

MEDIUM-VOLTAGE DISTRIBUTION SWITCHGEAR TECHNOLOGIES – DEVELOPMENTS AND SOLUTIONS FOR END-USERS

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Synopsis

This paper aims to present an argument for the use of medium voltage (MV) distribution switchgear – and in particular secondary switchgear (e.g. ring main units) – having alternative insulating/interrupting technologies to oil, based on safety, environmental and economic considerations. The paper also addresses recommendations relating to the management of existing oil-filled switchgear.

1. Introduction

The use of medium voltage oil-filled switchgear is widespread in electricity networks in the South African Electricity Distribution Industry (EDI). Although generally reliable, most switchgear installed before 1970 has reached the end of its design life and may be unsafe. Oil-filled switchgear, especially that which is either un-maintained, dependent manually-operated (DMO) and/or overstressed, can fail with catastrophic results for the operator, equipment, property and general public. The likelihood of failure increases with the following factors: the age of the switchgear, inadequate maintenance, modifications not done in accordance with the manufacturer's recommendations and operation by inadequately trained operators. These factors are exacerbated by skilled and experienced staff leaving the EDI, either through natural attrition or migration to more lucrative positions in private industry.

Users have a duty, in terms of safety legislation (most notably the Occupational Health and Safety Act 85 of 1993) to their employees and the public to provide an acceptably safe environment and to take reasonable measures to mitigate against possible dangers. Since the risk described above may involve severe injury and/or death, the level of assessment and corrective action is required to be comprehensive.

Recent developments in distribution switchgear technologies have presented end users with a compelling argument for the use of lower cost, safer and more reliable equipment. This includes the use of switchgear having an insulating/interrupting medium of gas, air, vacuum and/or solid dielectric that is 'sealed for life' – requiring minimal maintenance and intervention over its lifetime. With developments in both technology and knowledge, it is now possible to use safer switchgear that is fully tested not only to withstand the effects of, but to safely 'vent' the emissions generated by, an internal (arc) fault.

2. Definitions and abbreviations

Anti-reflex handle: a one-way operating device that must be removed and relocated before performing another switching operation, thus preventing an operator from attempting to reverse an incorrect operation.

DMO: Dependent Manual Operation: an operation solely by means of directly applied manual energy such that the speed and force of the operation are dependent upon the action of the operator.

Overstressed: a situation arising when the prospective fault current of the electrical system at the switchgear location exceeds the fault current rating of the switchgear.

3. History of medium voltage switchgear in the South African Electricity Distribution Industry (EDI)

3.1 Oil-filled switchgear

For many years, the primary insulating and interrupting medium for MV switchgear was oil and a significant portion of the installed medium voltage switchgear base in the SA EDI is classified as oil-filled. Although, the scope of this paper primarily addresses oil-filled secondary switchgear (e.g. ring main units (RMUs)) – many of the issues addressed are also applicable to primary oil-filled switchgear and users are encouraged to apply similar principles to any base of installed oil-filled switchgear which they may have.

In the more recent years, an alarming trend has surfaced, i.e. that oil-filled switchgear is not being adequately maintained. If maintenance is being carried out, in many cases it is not in accordance with the requirements of the original equipment manufacturer (OEM). Historically, most switchgear has been maintained on an interval- and event-based maintenance schedule. In some cases, a 'run to failure' philosophy has been adopted i.e. as if this was considered an acceptable option irrespective of the risk involved.

Most oil-filled secondary switchgear (i.e. RMUs) is classified as 'free-breathing' and therefore prone to moisture and pollutants resulting in what is referred to as an 'uncontrolled environment'. In order to obtain access to the oil, the switchgear must be isolated and earthed in terms of operating regulations before any maintenance can be performed. Due to ever-increasing quality of supply expectations from customers, it is becoming increasingly difficult to schedule the onerous outages required.

In certain instances, maintenance is simply not being scheduled, often as a result of pressure on maintenance budgets. The above factors have all lead to an all too common trend that the required maintenance is not being performed on aging switchgear. This leads to a gradual deterioration of the insulating, and in particular, the interrupting properties of the oil. The probability of mechanism failure in an 'uncontrolled environment' also increases through lack of maintenance. As a direct result, numerous switchgear failures have occurred which have been accompanied, in many instances, by serious injuries, and in some more severe cases, fatalities. The overall risk of failure increases with the age of the inadequately maintained switchgear.

Clause 5 of the British national Health and Safety Executive (HSE) document 483/27 '*Oil-filled electrical distribution and other switchgear*' [1] states, "*In general, oil-filled switchgear has a proven record of reliability and performance. Failures are rare but, where they occur, the results may be catastrophic. Tanks may rupture, resulting in the ejection of burning oil and gas clouds, causing death or serious injury to persons and major damage to plant and buildings in the vicinity of the failed equipment. Accident experience has shown that failure usually occurs at, or shortly after, operation of the equipment. Thus, the way switchgear is operated, its condition and the circumstances existing in the system at the time of operation, to a large extent, determines whether the equipment will safely perform its duty.*"

A number of failures have also occurred as a direct result of sub-standard oil-type MV HRC fuses used in switch-fuse combinations. Users are cautioned regarding the serious risk associated with the use of inferior quality and/or non type tested fuses that have entered the South African market in the past. Tests carried out on such fuses by Eskom Distribution at the SABS national electrical test facility (Netfa) have proven that they are unable to interrupt current up to their rated capacity and in fact have exploded at current magnitudes of only 10kA (i.e. < 25% of the rated interrupting capacity). This, coupled with fact that oil-filled switchgear is not internal arc rated, presents a potentially fatal hazard to operators and the general public in the event of the fuse attempting to

interrupt a downstream short circuit. In the Western Cape, an Eskom employee was fatally injured as a result of such a fuse. In addition, these fuses do not provide adequate 'oil-tight' seals to prevent the ingress of oil into the fuse.

