# OPTIMISATION OF MINISUBS AND ASSOCIATED DISTRIBUTION TRANSFORMERS

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## INTRODUCTION -

Minisubstations are defined as substations which comprise of a transformer, low voltage and high voltage switchgear, connections and auxiliary equipment in an enclosure to supply low voltage energy from a medium voltage network. These substations can be installed in locations accessible to the public and with the greater awareness of safety in the last couple of years changes and improvements are taking place which need to be clearly implemented and understood. The purpose of this paper is to ensure that the safety role is understood and at the same time all other parameters are optimised to provide maximum efficiency. We also discuss a number of failures experienced and some innovative solutions related to the latest requirements.

## HISTORY -

The concept of minisubs was introduced in the early 1960’s. This service was previously provided through expensive to build, brick walled distribution substations that, because of their size, had to be sited well away from vehicle and pedestrian traffic. In South Africa, English Electric introduced a small, rugged, tamper – proof compact substation which they named MinEEsub. This resulted in the company obtaining a registered trademark on the MinEEsub name. It was small 600mm wide x 1500mm high and could be mounted on pavements without disrupting pedestrian or vehicle traffic. By the end of 1962 the MinEEsub had been fully tested and was ready for the market in 1963.
The continuous success of these substations led to the introduction of standard specifications for miniature substations namely SABS 1029 and SABS 1030 in 1975, where all major role players were involved to form the main core committee. Interestingly this specification covered units with distribution transformers up to 630kVA and a system voltage not exceeding 12kV and a clear note was made, that for residential areas only, units with ratings up to 315kVA should be specified. This resulted in the introduction of a standard longitudinal miniature substation with power ratings of 100, 200 and 315kVA.These units were named or labeled Type A and the larger units Type B.
For many years these units were fitted with links, fuses and single phase switches in the high voltage compartment and only later were “slim” type ring main units introduced.
From the outset it was agreed that all Type A units would be so designed that the housing of the high and low voltage compartments could be removed without disturbance of the transformer, contents of the compartments or the underground cables.
This philosophy has continued over the years and even though a lot of similar designs have been developed and applied all over the world, the minisubs currently supplied by the various local manufacturers still meet most of these original requirements. It may also be added that in comparison with our European colleagues, our units are normally more compact for the same kVA rating. Contrary to our standard designs a number of overseas designs have the radiators of the minisub transformer inside the enclosure. These units have also, over the years, been manufactured in different materials with mild steel and fibreglass being the most common materials. Fibreglass or glass re-enforced resin, being the preferred design for a number of coastal applications. More recently a national rationalisation specification NRS004 and SABS 1029:2002 were compiled and introduced.
With the recent changes and amendments of IEC the South African Engineering fraternity has engaged in a number of projects and the latest trend is to specify minisubs that comply with the latest SABS IEC 1330 : 1995 and IEC62271-202.
Additionally over the last couple of years we have also witnessed a requirement to meet certain noise restrictions which is resulting in units that are now more conducive to safety and environmental issues but not so “friendly” towards natural cooling.

## RATING OF TRANSFORMERS IN AN ENCLOSURE-

It is important to note that when transformers are installed in an enclosure such as a minisub, the value of the rated maximum power can differ based on for different enclosure classes and ambient temperatures. A simple method of calculation is defined in IEC1330.
Once we understand distribution transformer behaviour in terms of maximum power and enclosures we need to ensure that the loading is kept within values that will not exceed the designed thermal aging characteristics.
Although the actual service life of a transformer depends, to a high degree, on uncontrolled events, such as overvoltage and short circuits overloading can be monitored and controlled.

Even though a number of engineers have suggested that the life of transformers is equal to the life of the oil and the paper, the latter should be seen as the critical component as oil can be changed during the service life of the transformer.
Having said this, most distribution transformers designed and supplied these days for minisub applications are sealed for life so the above claim that insulating oil can be replaced is not strictly applicable. Most recent studies still confirm that insulation breakdown is the largest contributor to failure.
It is often quoted that transformers are one of the weakest links in a power distribution system but experience and track record has proven that with correct preventative maintenance and controlled loading characteristics we can obtain indefinite life.

