Miniature substations: What they are really capable of delivering

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The latest edition of the South African national standard for miniature substations, SANS 1029 Edition 3, was published in 2010 and has thus been in place for at least six years. Both users and manufacturers have been referencing this standard, but few people in the industry really understand some of the key concepts relating to the on-site capability of miniature substations to deliver their rated maximum power.

SANS 1029 Edition 3 (previously dual numbered as NRS 004) now references SANS (IEC) 62271-202 as the primary normative reference to which miniature substations in South Africa are to be designed and tested. Previous editions of SANS 1029 (and NRS 004) made reference to SANS (IEC) 61330 – but only with respect to the internal arc testing of the miniature substation. In 2007, SANS (IEC) 61330 was withdrawn and replaced by Edition 1 of SANS (IEC) 62271-202 – the international standard for high-voltage/low-voltage prefabricated substations.

SANS 62271-202 provides a clear definition of the rated maximum power of a miniature substation and provides the temperature rise type test requirements applicable to complete miniature substation assemblies. Furthermore, it provides clear guidelines on how to determine the rating of a transformer within an enclosure. However, in most cases, many users and engineers have either not read or not understood exactly what the rating of a mini-substation is, and more importantly, what it is really capable of delivering. The impact and relevance of concepts such as the temperature class of the enclosure, transformer de-rating, load factor, transformer temperature rise limits, solar radiation and average site ambient temperature conditions are poorly understood and applied in the real world.

This paper aims to highlight the common misconceptions in the industry and present the truth behind what miniature substations are really capable of delivering. It would surprise many that the actual output power capability of miniature substations having the same nominal rating (e.g. 500 kVA) supplied by different manufacturers can vary significantly. Power utilities and users would do well to take note of and understand the key issues discussed in order to better understand what they are really purchasing – and the possible financial implications.

References

SANS 780, Distribution Transformers
SANS 1029, Miniature substations for rated a.c. voltages up to and including 24 kV
SANS 61330, High-voltage/low-voltage prefabricated substations [withdrawn and replaced by SANS 62271-202]
SANS 61439-2, Low-voltage switchgear and controlgear assemblies – Part 2: Power switchgear and controlgear assemblies
SANS 60076-1, Power transformers – Part 1: General
SANS 60076-2, Power transformers – Part 2: Temperature rise
SANS 60529, Degrees of protection provided by enclosures (IP Code)

Important concepts and definitions

SANS 62271-202 and SANS 60076-2 introduce some important concepts and definitions, including the following:
Prefabricated substation (e.g. miniature substation): type-tested assembly comprising an enclosure containing in general transformers, low-voltage and high-voltage switchgear, connections and auxiliary equipment to supply low-voltage energy from a high-voltage system or vice versa.

Class of enclosure: the difference of temperature rise between the transformer in the enclosure and the same transformer outside the enclosure at normal service conditions.

Rated class of enclosure: The rated class of the enclosure is the class of the enclosure corresponding to the rated maximum power of the prefabricated substation. It is important to note that the transformer rated values (power and losses) correspond to the maximum rated values of the prefabricated (miniature) substation.

The rated class of the enclosure, the transformer temperature rise and the service conditions are used to determine the load factor of the transformer. There are six rated classes of enclosure: classes 5, 10, 15, 20, 25 and 30 corresponding to a maximum value of difference of the temperature rise of the transformer of 5 K, 10 K, 15 K, 20 K, 25 K and 30 K.

IP Code: a coding system to indicate the degrees of protection provided by an enclosure against access to hazardous parts, ingress of solid foreign objects, ingress of water and to give additional information in connection with such protection.

Transformer load factor: per unit value of constant current that can be taken from the transformer at constant rated voltage.

Rated maximum power of the prefabricated substation: The rated maximum power of the prefabricated substation is given by the maximum rated power and the total losses of the transformer (as defined in SANS 60076) for which the substation has been designed. It is critical to note therefore that the rated power of the miniature substation is determined from the transformer nameplate rated power.

Ambient air temperature: temperature, determined under prescribed conditions, of the air surrounding the enclosure of the prefabricated substation.

Yearly average temperature: the calculated yearly average ambient air temperature at the installation site – equal to one-twelfth of the sum of the monthly average temperatures. For air-cooled, oil-immersed transformers, the yearly average temperature should not exceed 20°C.