3.2 Other insulating mediums

The use of cast epoxy resin as an insulating medium (often in combination with free air) is also fairly widespread in what is called MV 'insulation-enclosed' switchgear where all the conductors are completely embedded in insulation material (except for the external connections). Users are encouraged to apply the principles given in this paper to existing insulation-enclosed switchgear as many of the failures experienced are also due to inadequate maintenance, adverse service (environmental) conditions and even inadequate operator training/experience.

Air-filled enclosures (of the 'free-breathing' or 'free-air' type) have been and are still widely used today, for example in indoor metal-enclosed ('metal-clad') switchgear (e.g. busbar enclosures, cable termination enclosures, etc.) and outdoor switchgear (e.g. cable termination enclosures of RMUs). Air-filled switchgear enclosures are certainly not exempt from having a relatively problem free track record in South Africa. Suffice is to say that many of the problems experienced in the past with switchgear having 'air-filled' enclosures can be overcome by correctly applying the minimum insulation requirements specified in NRS 012 [2]. Users should be aware of the four types of cable terminations and live conductors defined in this specification when specifying and purchasing switchgear. Users are also cautioned regarding the wide-spread misconception that pollution conditions within a brick-built room (or even an outdoor enclosure) are necessarily of lesser concern when compared to an outdoors environment. Polluted indoor insulation surfaces do not have the benefit of being washed by rain and therefore may require periodic cleaning – especially if creepage distances are insufficient. It is well known that installations in the South African environment experience large cyclic temperature fluctuations over a 24 hour period – accompanied by relatively high amounts of condensation – resulting in the 'wetting' (not washing) of polluted surfaces. This scenario only exacerbates any leakage current and/or surface tracking activity and subsequent probability of failure. Only if adequate measures are taken to air-condition the room, filter the incoming air and develop a positive pressure within the room can the pollution and condensation problems be reduced.

Irrespective of the switchgear primary insulation medium, it is acknowledged that many of the failures can be traced back to the cable terminations. It is the authors' opinion that only through the coordinated enforcing of insulation requirements as given in NRS 012 for air-filled enclosures can these problems be adequately addressed. Many failures can be attributed to an uncoordinated transition from compound filled boxes to the use of modern dry-type accessories in air (e.g. heat/cold shrink, slip-on or other cold applied technologies) without due consideration for the termination enclosure insulation coordination requirements. Amongst others, NRS 012 addresses minimum requirements for clearances, creepage distances, pre-defined cable termination bushings and insulators. Cable accessories in accordance with NRS 053 [3] should then be used – providing a complete integrated solution for the switchgear-cable interface.

4. Alternative solutions to oil-filled switchgear

Prior to the advent of suitable alternatives to oil-filled switchgear (e.g. gas-insulated metal-enclosed switchgear), requirements such as internal arc classification could not be seriously considered. At best, oil-filled switchgear having internal arc tested air-filled cable termination enclosures may be available. The concept of internal arc testing has emerged in the process of addressing the safety concerns around increasing switchgear failure risks. The now well known concept of internal arc classification (IAC) involves designing and testing equipment that, should an internal short circuit fault (arc) should occur in any of the switchgear enclosures, it will fail in a controlled, 'safe' and predictable manner. The nature of an internal arc fault in oil (i.e. between live parts not designed to interrupt current), is deemed to be uncontrollable. Explosion vents, if provided, would simply allow burning oil and vapour (at temperatures of a few thousand degrees

Celsius) to spew into the surrounding atmosphere – resulting in significant damage to property and people. As a result, it is simply not possible or practical to internally arc test oil-filled switchgear. Photo 1 shows an example of a failure due to an internal arc fault in oil-filled switchgear. In contrast, internal arcs faults in air-filled and gas-insulated switchgear are classified as 'dry-arcs'. 'Dry-arcs' can be simulated in a test laboratory and therefore suitable methods developed to contain and/or safely vent the emissions (including conductive vapour and molten metal) created during an internal arc fault.



Photo 1 – Examples of switchgear failures due to an internal arc fault in oil

Sulphur hexafluoride (SF_6) has proven itself to be a preferred gas for filling enclosures – for example busbar compartments housing live equipment in compact switchgear. SF_6 is a relatively new development in comparison with the other technologies and offers superior performance in terms of insulation and arc extinction. It is electronegative (i.e. it absorbs free electrons) making it an excellent medium for arc quenching because it absorbs the free electrons produced in an arc. It has a dielectric strength three times that of air at atmospheric pressure and the dielectric strength rapidly increases with increasing pressure. Its arc extinction properties are three to four times superior to that of air at the same pressure. The gas is odourless, non-toxic, chemically inert, and non-flammable. Nevertheless, it is classified as a greenhouse gas and fairly stringent procedures have to be complied with to recover, store and recycle SF_6 . In addition, the gas is denser (and hence heavier) than air and it therefore has a tendency to collect in low-lying places e.g. basements in the event of it escaping. Since it displaces air, in sufficient concentration it may be hazardous as it is non-life-supporting. The gas is under positive pressure to prevent the ingress of any air or moisture. Gas loss is typically less than 1% per annum and this is taken into account by manufacturers at the time of filling. The expected service life before maintenance/refilling of an SF_6 switch is up to 30 years. Arcing does cause decomposition of the gas, but in very small amounts. The products of decomposition are toxic and react with water, but since the tanks are sealed and filtered neither of these issues present a problem. Note that for high voltage (>33kV) GIS switchgear, SF_6 is the most prevalent insulating and interrupting medium available and used.