Aging or gradual degradation is the result of several chemical reactions within the transformer over the years and this is an irreversible action. Aging cannot be stopped but can be easily slowed down by certain actions such as, controlled loading cycles and reduced maximum operating temperatures as already pointed out above. Many transformer designers still believe that if definite temperatures are not exceeded the aging process is negligible but if the temperature exceeds certain values then aging may take place at values up to double its relative value.

## RATED CLASS OF ENCLOSURE-

The **rated class of the enclosure** is defined as the class of the enclosure corresponding to the rated maximum power of the prefabricated substation.
The rated class of the enclosure is used to determine the load factor of the transformer without exceeding the temperature limits given in IEC76 or IEC726 or IEC60076 or IEC60726 and described in Annex D.
There are three rated classes of enclosure: class 10, 20 and 30 corresponding to a maximum value of difference of the temperature rise of 10K, 20K and 30K respectively. (This may change if the latest requirements as per IEC 62271-202 are approved.

## TEMPERATURE RISE TESTS-

The purpose of this test is to check and confirm that the design of the prefabricated substation enclosures do not impair the life expectancy of the substation components. The tests measure the temperature rise of fluid and windings (or windings only for dry type) of the transformer and the low-voltage equipment. The test will demonstrate that the temperature rise of the transformer inside the

enclosure does not exceed those measured on the same transformer outside the enclosure by more than the value which defines the class of enclosure, e.g 10K, 20K or 30K.
It is not considered necessary to measure the temperature rise of the high-voltage components because the rating of the transformer to the class of enclosure will result in a practical rating of the high-voltage circuits.

This test is to be completed with all its components positioned as designed for service. It is also mandatory that where special components or ducts are necessary for internal arcing and/or sound requirements be fitted during the test. The power and losses of the transformer should be those corresponding to the rated maximum power of the minisub under these test conditions and not of the free standing unit. The positioning of the unit on site should always be carefully considered to ensure that it does not compromise the above requirements. Often we encounter units overloading due to commissioning in extremely restricted conditions, for example, back alleys and basements. Underground units have been investigated for premature failures mainly due to basic pre-requisites not being considered. De-rating is imperative where high ambient temperatures are present to avoid overloading which will lead to premature failure.

**RATED MAXIMUM POWER AND ALTITUDE-**

The rated maximum power of the minisub is given by the maximum rated values of the distribution transformer for which the substation has been designed; however, in certain cases the power should be limited to a value less than the maximum power based on altitude as well as the class of enclosure and ambient temperature conditions. Altitude is normally defined for a given value and where the installation is at an altitude higher than where it was tested special de-rating factors may apply and should be introduced. It must be noted that different altitude reference points are applicable to, low and medium voltage switchgear.

**SOUND EMISSION-**

The level of sound emission from a minisub is governed by the relevant specifications. Where necessary a type test to evaluate sound emission can be performed. We have however, witnessed the size of minisubs in housing complexes increasing and subsequently the sound values. This has resulted in more sophisticated methods of sound profiting which if not properly engineered may reduce the natural ventilation and compromise the cooling system.

**INTERNAL ARC FAULTS-**

Failure within the prefabricated substation due either to a defect, an exceptional service condition or mal-operation may initiate an internal arc. There is little probability of such an event occurring in constructions which satisfy the requirements of this standard, but it cannot be completely disregarded. Such an event may lead to the risk of injury if persons are present.
It is desirable that the highest practicable degree of protection to persons should be provided.
The principal objective should be to avoid such arcs or to limit their duration and consequences.

There is a growing trend towards having minisubs internal arc tested. The negative impact of these designs is that they can obstruct the natural cooling paths and possibly result in equipment being de-rated in terms of its thermal characteristics.

**INTERNAL ARC REQUIREMENTS-**

It is important to note that internal arc in terms of minisubs has 3 classes of protection which can be considered. This standard covers only internal arc occurring in the high voltage side including the interconnections between the switchgear and the transformer.
The three classes are rated depending on the protection of the operators and/or the general public in the vicinity of the substation. Obviously for most of our uses the ideal rating is the one covering the safety of the operator and the general public. The method of evacuation of the gases generated during the internal arc can be achieved by an exhausting duct or by way of the cable access.