Monthly average temperature: the calculated monthly average ambient air temperature at the installation site – equal to half the sum of the average of the daily maxima and the average of the daily minima during a particular month (over many years). For air-cooled, oil-immersed transformers, the monthly average temperature, for the hottest month, should not exceed 30°C.

Maximum ambient air temperature: the upper limit of the permissible ambient air temperature. For air-cooled, oil-immersed transformers, the maximum ambient should not exceed 40°C.

It is important to note that the above temperature limits are used to determine the allowable temperature rise limits of the transformer. They correspond to the normal transformer temperature rise limits of 60 K and 65 K for the transformer top oil and windings respectively. The normal temperature-rise limits apply unless the enquiry and contract indicate “unusual service conditions”. In such cases the limits of temperature rise are modified. If the temperature conditions at site exceed one of these limits, the specified temperature-rise limits for the transformer shall all be reduced by the same amount as the excess. Many users loosely specify ambient air temperature conditions, without necessarily understanding or defining whether they are referring to the yearly average, monthly average or maximum ambient air temperature.

**Transformer nameplate and continuous output power**

In accordance with SANS 780 and SANS (IEC) 60076-1, the transformer nameplate is required to include, amongst other ratings, the rated power (in kVA or MVA), the rated voltages and rated currents. Note that the secondary rated voltage is the transformer.

<table>
<thead>
<tr>
<th>Location</th>
<th>Yearly average temperature [°C]</th>
<th>Monthly average temperature (hottest month) [°C]</th>
<th>Average of the daily maximum temperatures (hottest month) [°C]</th>
<th>Highest recorded temperature [°C]</th>
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<tbody>
<tr>
<td>SANS 60076-2 limits</td>
<td>20</td>
<td>30</td>
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<td>40</td>
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<tr>
<td>Johannesburg</td>
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<td>Skukuza (Kruger Park)</td>
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<td>Nelspruit</td>
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Table 1: Average and maximum temperatures recorded for some locations in South Africa.
no-load voltage. In the case of SANS 780
distribution transformers (as specified for
in miniature substations), the rated (no-
load) secondary voltage is the appropriate
system nominal voltage increased by 5%.
This is done primarily for voltage regulation
reasons to compensate for the transformer
impedance and volt-drop on the LV networks.
For example, the no-load secondary voltage
for three-phase transformers used in 400 V
systems is 420 V. What many people do not
realise is that this specific requirement of
SANS 780 effectively de-rates the output
power of the transformer by 5%. This is
because the rated secondary is determined based on the transformer rated
power and rated no-load secondary voltage.

For example, the maximum continuous power
a 500 kVA distribution transformer can deliver
at nominal voltage (i.e. 400 V) is 475 kVA. A
1000 kVA transformer can deliver 950 kVA.
So before the transformer is even installed
inside the enclosure of a miniature substation,
the transformer is unable to deliver its rated
power at the system nominal voltage. The next
issue to consider is the effect of the enclosure
on the internal ambient temperature inside the
miniature substation.

Substation class of enclosure

A foundational principle of
SANS 62271-202 (and thus SANS 1029)
is that the key components housed in the
miniature substation, being the HV switchgear
(e.g. RMU), the transformer and the LV
switchgear (LV Assembly) are each required
to be designed and type tested as individual
components in accordance with their own
product standards. Once assembled in the
complete prefabricated substation, the correct
design and performance of the prefabricated
substation as a whole are verified by means
of relevant additional type tests described in
SANS 62271-202. These tests include:

- Temperature rise tests on the complete
  substation
- Relevant tests on the HV and LV
  interconnections (where applicable)
- Mechanical and corrosion tests (e.g. IP
  Code)
- Internal arc tests

For the purposes of this paper, the authors are
only concerned with the temperature rise tests.
Accordingly, the HV switchgear, the power
transformers and LV switchgear are each provided
with their own individual nameplates,
as defined in their respective product
standards.

The prefabricated substation is designed to
be used under normal service conditions for
outdoor switchgear and controlgear according
to SANS 62271-1. Inside the enclosure it is
assumed that normal indoor conditions prevail
according to SANS 62271-1. However, the
ambient temperature inside the enclosure of
the prefabricated substation will be different
to the (surrounding) ambient temperature as
defined in the previous section. Note that
SANS 62271-202 (and thus SANS 1029)
only covers designs using natural ventilation.
Therefore, specified requirements such as the
enclosure IP Code may have a profound effect
on the internal ambient temperature and thus
the temperature rise of internal components.