It is worth noting that oil, when used purely as an insulating and/or cooling medium (e.g. in conventional power transformers), is not considered to present the same safety risk to the user. The principle of operation of a transformer (i.e. mutual induction) is different to that of oil-filled switchgear, where contact separation through moving parts occurs in the oil. The drawing of an electrical arc within oil and in particular contaminated oil between conductive parts not designed to interrupt current (i.e. under conditions of a short circuit internal arc) results in the rapid expansion of the oil and vaporisation of moisture in an uncontrolled and explosive manner as described in 3.1 above.

5. Safety considerations

5.1 Risk

Safety is achieved by reducing risk to a tolerable level. Tolerable risk is determined by the search for an optimal balance between the ideal of absolute safety and the demands to be met by a product, process or service, and factors such as benefit to the user, suitability for purpose, cost effectiveness, and conventions of the society concerned. 'Risk' is considered to be the combination of the probability of occurrence of a harm and the severity of the harm [4]. It follows that there is a need to continually review the tolerable level of risk – in particular when developments in both technology and knowledge can lead to economically feasible improvements – in order to greatly reduce the risk associated with the use of a product, process or service.

5.2 Internal arc

In essence, an internal arc is a short circuit between components having different electrical potentials within a chamber filled with a particular insulating medium. It is an uncontrolled conduction of electrical current from phase to earth and/or phase to phase accompanied by ionization of the surrounding medium (e.g. air/SF₆). Because of the expansive vaporization of conductive metal, a line-to-line or line-to-ground arcing fault can escalate into a three phase arcing fault in less than 1 ms. Arc energy is a function of system voltage, short circuit current, and the time until the upstream protection operates. Voltage is a function of system design, current is a function of system design and operation. Arc time is a function of protective device response. The heat energy and intense light at the point of the arc is called an arc flash. Arc flash energy absorbed by a person is a function of arc energy, distance from arc and personal protective equipment (where applicable). An internal arc is accompanied by a rapid rise in pressure followed by a burn-through period as indicated in figure 1. In the absence of suitable pressure release mechanisms (e.g. 'venting ducts or flaps'), arc faults are extremely dangerous and potentially fatal as temperatures at the arc can reach four times the temperature of the sun's surface. The high arc temperature vaporises the conductors in an explosive change in state from solid to vapour. Copper vapour expands to 67 000 times the volume of solid copper. Photo 2 shows an example of the release of arc flash energy where inadequate pressure release mechanisms were provided. However, through the specification and design of internal arc classified switchgear, where the energy and emissions resulting from an internal arc are suitably vented away from the operator and/or people in the vicinity, the 'safe' working distance can be effectively reduced.

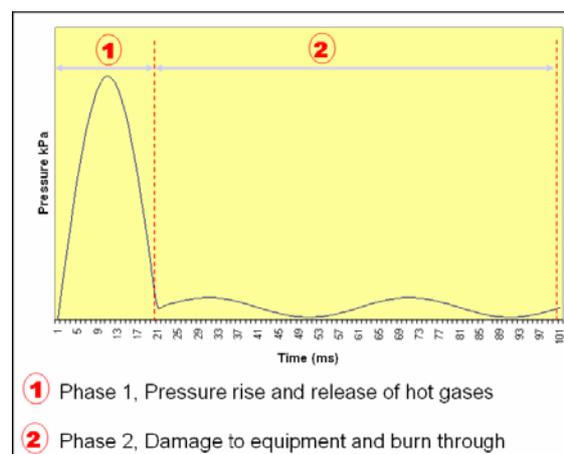


Figure 1 – Typical pressure rise in switchgear

The most common causes of an internal arc fault are:

- Insulation defects due to quality deterioration of the components (including oil). The causes can, for example, be adverse environmental conditions, a highly polluted environment and lack of maintenance;
- Overvoltages of atmospheric origin or generated by operation of a component (inadequate insulation co-ordination);
- Incorrect operations due to not respecting the procedures or to inadequate training of the personnel in charge of the installation. Note however that when evaluating switchgear performance, it is important to distinguish between limitations placed on equipment by design and by operating procedures. For example, the ring switches of an RMU are designed as load-break, fault make devices. Failure of the switchgear to perform these functions cannot be excused despite any restrictive local operating procedures;
- Breakage or tampering of the safety interlocks;
- Overheating of the contact area, due to the presence of corrosive agents or when the connections are not sufficiently tightened;
- Entry of vermin into the switchgear live compartments;
- Material left behind inside the switchboard during maintenance operations;
- Interference with cable terminations during cable testing. This can be eliminated through the specification of integral cable test facilities that are independent of the cable termination enclosures (eliminating the need to access and interfere with the cable terminations);
- Use of inferior quality and/or non type-tested MV HRC fuses (see 8.7 below); and
- Incorrect installation (e.g. striker pin facing wrong direction) and/or replacement of MV HRC fuses (i.e. all three fuses of the same make and rating not replaced at the same time after a fuse operation – see 8.7 below).



Photo 2a – Enclosure prior to test



Photo 2b – Resulting arc flash

5.3 Risk reduction

The basic philosophy adopted for risk reduction can be summarised as shown in figure 2. It is important to note that, as always, personal protective equipment (PPE) should be considered as a last line of defence, and not as a replacement for appropriate equipment design and testing (e.g. internal arc compliance), safe work practices or engineering controls that can help limit exposure to arc-flash hazards.

