuits of magnitude greater than 10 kA.

This paper will focus primarily on the major findings with regards to the temperature rise and short-circuit type tests, specified for the category STA in standard SANS 1473-1:2003 [2]. A brief discussion will be presented on the safety risks posed by the exclusion/modification of the other five type-tests specified for category TTA.

Type-tests and the categories of assembly specified in standard IEC 60439-1:1999 and SANS 1473-1:2003

Standard IEC 60439-1:1999 [1] provides the following definition for type-tests: 'Type-tests are intended to verify compliance with the requirements laid down in this standard for a given type of assembly. Type tests are carried out on a sample of such an assembly or such parts of assemblies manufactured to the same or similar design. They shall be carried out on the initiative of the manufacturer' [1] Type-tests, therefore, allow for actual

Fig. 2

verification of designs through a series of tests, and do not rely on subjective engineering assessments or calculations. Table 1 shows the various type-tests specified for certification as a TTA, PTTA or a STA in accordance with standards IEC 60439-1:1999 [1] and SANS 1473-1:2003 [2].

Standard IEC 60439-1:1999 [1] distinguishes between two categories of switchgear assemblies:

- TTA (Type-tested assemblies)
- PTTA (Partially type-tested assemblies)

There are no other classifications of assemblies in standard IEC 60439-1:1999[1] and the standard does not provide for assemblies that have fulfilled only some of the requirements (type tests).

Standard SANS 1473-1:2003 [2] distinguishes between three categories of switchgear assemblies:

- TTA (Type-tested assemblies)
- PTTA (Partially Type-tested assemblies)
- STA (Specially tested assemblies)

The specially tested assembly (STA) is a unique category of assembly only found in the relevant South African standard i.e. SANS 1473-1:2003 [2], and nowhere else in the world. It is common for some countries to amend the IEC standards to suite specific requirements, but perhaps not as radical as SANS 1473-1:2003.

Technical study of the type-tests included in both standard IEC 60439-1:1999 and SANS 1473-1:2003

The suitability of the temperature rise, short-circuit and dielectric tests included for qualification as a specially tested assembly (STA), specified in standard SANS 1473-1:2003 [2] are investigated.

The temperature rise test

The purpose of the temperature rise type-test is to provide a method of verification of the operating current of an assembly. The design of low-voltage switchgear and controlgear assemblies has progressed from the basic 'open-type' assembly of a few decades ago to the modern compact units in use today. As the packing density, rated current, form of internal separation and degree of protection of the assembly increases, the verification of the temperature-rise within the enclosures becomes an issue of ever increasing importance. Excessive temperatures within assemblies are potentially damaging to electrical and electronic devices, and can result in premature ageing of components and insulation which can ultimately lead to catastrophic failure. Temperature rise verification by calculation alone is an involved and complex subject since components operate and thermally interact with one another at different temperatures for a given load. Standard IEC 60439-1:1999 [1], therefore, specifies that actual temperature rise tests (type-tests) are undertaken on the assemblies, thus eliminating any possible errors that can result from poor engineering judgments or incorrect calculations.

There are many factors that can directly influence the current carrying capacity of a busbar e.g. skin effect, proximity effect, installation in enclosures, emissivity of the busbar surface, profile selection and arrangement. It follows that the design of busbars must attempt to select the appropriate profile and arrangement so as to minimize the factors that tend to decrease the current carrying capacity, while maintaining a large, unrestricted heat-emitting surface area. The current carrying capacity is further reduced when the bars are installed in enclosures, which is applicable to most modern applications, with IP ratings of IP4X not uncommon. With reference to Table 1, Standard IEC 60439-1:1999 [1] stipulates that the temperature rise test shall normally be carried out at the values of rated current in accordance with Section 8.2.1.3, with the apparatus of the assembly installed (unless the main and auxiliary circuits have comparatively low-rated currents where heating resistors may be used to simulate the heat loss) [1]. Standard SANS 1473-1:2003 [2] exclusively employs the use of heating resistors for the verification of the temperature rise of the busbars for a STA (assuming that the temperature rise test is actually required) regardless of the magnitude of the rated current. This can result in a practical problem of finding the correct declaration of the power loss for a STA, since the various combinations of switchgear components are not required to be tested in the assembly, as it is tested in the unpopulated state. The actual temperature rise test carried out on

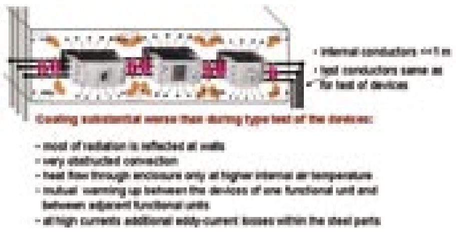

Fig. 3

an assembly being verified as a STA will be of very little use since verification will be done in accordance with Table 2 of IEC 60439-1:1999 [1]. This will only be the verification of the temperature rise limit of accessible external enclosures and covers of the busbar chamber of an unpopulated assembly.