If the ambient temperature inside the substation
is higher than the limits fixed for the components
in their respective product standards, de-rating
may be necessary. A transformer loaded with
rated normal current inside an enclosure
has a temperature rise which is higher than
when tested on its own in free-air conditions,
and the temperature limits as defined in
SANS 60076-2 can be exceeded. The
maximum hot-spot temperature of the
transformer should be maintained irrespective
of the enclosure, and therefore, it may be
necessary to de-rate the transformer to ensure
that this hot-spot temperature is not exceeded.

The concept of the “class of enclosure”
is based on this fact and effectively makes
 provision for the conditional de-rating of the
transformer once installed inside the miniature
substation. Accordingly, the service conditions
of the transformer are determined according to
the local outside service conditions and the
class of the enclosure. This enables the
transformer manufacturer or user to calculate
its possible de-rating using Annex DD of
SANS 62271-202.

The required class of enclosure should
actually be selected from the yearly average
ambient temperature at the installation site,
the required load factor and the actual
temperature rises of the transformer on
its own. Alternatively, for a given class of
enclosure, the permissible load factor of the
transformer depends on the temperature rises
of the transformer and the yearly average
ambient temperature at the installation site.

In most cases in South Africa, the required
class of enclosure is not specified and is often
ignored or left to the manufacturer to decide.
Furthermore, manufacturers themselves do not
understand the concept of “class of enclosure”
and it often comes as a surprise to many users
and manufacturers when they discover that
their miniature substation is simply unable to
continuously deliver the transformer’s
rated power under certain conditions. The
enclosure class is required to be confirmed
by test according to SANS 62271-202.
Few manufacturers have conducted temperature rise tests in accordance with SANS 62271-202 to verify the class of enclosure, and in many cases the manufacturer is unable to state what class of enclosure is being offered.

If the user is unaware of what class of enclosure has been offered, this can have significant and/or dire implications on the ability of the transformer to deliver its rated maximum power – particularly if a high class of enclosure is unknowingly offered. Furthermore, manufacturers offering better (i.e. lower) classes of enclosures at a cost premium may be disadvantaged – whereas in actual fact the manufacturer is offering a miniature substation that can deliver higher output power. However, in both cases, the transformers themselves may well comply with the temperature rise requirements of SANS 780 and SANS 60076.

Note that it is possible for a manufacturer to assign to the same enclosure different classes corresponding to different values of power and losses of the transformer. For example, a 5 K class of enclosure could be assigned when housing a 315 kVA transformer whereas a 10 K class of enclosure might be assigned when housing a 1000 kVA transformer (i.e. having higher total losses) in the same enclosure. It should further be noted that if an enclosure is tested for the highest transformer power and losses, the class of enclosure achieved may automatically be assigned for all transformers having lower power and losses – without the need for further testing. Such rules covering the extension of the validity of type tests carried out on prefabricated substations are currently being drafted into a new IEC standard.

Using the guidelines provided in Annex DD of SANS 62271-202, it is possible to determine the possible de-rating of a transformer based on the class of enclosure and the yearly average ambient temperatures at the installation site of the miniature substation. Fig. 1 has been extracted from Annex DD of SANS 62271-202. First, select the curve applicable for the class of enclosure. Then select the yearly average ambient temperature for the substation site on the vertical axis using the axis corresponding to the top oil and winding (O/W) temperature rise limits of the transformer outside of the enclosure. The intersection of the class of the enclosure curve and the ambient temperature line gives the load factor of the transformer allowed.

There are two ways in which this graph can be used:

- The first is when the user specifies an ambient temperature that is higher than one of the standard temperatures as defined in SANS 60076-2. For example, the maximum ambient temperature is stated as 50°C (i.e. 10°C higher than the maximum allowable ambient of 40°C). In this case the allowable transformer temperature rise limits are reduced by 10 K to 50 K and 55 K for the top oil and winding respectively. The appropriate Y axis is then selected to determine the allowable load factor depending on the class of enclosure.

- Alternatively, if the actual transformer temperature rise values obtained are lower than those allowed by the SANS 60076-2 (e.g. 50 K and 55 K for the top oil and winding respectively), then for the standard ambient temperatures, the allowable load factor would be greater than 1 (i.e. 1.1 in this case).

Therefore, depending on the class of enclosure, the transformer temperature rise and the actual service conditions, the transformer and thus the output power of the substation may well need to be de-rated. Conversely, if the conditions are favourable, the transformer could be up-rated.