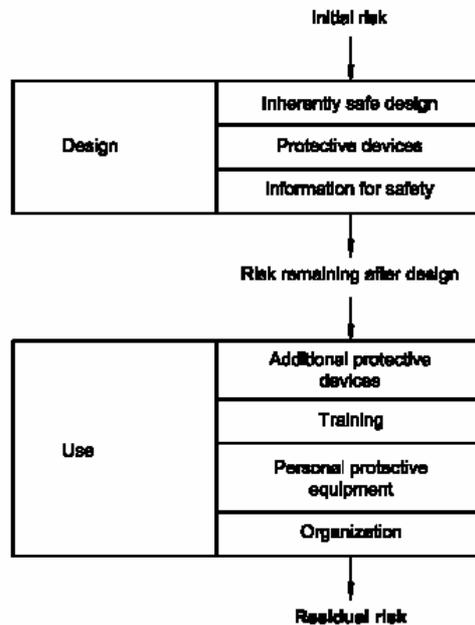


Figure 2 – Risk reduction

In South Africa, the Occupational Health and Safety Act (OHS Act) [5] has a general duty clause requiring employers to take reasonable precautions to ensure their employees' health and safety. Although it is not the primary objective of this paper to discuss the relevant safe working practices and appropriate personal protective equipment (PPE), due to the fact that there are currently no local electrical safety regulations relating to internal arc, users are encouraged to refer to the recommendations given in the National Fire Prevention Association document '*Standard for Electrical Safety in the Workplace*' (NFPA 70E) [6, 7] adopted by the U.S. Department of Labour, which, in short, requires that:

- 'Limited Approach', 'Restricted Approach', 'Prohibited Approach' and 'flash protection' boundaries need to be established in order to assure that personnel do not accidentally contact exposed, energized electrical equipment.
- Employees are aware of potential hazards when operating, changing the position of, or working in the proximity of energized electrical equipment.
- If an employee needs to enter a flash boundary to perform work that could possibly cause an arc flash, then appropriate PPE (personal protective equipment) needs to be worn.
- The type of PPE depends on the amount of energy to which an employee could be exposed.

This would require an arc flash hazard analysis (risk assessment) to be carried out in order to determine the type of PPE needed for the arc energy level, the duration of the arc flash and the working distance (degree of exposure or impact). For new equipment, it is possible to significantly limit the probability and impact of an internal arc – by providing switchgear that is specified and tested with a suitable internal arc classification (see 5.4 below). An implication of having internal arc classified (IAC) switchgear in accordance with SANS/IEC is that the clothing category of PPE required would be entry level, i.e. a single layer of untreated natural fibre clothing without any arc rating ('cal/cm²'). Note however that SANS 62271-200 states that classification IAC gives a tested level of protection of persons under normal operating conditions as defined in annex A.1 of SANS 62271-200 (i.e. including manual operating and monitoring of switchgear at normal working distances). It is concerned with personnel protection under these conditions and not under maintenance conditions nor with service continuity. The latter would require additional safety measures to be taken. Here, requirements such as having metallic partitioning (PM) between

enclosures and specifying an appropriate loss of service continuity (LSC) classification in accordance with SANS 62271-200 become relevant.

It is often beneficial to look into the introduction of other possible 'supplementary' measures such as internal arc detection for rapid fault clearance, current limiting devices (e.g. HRC fuses in combination with switching devices), 'arc eliminators/suppressors', remote control, motorised racking devices, pressure relief devices, and the transfer of withdrawable parts to or from their service positions only when the front doors are closed. A co-ordinated philosophy is required when approaching the subject of internal arc classification and specifying new equipment and safety measures. Users are cautioned that 'blindly' specifying combinations of various measures aimed at reducing the probability and impact of an internal arc can lead to unnecessary or wasteful expenditure. However, whether working with new or older equipment, the requirements of NFPA 70E and the OHS Act should always be considered.

In situations where elevated risks still exist (such as in the case of un-maintained oil-insulated switchgear), the only practical way to eliminate an internal arc flash risk is to remotely de-energize the electrical circuit(s) when the equipment is being operated, if it is going to be prepared for maintenance or inspection as well as when equipment is being returned to service following an interruption. However, such a decision has a significant impact on quality of supply and associated network performance indicators and it is therefore highly recommended that suitable plant management programmes be put in place in order to mitigate against the potential dangers associated with older oil-insulated switchgear. Section 8 below provides recommendations regarding the management of existing oil-filled switchgear.

5.4 Specifications for new switchgear

Since January 1998, Eskom Distribution has latched on to the international initiative of internal arc testing of indoor primary metal-enclosed switchgear. Four years later (August 2002), outdoor switchgear followed suit when internal arc rated compact secondary switchgear was specified and purchased for sub-switching stations (i.e. RMUs) and 'Type B' mini-substations (i.e. equipped with a RMU) – typically found downstream of primary switchgear. Operator and public safety has been put under the spotlight in the past few years following catastrophic failures of metal-enclosed and outdoor oil-insulated RMU switchgear – elevating arc flash safety and hazards to new levels. This has forced Eskom and other utilities to review the current design standards from a product compliance, testing and application perspective.

Eskom and other major utilities have recently been involved in the development and re-testing of switchgear products to meet the safety requirements of the Occupational Health and Safety Act and industry-aligned requirements utilising the recently published SANS 62271-200 [8] as well as SANS 61330 [9] (due to be replaced by SANS/IEC 62271-202) as reference.

The applicable specifications for distribution switchgear require that they be type tested to ensure the safe release of gases in the event of an internal arc fault – giving them an internal arc classification (IAC) in accordance with the relevant SANS specifications. This has been made possible due to the specification and purchasing of air-filled and/or gas-insulated switchgear. The SANS specifications for internal arc testing (detailed in annexures A of SANS 62271-200 for metal enclosed switchgear and SANS 61330 for prefabricated substations) cater for two relevant categories of internal arc classification – based on the type of accessibility required by the user. Type A accessibility is restricted to authorised personnel only and Type B accessibility caters for unrestricted accessibility – including that of the general public. Different types of accessibility may be applied to various sides of the switchgear / enclosure – i.e. front [F], lateral [L], and rear [R]. Each accessibility type requires specific test conditions designed to simulate the actual conditions on site. The philosophy applied by Eskom Distribution for specifying the internal arc classification for switchgear is based on the maximum prospective fault level applicable to the relevant part of the network, the protection philosophy relevant to the type of switchgear. If necessary, current

limiting devices (e.g. air-core reactors) may be required to limit the prospective fault levels to within the pre-defined limits. The internal arc rating and management of fault levels are taken into account in the planning and design of electrical networks in Eskom Distribution [10].