It will later be shown that it is necessary to test the various combinations of switchgear components that are installed in an assembly due to the interaction and varied temperature rises of components under differing installation methods.

Standard SANS 1473-1:2003 [2] provides a restriction of predetermined current densities, for various operating currents, above which the main and/or distribution copper busbars shall be subjected to a temperature rise test. The maximum current density stipulated in standard SANS 1473-1:2003 [2] is as follows:

- 2 A/mm² for a busbar rating up to 1600 A [2].
- 1,6 A/mm² for a busbar rating above 1600 A [2].

The above current density limits are applicable to copper busbars, which is the most common material currently used, and temperature rise testing is required for busbars manufactured from any other material. Should the busbar current density not exceed the above values, standard SANS 1473-1:2003 [2] does not require temperature rise tests.

This is in direct contradiction with the requirements of standard IEC 60439-1:1999, which specifies temperature rise testing for all

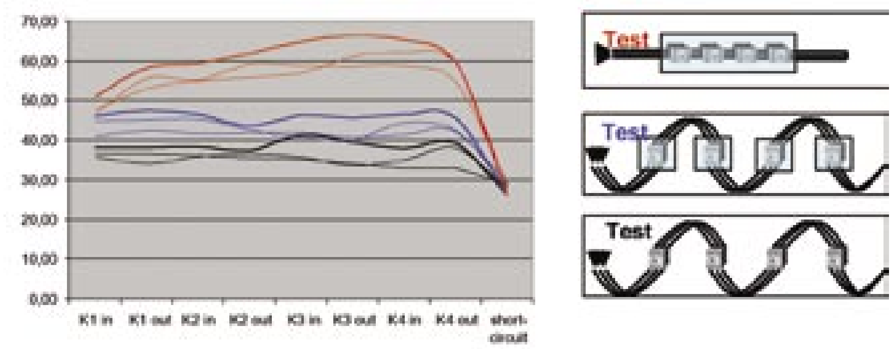

Fig. 4

assemblies [1]. The busbar current densities stipulated in standard SANS 1473-1:2003 are based on well established values, but are only applicable to certain types of installation set-ups and are essentially only guide values [2]. Bearing this in mind, it can be reasonably assumed that certain main and distribution busbars will be correctly selected according to the current density limitations specified in Standard SANS 1473-1:2003 [2], but will actually be operating outside the recommended operating temperature range of the busbars. The assumption in SANS 1473-1:2003 that the prescribed current density limits will be suitable for all cases is fundamentally flawed as the following test data shows [2]. Fig. 1 is taken from the Copper Development Association publication "Copper for Busbars" [5], and represents the maximum permissible current allowed per cross sectional area, for a maximum busbar temperature of 90°C, for busbars installed in various enclosures. Busbars installed in the majority of assemblies will be categorized somewhere between the 'Switchboard cubicle ventilated' and the 'Busbar trunking' trends shown in Fig. 1. Tables 2, 3 and 4 show the interpolated values from Fig. 1, and the figures obtained for busbar current densities for busbars installed in ventilated switchboards and busbar trunking, are not in agreement with the current density limits stipulated in SANS 1473-1:2003 [2]. Should the ventilated busbar be enclosed, a further de-rating of approximately 20% may be required.

Table 5 shows results obtained at a local testing authority for various busbar configurations. The busbars of the various test specimens were installed in assemblies of differing dimensions and busbar arrangements, and the results obtained differ due to the factors mentioned previously. The results obtained unquestionably show that the current densities stipulated in SANS 1473-1:2003 [2] for currents above 1600 A will be exceeded, resulting in busbar temperatures higher than the 90°C limit recommended by the Copper Development Association [5].

Even with a good design, it is evident from the data presented that the current density tends towards 1 A/mm² for currents above 3000 A.