The next factor to consider is the effects of solar radiation on the enclosure.

**Effects of solar radiation**

The temperature rise type tests for the HV switchgear, LV switchgear, transformer and complete prefabricated substation currently do not take into account the effects of solar radiation. Only until very recently has a type test for LV power switchgear assemblies used in PV applications been proposed in annex DD of a committee draft (CD) of IEC 61439-2. It is fairly intuitive to appreciate that solar radiation on the miniature substation housing does have a direct effect on the internal ambient temperature of a miniature substation and thus the temperature rises of the various components – in particular the transformer and LV assembly.

The most onerous solar radiation effects on the miniature substation are assumed to be mid-morning or mid-afternoon when the top, back or front and one adjacent side of the substation enclosure is subject to solar radiation. At these times during the day, the solar radiation is approximately 90% of the radiation experienced at midday (i.e. 1.2 kW/m²). For the duration of the temperature rise test, radiant heat lamps are used to simulate the effects of solar radiation on the top, front or back and one adjacent side of the tested substation. Fig. 2 shows the proposed arrangement of radiant heat lamps for temperature-rise test with simulated solar radiation. The radiant heat lamps are arranged so that the average solar irradiance received by the substation under test, perpendicular to the surface being considered is:

If the manufacturer or user proposes to use different external colours of the substation, the substation test shall be done with the darkest colour as this represents the worst case.

The authors, through their participation in the international working group (maintenance team) responsible for IEC 62271-202 have proposed that the effects of solar radiation are in future taken into account in the type tests given in IEC 62271-202. It will be proposed that a test set up similar to the one described in Annex DD of IEC 61439-2 be used. The authors plan to propose a new variation of class of enclosure which also takes the effects of solar radiation into account.

**Experience with temperature rise type testing to SANS 62271-202**

SANS 62271-202 makes provision for two methods for conducting the temperature
rise test on a miniature substation. The preferred method requires two separate power supplies – as shown in Fig. 3. The high-voltage side supply is used to supply the total rated transformer losses to the incoming MV switchgear terminals with the secondary side of the transformer short-circuited – in accordance with SANS 60076-2. The second supply is used to supply the LV assembly in accordance with SANS 61439-1 with the rated secondary current of the transformer and with the LV assembly isolated from the transformer and short-circuited at the point of isolation.

The alternative method can be used if the test facility only has one source of current (as is the case in most test facilities in South Africa) or the design of the miniature substation makes the connection arrangements of the two sources of current impossible. It requires only one power supply connected to the high-voltage side of the miniature substation. The test is conducted with the LV assembly connected to the transformer secondary side and with the LV assembly short-circuited at the outgoing terminals or furthest end – as shown in Fig. 4. In accordance with SANS 60076-2 (in the case of liquid-filled transformers), the first stage of the test requires sufficient current to be supplied to generate the total rated losses of the transformer. For the second stage, the current is reduced so as to produce the rated secondary current of the transformer for one hour. While it is not explicitly stated in SANS 62271-202, as the test method is required to be in accordance with the relevant transformer product standard (e.g. SANS 60076-2 for liquid-filled transformers), at the end of the first stage, the transformer top oil temperature-rise is measured and at the end of the second stage, the transformer winding and LV assembly temperature rise values are measured. It is the authors opinion that clarity is required in SANS (IEC) 62271-202 on the two-stage test method given in the transformer product standard and whether the measurement of both the transformer top-oil and winding temperature-rises are required when assessing the acceptance criteria in relation to the temperature class of the enclosure.

Based on the authors’ experience with temperature-rise testing of miniature substations in accordance with SANS 1029, with the provision of optimally positioned and designed ventilation louvres in the enclosure, it is possible to obtain a temperature class of 5 K. In accordance with SANS 61439-1, simulation of the losses generated by the outgoing feeder circuit switchgear and cables is done through the use of heaters installed in the LV compartment. It is important that the information regarding the size and number of heaters provided is included in the type test report for evaluation by the user – as this could easily be overlooked.

It is particularly important to note the significant internal ambient temperature gradient within the miniature substation enclosure. Both calculations and measurements made during temperature rise type testing confirm differences in temperatures of up to 30°C between the bottom of the enclosure and the top.