In summary, for indoor metal-enclosed primary switchgear ('metal-clad'), the following is specified by Eskom Distribution:

Classification IAC	AR-BFL (SANS 62271-200)
Internal arc	25 kA 0,2 s (for 12 kV and 24kV);

Although the switchgear is generally housed indoors in a brick-built switch room, the rear of the switchgear is restricted to authorised personnel only, whereas the sides and front provide what Eskom regards as unrestricted accessibility (e.g. taking into consideration the possibility of having personnel indoors that are not classified as 'responsible' or 'authorised' in terms of the Eskom operating regulations for high voltage systems). The 0,2 s arc duration is based on the fact that internal arc detection systems are specified for indoor switchboards. These internal arc bus protection schemes employ detectors sensitive to light that are installed in all switchgear enclosures to act as fast sensing devices in the event of an arc. They are designed to initiate an upstream circuit breaker trip in less than 0,1 s. Arc venting is required to be upwards (without exhausting ducts) and the key switch room dimensions are standardised to coincide with the internal arc test requirements. The switch room is also designed for pressure relief.

For outdoor secondary switchgear (e.g. RMUs and miniature substations usually installed downstream of indoor metal-clad primary switchgear), the following is specified:

Classification IAC	AF-BFLR (SANS 61330) or 'AB' (proposed SANS/IEC 62271-202)
Internal arc	20 kA 0,5 s (for 12 kV); 16 kA 0,5 s (for 24 kV)

Outdoor switchgear is normally installed in areas of general public accessibility – requiring type B accessibility on all sides (with all doors closed). In addition, with the front MV doors open (front access only), type A accessibility is required for the operator. The 0,5 s arc duration is based on the upstream protection settings typically applied for grading considerations. No internal arc detection systems are employed. As this outdoor switchgear is usually installed on solid concrete plinths (usually pre-cast) with cable trenches that are backfilled and sealed (using a concrete screed), venting of the switchgear can only be directed upwards – requiring a 2m high arc venting duct – an example of which is shown in figure 3. The duct/venting system is designed and tested to vent emissions resulting from an internal arc fault in any of the gas and/or air-filled enclosures within the switchgear (i.e. a common venting system for the SF₆-insulated busbar enclosure and the air-filled cable boxes). Such a duct system can be applied to free-standing RMUs as well as RMUs installed within miniature substation. The proposed IEC 62271-202 makes special provision for the MV interconnections (jumper cables) between the RMU T-off and the MV/LV transformer. The enclosure/compartment housing the interconnections may be excluded from the internally arc tested zone either by specifying a (fast operating) HRC fuse (i.e. fuse-switch combination) in the RMU T-off or, if a circuit breaker is specified, by using fully screened cable jumpers and separable connectors onto the transformer.

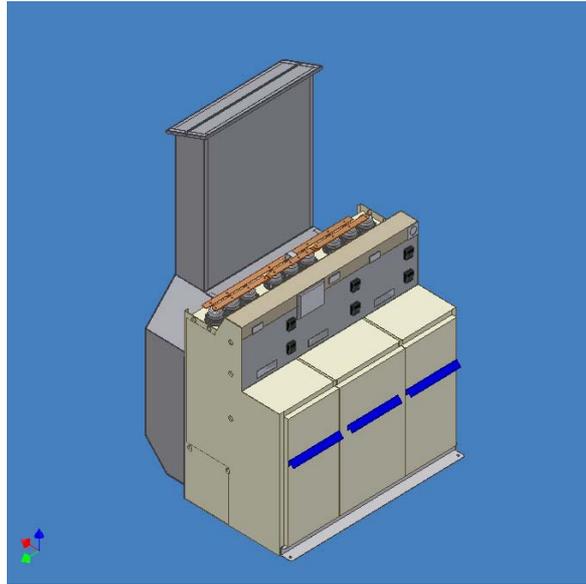


Figure 3 – RMU with internal arc venting duct for IAC AF-BFLR

It is the view of the authors that the introduction of mandatory type testing for internal arc classified (IAC) switchgear and controlgear as detailed in SANS 62271-200 and SANS 61330, together with the implementation of safe working practices (such as those detailed in NFPA 70E), has greatly enhanced the employer's ability to specify acceptable equipment that significantly improves both operator and public safety.

In addition, with the availability of switchgear requiring minimal maintenance intervention (e.g. circuit breakers of class 'E2-M2' in accordance with SANS 62271-100 [11]), fixed pattern metal-enclosed primary switchgear (normally 'partially' gas-insulated) can be considered in future – as an alternative to the more traditional withdrawable 'metal-clad' switchgear.

6. Economic considerations

It is well accepted that any sound engineering solution must take into consideration the total cost of ownership during the expected life-span of the design alternatives. This involves carrying out a comprehensive 'life-cycle costing' study – comparing alternatives available to the engineer from an economical point of view. Ultimately, all engineering alternatives can be compared in terms of economics – taking into consideration all the identified and quantified risks.