## MINISUB PROTECTION SPECIFICATIONS-

Minisubs are often specified without meeting the criteria of their original philosophy which called for a dedicated main low voltage circuit breaker or fuse link which provided at least overcurrent and short circuit protection for the associated transformer. These protection units should have thermal characteristics that match those of the transformer as well as matching time responses.
This practice is not always followed and in many applications users do not call for main low voltage protection and have feeder breakers connected in parallel often with total values in excess of the transformer full load rating. This problem is further compounded where high voltage protection is not correctly specified. It is common for users to request only isolation facilities on the primary of the unit. Often the protection specified and the protection settings are well above the permitted transformer characteristics with failures that are related to secondary continuous overloading. The most effective method of avoiding these failures and substantially increasing the unit life is to protect it with a circuit breaker or fuses which have thermal characteristics that match those of the transformer.
A sound protection design ensures that the unit will permit the transformer to deliver as much load as it is capable of without severely stressing its insulation system, or exceeding its thermal capabilities. Users must always remember that load time curves generally vary between different transformer designs and manufacturers.
Often it is also assumed that the protection on the high voltage side is capable of monitoring all possible faults and conditions. Contrary to a lot of engineers perception the HRC fuse links commonly fitted on the T- off circuit of the associated ring main units do not protect the transformer for overload conditions with great sensitivity but simply for short circuit protection resulting in unprotected zones which can lead to failure. The use of uncertified HRC fuse links has compounded this problem.
It is recommended that where the possibility exists of the above condition due to overloading, the protection scheme be supplemented with a preset temperature device wired onto a shunt trip coil configuration. More recently T- off circuits are being specified with circuit breakers but we need to be aware of the incapacity of most units to clear faults in the same clearing times as the fuse units, which obviously results in much higher “ let through” currents and related damage.
Co-ordination between the high and low voltage protection devices is critical. Although the earlier designs of the low voltage fuse carriers were not suitable for local switching, modern designs are available with more flexibility.
This can then be incorporated to offer characteristics that maintain the transformer within its designed loading cycles in order to prolong its life.

## INTERESTING FACTS-

- **Effect Of Colour and Paint Finish**

For many years electrical equipment has been painted with dark colours such as black, blue and green. This old theory held that while white bodies absorbed less heat than black bodies, black bodies tend to radiate internal heat better than white bodies. Practically the operating temperature rise of a white painted unit is only 10 to 20 percent lower than a black painted unit. So a 20ºC advantage did not justify a special paint finish and the dark colours remained popular. However, operating conditions have

changed and the 10 to 20 percent is becoming more attractive. Recent tests and investigations have confirmed that lighter painted units operate much cooler and ideally the finish should be of a reflective or light finish on the roof and a dark finish on the radiators and associated housing.
Recently we have noticed an increase in the number of specifications where a double roof arrangement is being called for to ensure reduced temperature rise in the minisub compartments.
Further temperature decreases can be achieved by using the above reflective method on the second roof.

It is important to ensure that refurbished minisub transformers have the correct paint applied to the radiator tubes and fins. Inferior applications can result in limited heat dissipation and thick finish coatings can lead to early flaking.
Where abnormal conditions are expected, such as wind, abrasion, pollution or humidity, additional protection measures must be implemented.

- **Transformer Insulation**

Most of the distribution transformers supplied in minisubs are liquid filled using mineral oil, but there are rare occasions where a fire resistant liquid, such as silicone liquid or synthetic hydrocarbon is specified as well as dry type transformers.  Where non oil insulated units are used the housings may require special ventilated constructions.

- **Fire Resistance Insulation**

There are companies that offer to convert normal mineral oil filled transformers with fire resistance liquids. Although this is possible and the flash point can be increased to at least 300ºc, the thermal characteristics of the transformer in most cases has to be derated. Silicone fluids normally have viscosity of approximately twice that of the mineral oil used at 20ºc.
Certain gaskets and fittings may also not be compatible for use with synthetic fluids. It must be stressed that under no circumstances can synthetic fluids be used in oil filled ring main units.

- **Minisub Losses**

On standard minisubs losses can be grouped into 3 categories namely high voltage, low voltage and transformer losses. High voltage losses are negligible except where T-off fuse ring main units are installed, which may have a high $IR^2$ heating value. On the low voltage side the losses are dependant upon the number and configuration of the circuits.
Transformer losses are however two fold, as there are no load and load losses. Where heat dissipation and lower running costs are a prerequisite low loss units may be a proposition.
Some engineers have even opted for minisub designs where the low voltage compartment is remotely installed as a free standing compartment to reduce the overall heating effect.