The current density limits that are specified in SANS 1473-1:2003 [2] should only be used as a basic guide to estimate the likely size of busbar, and the standard should categorically state that the final size be determined by testing. Temperature rise tests cannot be avoided if confirmation of an assembly's performance is required.

Temperature rise of switchgear and controlgear components installed within assemblies

Each component/device within an assembly has a specific function to serve. Accordingly, a standard is written for each type of equipment. For example, where circuit interruption is the function of the device, a standard prescribes a qualification schedule that ensures that the product will interrupt current without creating an environment that

No.	Characteristics	Subclauses IEC 60439-1	TTA	PTTA	Subclauses SANS 1473-1 for STA	STA	SANS 1473-1 for STA in accordance with IEC 60439-1
1	Temperature-rise limits	8.2.1	Verification of the temperature-rise limits by test (type-test)	Verification of the temperature-rise limits by test or exploration	4.4.1	Verification of the temperature-rise limits by test (type-test) - Only required for busbar current density values exceeding those specified in 4.4.1.1, or for any busbar material other than copper	NO
2	Dielectric properties	8.2.2	Verification of the dielectric properties by test (type-test)	Verification of the dielectric properties by test according to 8.2.2 or 8.3.2, or veerification of insulation resistance according to 8.3.4	4.4.2	Verification of the dielectric properties by test (type-test) - Only required in the case of an unpopulated assembly	NO
3	Short-circuit withstand strength	8.2.3	Verification of the short-circuit withstand strength by test (type-test)	Verification of the short-circuit withstand strength by test or extrapolation from similar type-tested arrangements	4.4.3	Verification of the short-circuit withstand strength by test (type-test) - Only required in the case of an unpopulated assembly	NO
4	Effectiveness of the protective circuit	8.2.4		Nil			NO
	Effective connection between the exposed conductive parts of an assembly and the protective circuit	8.2.4.1	Verification of the effective connection between the exposed conductive parts of the assembly and the protective circuit by inspection or by resistive measurement (type-test)	Verification of the effective connection between the exposed conductive parts of the assembly and the protective circuit by inspection or by resistive measurement			
	Short-circuit withstand strength of the protective circuit	8.2.4.2	Verification of the short-circuit withstand strength of the protective circuit by test (type-test)	Verification of the short-circuit withstand strength of the protective circuit by test or by appropriate design and arrangement of the protective conductor (see 7.4.3.1.1: last paragraph)			
5	Clearance and creepage distances	8.2.5	Verification clearances and creepage distances (type-test)	Verification clearances and creepage distances	Nil		NO
6	Mechanical operation	8.2.6	Verification of the mechanical operation (type-test)	Verification of the mechanical operation	Nil		NO
7	Degree of protection	8.2.7	Verification of the degree of protection (type-test)	Verification of the degree of protection	Nil		NO

Table 1: Tests to be performed for assembly verification as a TTA and PTTA in accordance with IEC 60439-1, and a STA in accordance with SANS 1473-1

will compromise safety. The relevant product standards applicable to South Africa is the IEC 60947 series for low voltage switchgear and controlgear.

When components are installed in an assembly, the surrounding conditions differ considerably from the component type tests specified in IEC 60947-1 [6]. As a result, the specified rated currents of the components are not applicable when they are installed in a low voltage assembly, since the components are 'bench-tested' in free-air. It is of utmost importance for assembly designers to have a thorough knowledge of the operating temperatures within the assembly and apply the correct derating factors to the devices.

Cross section (mm²)	Busbar current (A) Free air	Current density (A/mm²) Free air
500	1333	2,7
1000	2266	2,3
1500	2933	2,0
2000	3666	1,8

Table 2: Busbar current densities for busbars installed in free air

Fig. 2 details the test conditions applicable for the testing of a device in accordance with IEC 60947-1 [6]. Heat is easily dissipated away from the device by natural convection and thermal radiation into the surrounding air, as well as by conduction through the test conductors. When these components are installed inside an assembly, the enclosure surrounding the equipment, combined with complex interactions between equipment and the surroundings, significantly impair the cooling of the devices as detailed in Fig. 3.

It is for this very reason that standard IEC 60439-1:1999 specifies a temperature rise test for the complete assembly, including all components, albeit that the components have previously been type-tested to the relevant product standard [1].