Life cycle costing can be approached in several ways but the fundamental principles are the same in each case. The factors considered important and the weighting given to them will have a significant impact on the result. The following factors are considered to be the most important and should be taken into consideration in the comparison of various planning variants:

- Initial capital cost (cost of acquisition)
- Future upgrade/replacement costs
- Cost of technical losses
- Cost of unserved energy
- Maintenance costs (normally periodic)
- Dismantling / residual costs
- Liability costs
- Operating costs

Included here is the ever increasingly important cost of 'un-served energy' (COUE) or the cost that the customer incurs due to plant interruption during an outage, whether planned or unplanned. This is in effect the cost to the economy of a power outage. The COUE is based on the class of customer being supplied. Table 1 shows the costs of unserved energy for the different customer classes used by Eskom [10] (2005 figures shown). Note that one of the realities experienced in Eskom and other major utilities is that there are few areas that are made up of one single class of customers. It is often the case that there is a mixture of, for example, commercial and residential customers. Many light commercial businesses are now operated from homes that would normally have been classed as residential. In such areas, a R/kWh value is to be determined that is representative of the mix of customer classes in the particular area.

1	2
Customer Class	R/kWh
Industrial/Mining	20.47
Commercial	15.95
Agricultural/Rural	2.80
Residential	2.38
Traction	1.26

Table 1 – Costs of unserved energy (average customer interruption cost) – 2005 Rands [Eskom]

In 2002, Eskom carried out a comprehensive life-cycle costing comparison between oil-filled and gas-filled (i.e. SF₆) RMUs and then again in 2004 using the Electric Power Research Institute (EPRI) Life-Cycle Cost Management System (LCCMS) and Life-Cycle Decision Making (LCDM) software. The results from both studies were consistent – indicating overwhelming support for the use of SF₆-insulated switchgear. For the purposes of this paper, the results of the more recent (2004) study [12] are summarised below.

The two alternatives evaluated were:

- oil-insulated switchgear that undergoes routine maintenance every three years (minimum). Note that the assumed maintenance frequency and average cost of maintenance were based upon Eskom experience with the installed base of oil-insulated compact switchgear;
- SF₆ gas-insulated switchgear that is considered to be maintenance-free and requires no intervention requiring a prolonged outage.

The two alternatives were analysed for the acquisition, use and disposal phases of their life-cycle and the results are shown in figure 4. The two most significant cost elements that make up the "use" cost factor for oil-insulated switchgear are:

- the 3 yearly maintenance cost; and
- cost of unserved energy that occurs while doing maintenance.

Life-Cycle Costs (Rands)

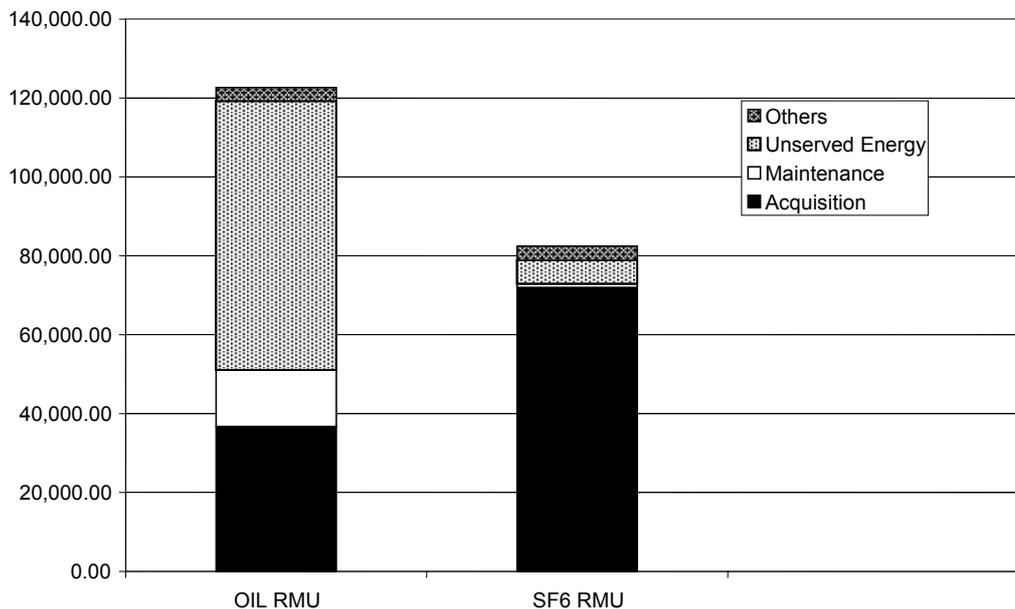


Figure 4 – Total cost of ownership of oil versus SF₆ gas-insulated switchgear (2004 Eskom study)

A number of the key differences giving rise to the results shown in figure 4 (between oil-insulated and SF₆ insulated switchgear) are now briefly discussed.

The purchase price ('acquisition') of an SF₆-insulated RMU is (to-date) higher than that of an oil-insulated RMU. These prices are effectively determined by market dynamics. However, it is worth noting that the commercially available SF₆ switchgear used by Eskom and other utilities is manufactured to more stringent international specifications (e.g. internal arc classification and other specifications given in section 7 below). It is also worth noting that the difference in cost has been decreasing over the last number of years.

Most modern SF₆ equipment is marketed as being 'maintenance free' due to the fact that they are considered to be 'sealed for life' and thus environmentally controlled. In comparison to the amount of maintenance required for oil equipment, this is a fair statement to make. It was assumed that the operational life of the equipment is 25 years as recommended by the major manufacturers.