- **Incorrect Installation**

It is important that minisubs are fully assembled, tested and commissioned as per the manufacturer's recommendations. Over the years we have witnessed numerous failures caused purely by poor workmanship during the installation phase. Simple procedures such as leveling and compacting of the ground are often overlooked. Cabling terminations, especially on the high voltage compartment are also a large culprit in premature failures. Even though most manufacturers' offer vermin protection, it is often not commissioned. Clearing of the ground around the unit and maintaining it is also responsible for failures in such conditions as veld fires.

Where units are to be installed in rain catchment areas all attempts must be made to avoid the unit being flooded during the rainy season, by at least building a brick wall enclosure or specifying a higher concrete plinth.

- **Failures Related To Temperature Rise**

During design it is imperative that site conditions are carefully examined to ensure that cooling is not compromised by external factors.
Dust laden atmospheres such as installations in the vicinity of wood mills could cause a problem if the radiators become coated with dust. On applications where dry transformers are used in minisubs installed in damp conditions special precautions must be taken to avoid premature failures.
The installation of minisubs in restricted areas which may block the natural cooling must be avoided as the efficiency of the equipment could be compromised.

- **Tap Changer Control**

Most distribution transformers used on minisub applications are fitted with off line tapchangers which clearly are not to be used on line, a number of failures have been recorded following switching while the supply is still connected. Interlocking mechanisms are available to inhibit this and can be specified or retrofitted. Often units operate for years on the original tap position; even the load profile may have changed.

- **Earthing**

It is imperative the earthing systems are properly designed, installed and maintained in the interests of safety and to maintain the voltage of the network at definite potential with respect to earth.
As previously discussed in the protection section, earthing is a prerequisite for the correct operation of the respective earth fault protection. With the increase of copper theft innovative earthing techniques have been introduced and are assisting with the curbing of this problem.

- **Harmonics**

With the recent rapid growth of power electronics applications we have encountered an increase in the number of harmonic related problems. These vary from excessive neutral currents to continuous nonsense circuit breaker tripping and transformer overloading. It is recommended that harmonic surveys be carried out on applications with these types of loads.

- **Minisub Derivatives**

The minisub concept has, over the years, become a permanent feature of electrical engineering mainly due to its cost saving on site. It is therefore not difficult to understand why over the years a number of products have been designed with this principle in mind. The most notable ones being the mobile and skid mounted minisubs widely used on mining applications. Other variables include trailer mounted, double type and single phase units. Recently we have also witnessed an increase of units with medium voltage secondaries, which in turn feed 1Ø miniature localized units.

## GENERAL MAINTENANCE –

Although rigorous maintenance of minisub units may not always be required, unless very severe and harsh conditions are present, maintenance in general ensures the safety of personnel and plant, improves reliability and availability and reduces breakdown costs in the long term. The inconvenience caused by planned shutdowns to facilitate such maintenance is certainly worthwhile. As previously pointed out maintenance of minisubs can be successfully and economically carried out, without spending exorbitant amounts of capital, provided that it is clearly identified, planned, actioned and supervised. It is also important to note that safe maintenance or repair of minisub equipment requires a thorough knowledge of engineering safety and repair techniques and familiarity with the particular features of the apparatus involved and that, where necessary, the extra amounts must be spent on the expert assistance to avoid costly embarrassment.

## CONCLUSION-

Even though design changes and improvements have taken place over the last couple of years with regards to minisubs and associated equipment most development tends to follow an evolutionary process rather than a revolutionary one. The most vulnerable component for premature failure continues to be the distribution transformer so it is important that correct use and loading is maintained to preserve, protect and prolong its service life.
Correct pre-calculated loading can still provide almost indefinite unit life for not only the transformer but also the associated components. Lastly, it is also imperative that the protection is carefully selected as well as co-ordination between the primary and secondary voltages.

## REFERENCES-

SABS IEC 130: 1995 – High Voltage / Low Voltage Prefabricated Substations
SABS1029 : 2002 – Miniature Substations for Rated AC Voltages upto and Including 24kV.
IEC 62271 – 202, Ed.1: High Voltage / Low Voltage Prefabricated Substations
IEC 354 – Loading Guide for Oil Immersed Power Transformers