Actual tests undertaken by Dr. Drebenstedt of Siemens, Germany, show the temperature rise for a number of devices installed in conditions varying for fee-air (Fig. 2 and 3) to all devices enclosed, as shown in Fig. 4. The tests were conducted with contactors, identified as K1 to K4, and rated 12 A (AC3)/20 A (AC1) at a test current of 20 A. The devices were placed on a table in a row and interconnected with 2,5 mm² copper conductors. Temperatures of the devices were measured for three separate tests that were conducted as follows:

- Test 1: Devices in free air, distance 40 cm apart, conductor length 1,2 m between devices
- Test 2: Devices in separate boxes, distance 40 cm, conductor length 1,2 m between devices
- Test 3: Devices in one box, distance 10 cm, conductor length 5 cm between devices

If one compares the actual temperature rise from Test 1 to that of Test 3, the temperature rise is vastly different due to the enclosure, which is representative of anassembly cubicle.

The interaction of the various functional units, incomers and busbars, all contribute to the overall temperature rise of an assembly and, therefore, cannot be viewed in isolation, but rather as a complete system. Calculation of the effective power loss should be made for the complete assembly i.e. the sum of the power losses (heat) produced by the installed equipment including busbars and power conductors. Specially Tested Assemblies, tested in accordance with standard SANS 1473-1:2003, completely ignore this important fact, as only the busbars require temperature rise verification, even though the majority of assembly failures occur on the functional units and incomers.

Cross section (mm²)	Busbar current (A) Ventilated switchboard	Current density (A / mm²) Ventilated switchboard
500	1000	2,0
1000	1800	1,8
1500	2400	1,6
2000	2800	1,4

Table 3: Busbar current densities for busbars installed in a ventilated switchboard

In the case of components installed in an assembly, it has been shown that the type tests performed for temperature rise verification in accordance with IEC 60439-1:1999 and IEC 60947-1, are not equivalent. The exclusive use of heating resistors to simulate actual running conditions of an assembly also has its shortfall (as used in the temperature rise verification for a STA, in accordance with standard SANS 1473-1:2003). If functional unit temperature rise tests are not done, it becomes very difficult to determine the actual functional unit losses within the assembly, in relation to the declared heating resistance value.

Cross section (mm²)	Busbar current (A) Busbar trunking	Current density (A/mm²) Busbar trunking
500	800	1,6
1000	1333	1,333
1500	N/A	N/A
2000	N/A	N/A

Table 4: Busbar current densities for busbars installed in busbar trunking

The short-circuit withstand test

The principle concern over high fault currents in the busbar chamber is the ability of the busbar structure and supports to withstand the magnetic forces accompanying the current peaks. Withstanding these stresses is essential in avoiding the potential danger i.e. flying of broken components, arc generation and propagation outside the switchboard. These forces are a function of the square of the current (peak short-circuit current value) and the linear distance between the parallel current paths. It is this current peak that generally occurs in the first cycle of a fault which generate the highest stresses on the busbar. The closer the current paths are, the stronger the accumulative force is. This force will cause the conductors to be pulled together if the current in both paths is flowing in the same direction. The force will push conductors apart for currents flowing in opposite directions.

Busbars are also stressed thermally under short-circuit conditions and it is, therefore, necessary to check that the conductors are suitably sized for the short-circuit current not only mechanically, but also thermally.

IEC 60439-1:1999 states that "Assemblies shall be constructed as to be capable of withstanding the thermal and dynamic stresses resulting from short-circuit currents up to the rated values" [1]. Essentially, the short-circuit tests that are carried out on the main and distribution busbars for certification as a STA are in accordance with IEC 60439-1:1999. The short-circuit tests are carried out by using bolted connections at the ends of the main or secondary busbars.

Busbar configuration (per phase)	Test current (A)	Busbar current density (A/mm²)	Busbar temperature rise (K)	Ambient temperature (˚C)	Busbar surface temperature (˚C)	Busbar chamber air temperature rise (K)
1 x 125 mmx 16 mm	3000	1,5	76	27	103	44
2 x 100 mm x 10 mm	2500	1,25	52	25	77	31
2 x 120 mm x 10 mm	3000	1,25	40	30	70	-
1 x 100 mm x 16 mm	2200	1,375	64	27	91	32
1 x 100 mm x 16 mm	2000	1,25	69	26	95	48
1 x 120 mm x 12,5 mm	2000	1,333	65	17	82	49
2 x 80 mm x 10 mm	1700	1,063	82	29	111	38