The SF₆ insulating medium has a very long service life, far in excess of the RMU itself, whereas the oil's dielectric strength deteriorates over time and so requires regular checking – especially considering the fact that oil-filled enclosures are 'free-breathing' to the outside environment. Maintenance on oil units implies an 8 hour outage which is required every 3 years, whereas maintenance of SF₆ units is scheduled for once every 12 years which involves a 4 hour outage. The latter includes visual inspections, basic operating mechanism maintenance and if necessary the cleaning of the cable termination enclosures (due to vermin and other possible environmental pollution). No maintenance is required within the SF₆ chamber housing the switchgear itself as this chamber is regarded as a 'non-accessible compartment' in accordance with SANS 62271-200. Note that despite the assumption that 20% of the outages can be scheduled over weekends

with little impact on business, the maintenance outages result in significant costs to businesses due to unserved energy. Of course any interruption, whether planned or un-planned negatively affects customer relations.

Unlike SF₆-insulated equipment, oil-filled equipment is delivered devoid of its insulating medium. In addition, the oil has to be replaced or recycled usually 3 – 5 times during its life. This also implies down time, labour, transport and specialised tools such as oil filtration plants. This incurs additional logistical considerations involving filling the switchgear with oil, testing and de-tanking. The storage of the oil raises other concerns as aside from the sheer bulk and movement of the oil drums, they have to be stored in a particular manner. They cannot simply be left standing upright in their 'natural' state, as the breather valve on the lid of the drum would draw in water and contaminate the oil – impairing its dielectric strength. The drums are required to be stored in a demarcated area in a horizontal manner and must further be kept on a raised surface – preferably undercover to avoid large temperature fluctuations. Using SF₆ insulated equipment in place of oil can also result in simplified installation and commissioning procedures. In particular, the installation time of SF₆ equipment is inherently shorter due to the fact that the oil-filled RMU has to be filled with oil on site. Filling of outdoor RMUs with oil introduces other risks due to the possible contamination of the unit whilst open. These factors associated with oil-insulated equipment all contribute to both direct and indirect costs – which are not an issue with 'sealed-for-life' and factory tested SF₆ insulated equipment. Manufacturers of SF₆ switchgear also offer free end-of-life equipment disposal services – based on acceptable environmental considerations.

Notwithstanding the safety aspects, the economic outcome is significant and clearly in favour of the gas-insulated 'sealed-for-life' technology (e.g. SF₆). Note that at 22 kV and above, there is no option but to use SF₆ gas-insulated RMUs as no suitable alternative currently exists.

7. Other considerations and benefits

Other benefits, in addition to those mentioned above, of modern compact gas-insulated RMUs complying with the specified user requirements include:

- cable termination enclosures and operating facilities that are accessible from the front providing:
 - practical (cost saving) benefits when achieving the required internal arc classification,
 - the ability to standardise on a footprint and hence introduce pre-cast concrete plinths having a common design and dimensions;
- full switchgear interlocking facilities (including all cable termination enclosures) eliminating undesired switching sequences and/or unsafe situations;
- independent manual operation with anti-reflex provision;
- the option of specifying a circuit breaker (as opposed to a switch-fuse combination) having an class C2-E2-M1 (i.e. vacuum or SF₆) in accordance with SANS 62271-100 (as opposed with a switch-fuse combination), providing:
 - appropriate electrical and mechanical endurance without requiring internal maintenance or replacement of HRC fuses for its expected life span;
- the option of specifying up to five-way non-extensible RMUs of varying configurations;
- the ability to introduce SCADA and ultimately full distribution automation functionality; and
- cable termination enclosures compliant with NRS 012 providing:
 - horizontally positioned MV bushings at standardised heights above the cable support clamps,
 - MV bushings ('Type C' or 'Type A') with pre-defined profiles suitable for separable connectors (screened and unscreened).

8. Management of existing oil-filled switchgear

As described above, the known risk profile associated with oil-filled switchgear is in most instances steadily increasing. Users have a duty, in terms of safety legislation (most notably the Occupational Health and Safety Act No. 85 of 1993) to their employees and the public to provide acceptably safe working conditions and to take reasonable action to mitigate against possible dangers. Since the danger in this case is severe injury and/or death, the level of assessment and corrective action is required to be comprehensive. In order to meet their obligations in terms of the OHS Act, it is recommended that users adopt the principles of HSE 483/27, in conjunction with the additional requirements detailed in this paper, as the basis for their strategy or policy for the management of their installed base of oil-filled switchgear.

The recommendations contained in this paper are based extensively on the content of the Health and Safety Executive document HSE 483/27. Users therefore need to obtain a copy of this document to read in conjunction with this article. The document is 20 pages in length and is therefore too lengthy to include in this paper. However, 'PDF' copy may be downloaded from http://hse.gov.uk/fod/infodocs/483_27.pdf. For the purposes of this part of the paper, all references to 'switchgear' imply 'oil-filled switchgear' including oil circuit-breakers, oil-isolators, oil-switches and oil-switch-fuse combinations. See Appendix 1 of HSE 483/27 for definitions for these devices as well as their respective operating duties.

The recommended process to be followed is detailed below.

NOTE: In the following sections, the prescriptive words "shall" and "will" are used, so that the wording can be used as is in the event that users wish to use the clauses as a basis for their own policy/strategy documents.

8.1 Identification

- a) An inventory of all oil-filled switchgear shall be compiled and maintained.
- b) For each piece of equipment, all information (quantity, type, location, etc) as detailed in paragraph 24 of HSE 483/27 shall be recorded.
- c) For each piece of equipment, the actual system fault levels shall be compared to the equipment rating. If the actual fault level exceeds the equipment rating, immediate remedial action is indicated. This may be achieved by various means (see "8.2 Overstressed switchgear" below).
- d) It shall be ascertained whether all modifications as recommended by the manufacturer have been implemented.
- e) All switchgear identified as either overstressed or DMO shall be suitably and clearly marked as such as soon as possible.