Historical performance of miniature substation transformers

Considering the various issues raised above, the question has to be asked why the failure to appropriately de-rate transformers that are housed in miniature substations has not resulted in any significant problems or premature transformer failures on site. The following factors are considered to be relevant regarding the performance of miniature substation transformers:

- At many installation sites in South Africa, contrary to popular belief, the yearly and monthly average ambient temperatures are reasonably favourable when compared to those allowed by the SANS 60076-2 standard. Table 1 shows some of the average and maximum temperatures recorded for some locations in South Africa.
- In many cases, miniature substations are installed in residential areas where the typical load profile is substantially cyclic in nature. This implies that in between the morning and evening peak demand times, the transformer has time to cool down when the load is well below the rating of the transformer. Due to the relatively long thermal time constant of the transformer, when the load increases and even exceeds the transformers continuous rating, the winding and oil temperatures often stay within their limits.
- In many cases, large utilities have rationalized their transformer power ratings in order to minimise stock variations and ultimately optimise through economies of scale. In some cases, some utilities only purchase 500 kVA miniature substations – irrespective of the actual size of the load to be supplied – resulting in the fact that the transformer power rating often well exceeds what is actually required.
- The typical Type A or Type B miniature substation designs in accordance with SANS 1029 have the transformer cooling radiators located external to the enclosure, and in some cases (i.e. certain Type A designs), the radiators are not only external to the enclosure but also sheltered from solar radiation by the substation roof.

Having said that, in many cases the user may not even be aware that their miniature substation transformer is being loaded beyond its designed capability and questions will only be asked if and when the transformer eventually fails prematurely. In other cases, and often to the surprise of the user, the transformer thermal overload protection (e.g. linked to the top oil temperature thermometer – if fitted) may trip with a transformer load factor of less than 1.

In the majority of cases, problems relating to the ability of miniature substation transformers to deliver their maximum rated power have surfaced in the following cases:
- Industrial or commercial areas where the load profile is less cyclic (i.e. continuous...
loading with no in-between periods of reduced load for cooling down).

- Installation sites where the yearly and monthly average ambient temperatures as well as the maximum ambient air temperatures are higher than those allowed by the SANS 60076-2 standard.
- Any of the above conditions coupled with high levels of solar radiation. The most common example and worst case being where miniature substations are used in solar farm applications.

Conclusion

In general, there is very little understanding of the thermal behaviour and performance of transformers and other equipment installed in miniature substations. While the relevant standards have been in place since 2010, most users and manufacturers remain unaware of the “class of enclosure” concept and its impact on the rating of the transformer (and LV assembly) housed in the enclosure. Temperature-rise type testing in accordance with SANS 62271-202 in general is not done and most users expect that their miniature substation transformers are able to deliver the power indicated on the transformer nameplate. This is particularly evident when looking at the increasingly popular “high-risk” miniature substations being designed and built with 6 mm steel enclosures and, in many cases, with minimal ventilation provided.

Miniature substation enclosure colours have in the past generally been selected without any regard for the effects of solar radiation. Avocado green, a relatively dark colour, is one of the preferred colours given in SANS 1029. It is suggested that the preferred colours should be reviewed in future. Users should also be mindful of the installation orientation of miniature substations and that positioning of the transformer radiators to minimise exposure to the sun (e.g. south or east facing for the Southern Hemisphere) can optimise the performance and life of the transformer.

Being mindful of the internal ambient temperature gradient from the bottom to the top of the enclosure, it is also recommended that LV equipment, and in particular sensitive electronic equipment, be positioned as low down as possible. Due to the maximum conductor temperature limit of 70°C for PVC insulated LV interconnections, particular attention must be given to the location of these cables within the enclosure. It is recommended that cable insulating materials that can operate at a higher temperature be considered in order to minimise thermal aging.

The authors also propose that a main circuit resistance measurement test be carried out on the LV interconnections and included as a routine test in SANS (IEC) 62271-202 as no such routine test currently exists in this standard. This will assist in verifying the integrity of the LV interconnections between the transformer, the main circuit-breaker and the LV assembly.

Finally, it is recommended that purchasers should ensure that manufacturers have carried out the required temperature rise type tests given in SANS 62271-202 on at least the highest miniature substation power rating offered. An IEC technical report is currently being developed to assist users with the extension of the validity of type tests carried out on a particular miniature substation to another miniature substation. In the interim, it would be prudent to ensure that, for a given enclosure design, the total losses generated as well as the current densities of the LV assembly are equal to or lower than those of the type tested miniature substation.

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