Table 5: Temperature rise type test data for busbars installed in various enclosures for currents exceeding 1600 A

Short-circuit tests on functional units

As shown in Table 1, the verification of the short-circuit withstand strength by test (type-test) is only required in the case of an unpopulated assembly in accordance with SANS 1473-1:2003, for the category of Specially Tested Assembly [2]. In the practical situation when a functional unit develops a short-circuit, the short-circuit protective device is required to clear this fault and this must be verified for a number of reasons:

- Every MCCB provides a pressure increase in the functional unit cubicle due to the exhausting of hot gas under a fault condition. The increase in pressure may cause the dislodging of devices within the cubicle and may cause doors to fly open or dislodge.
- Should the short-circuit protective device in the cubicle fail, the upstream incomer circuit breaker will be required to clear the fault either at a much slower time than what the functional unit protective device would have operated at, or not at all if the fault is below the incomer circuit breakers minimum fault pick-up level.
- The switching off of a circuit breaker should not initiate an internal arc in the cubicle as a result of the hot gasses.
- The circuit breaker should remain in place and be re-usable after a fault has occurred.

As previously highlighted, the majority of faults occur in the functional units and incomers. SANS 1473-1:2003 does not perform short circuit tests on the functional units (break test under power frequency) to verify the above concerns, which may result in a safety hazard to those exposed to a Specially Tested Assembly. This is a true test of safety as it is carried out with all the doors of the assembly closed, and confirms that under short-circuit, components do not dislodge and doors fly-off, with the possibility of seriously injuring personnel.

Verification of Dielectric Properties test

Commonly referred to as 'flash tests', the dielectric type-test is used to verify the dielectric properties of insulating materials within the assembly. The test voltage is applied between all live parts and interconnected exposed conductive parts (frames), as well as between each pole and all the other connected poles. Two fundamental properties of insulating materials are insulation resistance and dielectric strength. These are two entirely different and distinct properties. Insulation resistance is the resistance to current leakage through the insulation materials. Insulation resistance can be measured with a 'megger' without damaging the insulation. Dielectric strength is the ability of an insulator to withstand potential difference. It is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress. A dielectric test measures the withstand capability of an insulator. Insulation resistance tests measures the resistance of an insulator or insulation during a test. SANS 10142-1:2003 [3] specifies insulation resistance tests in section 8.7.8 of the standard, and these tests must not be confused with the dielectric properties test required for certification as a TTA. IEC 60439-1:1999 requires that each circuit of the assembly be capable of withstanding the power-frequency withstand voltage and impulse withstand voltage, for values specified in the standard [1].

Tests in accordance with IEC 60439-1:1999 (section 8.2.2) require that main and auxiliary circuits undergo a type-test to verify the dielectric properties of the complete assembly, by application of a specified test voltages between all live parts and the interconnected exposed conductive parts of the assembly.

According to SANS 1473-1:2003 [2], for an assembly to qualify as a STA, it must be in the unpopulated state, and this is not in accordance with the IEC standard [1]. Ignoring this test could, therefore, result in faulty insulation only being exposed when the switchgear assembly is placed in service and subjected to a voltage transient of sufficient magnitude to cause insulation breakdown of the insulating material. Depending on the construction of the switchboard, the breakdown of dielectric material may further develop into an arc within the switchboard. The results of such arcs are often devastating. Unlike a bolted fault where the energy is dissipated in the equipment, an arc fault results in the energy being dissipated into the surrounding environment, in the form of heat, ionized materials and poisonous gasses. The heat energy and intense light at the point of the arc is termed 'arc flash'. The air surrounding the arc is instantly heated and conductors are vaporized causing a pressure wave called an 'arc-blast'. "Exposure to an arc flash frequently results in a variety of serious injuries and in some cases death. Plant equipment can be destroyed resulting in downtime and expensive replacement or repair of equipment may be required. Nearby flammable materials may be ignited resulting in secondary fires that can destroy entire facilities. An arc flash not only includes intense heat and light but also loud sounds and blast pressures. The arc blast often causes equipment to literally explode ejecting parts, insulating materials, and supporting structures with life threatening force. Heated air and vaporized conducting materials surrounding the arc expand rapidly causing effects comparable to an explosive charge. As conductors vaporize they may project molten particles" [7]. An interesting statistic from the USA is that an estimated 75% to 80% of all serious electrical injuries are related to electrical arcs [8].

To be continued in the next issue of ENERGIZE.

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