8.2 Overstressed switchgear

- a) In all instances where switchgear is overstressed, all live operation and automatic tripping of the switchgear shall be prevented.
- b) Access to the switchgear while it is alive shall be prevented.
- c) If possible and practical, the fault energy levels shall be reduced, for instance, by changing the system configuration.
- d) As soon as is practically possible, scheduling and budgetary constraints permitting, the switchgear shall be replaced with SF₆ or vacuum switchgear, which has been tested and proven to withstand the effects of an internal arc fault in the switchgear or any of its compartments.

NOTE: Wherever it occurs in this paper, reference to SF₆ or vacuum switchgear includes air-insulated switchgear (AIS) utilising vacuum as a medium of interruption or other metal-enclosed (either traditional withdrawable metal-clad or fixed-pattern) switchgear complying with SANS 62271-200.

8.3 DMO switchgear

- a) Operation and maintenance shall be restricted to trained personnel.

- b) All live operation of the switchgear shall be prevented.
- c) The switchgear shall be maintained in accordance with the manufacturer's instructions.
- d) If possible, remotely-operated power closing mechanisms shall be fitted to all DMO switchgear as a matter of urgency.
- e) When operating a DMO circuit-breaker, the method of operation given in paragraphs 33 and 34 of HSE 483/27 shall be followed.
- f) A phased replacement program, as detailed in clause (d) of "8.2 Overstressed switchgear", shall be implemented for all DMO switchgear.

8.4 Other oil-filled switchgear

- a) In the case of oil-filled switchgear not covered by the preceding clauses, careful consideration should be given to the implementation of a phased replacement program.
- b) Decisions taken with respect to the replacement of oil-filled switchgear installed after 1970 that is neither overstressed nor DMO, shall weigh the cost implications against factors such as condition of the switchgear, its service life and the likelihood of failure.
- c) In all cases, the replacement of overstressed and/or DMO switchgear shall receive priority.
- d) In the interim, all oil-filled switchgear shall be properly maintained in accordance with the manufacturer's instructions.
- e) Operators shall confirm that the switching contacts are covered with insulating oil in good condition e.g. by means of an oil-level gauge and checking for oil leaks around the equipment. If any doubt exists, the switchgear shall not be operated alive.

8.5 Maintenance

- a) In order to maintain the reliability of oil-filled switchgear at a maximum, it is essential to maintain the switchgear properly and in accordance with the manufacturer's instructions.
- b) If any overstressed and/or DMO equipment has not been maintained within the past three years, such maintenance shall be carried out immediately.
- c) The work shall include the items detailed in paragraph 37 of HSE 483/27.
- d) All oil-filled circuit-breakers shall be maintained as soon as possible after closure onto a fault or automatic operation to disconnect a fault from the system. The maintenance shall be carried out in accordance with paragraph 38 of HSE 483/27.
- e) All maintenance shall be performed by trained and experienced personnel.

8.6 Replacement of oil-filled switchgear

- a) All oil-filled switchgear shall be replaced in terms of a phased program to be implemented after an analysis and database creation of all oil-filled switchgear in service.
- b) Priority shall be given to the replacement of overstressed and/or DMO switchgear in accordance with the requirements listed above.

8.7 HRC fuses (where applicable)

The following has been extracted from clause 8.103 (Operation) of SANS 62271-105 [13]:

- 'a) The three fuses fitted in a given combination shall all be of the same type and current rating, otherwise the breaking performance of the combination could be adversely affected.'*;
- 'b) It is vital, for the correct operation of the combination, that the fuses are inserted with the strikers in the correct orientation.'*; and
- 'e) All three fuses shall be discarded and replaced if the fuse(s) in one or two poles of a combination has operated.'*

The requirement for correctly replacing all three fuses of the same make and current rating at the same time is essential in order to reduce the probability of a fuse-related fault occurring. It is also critical that all fuses used are fully type tested in accordance with the SANS 60282 [14]

specifications and where possible, only the make and type recommended by the switchgear manufacturer should be used.

Inferior quality or non type tested fuses such as those described in 3.1 above shall be replaced. The live switching of a switch-fuse combination having such fuses installed shall be prevented until the fuses have been replaced. In addition, the switch-fuse combination shall not be energised from an adjacent switch-disconnector (i.e. sharing a common oil tank or common busbar).

8.8 Conclusion

While the above requirements may seem onerous, and involve the spending of capital which may be difficult to source where users are facing increasing expenditure with decreasing budgets, it should be borne in mind that the alternative (i.e. operating switchgear under de-energised conditions) may prove more costly to the business and economy, notwithstanding the risk that human lives may be exposed to if no action is taken. The OHS Act places a large burden on users of hazardous or potentially hazardous equipment and a reasonable person would agree that un-maintained, over-stressed and/or DMO oil-filled switchgear is potentially hazardous. Since the provisions of this act expressly forbid the sole use of PPE to mitigate a risk, it is recommended that the guidelines given in this paper are implemented by users.

9. Conclusions

Eskom and other major utilities in South Africa have responded to the changing risk profile associated with oil-filled switchgear in the light of developments in both knowledge and alternative technologies. They have and continue to engineer solutions for switchgear found in the distribution network that offers a significant reduction in both the total cost of ownership as well as the associated known risks. Air and/or gas-insulated switchgear utilising vacuum and/or SF₆ interrupting technologies provide the users with equipment that meets the required specifications and levels of performance in a world where there is an ever increasing focus on human safety (in respect to both employees and the general public), service delivery and cost reduction. These solutions offer improved reliability and require fewer and shorter scheduled power interruptions required for maintenance interventions. However, the existing installed base of aging oil-insulated switchgear will not disappear overnight and therefore suitable plant and safety management programmes – as described in guidelines given in this paper – are to be put in place by utilities in order to manage and reduce the associated risks.

10. References and bibliography

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