NEW TRENDS IN THE DESIGN OF MV/LV TRANSFORMER SUBSTATIONS

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INTRODUCTION

Transformer substations form the links between the power distribution grid and the low voltage network supplying the general public and industry. The expansion of urban areas has lead to a need for more power links. In addition concerns for the environment as well as the safety of the public have led to the development of more underground cable networks. These same factors have led to the fact that transformer substations now need to be increasingly compact, reliable [1], safe and intelligent [2][3]. The evolution of specifications together with the use of design tools, integrated functions and eco-design are all factors to be considered when designing transformer substations within increasingly shorter deadlines.

EVOLUTION OF DEMAND

History of the substations

Early transformers were located at the top of pylons and could achieve powers of up to 1000kVA. Column-type transformer substations provided the interface between overhead and underground networks. These were equipped essentially with air-insulated MV switchgear, a liquid-insulated transformer and a low voltage distribution switchboard. These were fabricated from bricks, and thanks to the chimney effect provided by the column the substations had good airflow, and consequently there were no problems with overheating of the equipment. However the next generation of substations for underground networks also built from brick, had a reduced height and no chimney effect, and for the first time the equipment designers had to confront overheating problems.

This second generation of transformer substations was also the subject of the first internal fault tests, intended to provide operating personnel and the general public with greater levels of safety. The next step was the introduction of factory assembled prefabricated transformer substations.

This third generation substations the first Utility specifications demanded small surface areas, leading to a standardised layout of the substations (Figure 1).This enclosure can be metallic, GRC (Glass Reinforced Concrete), GRP (Glass Reinforced Plastic), SFRC (Steel Fibres Reinforced Concrete). The world wide trend is for reinforced concrete enclosures for the following reasons: Improved mechanical strength, reduced effect of solar radiation, reduced condensation, improved fire behaviour, weathering, improved aesthetic.

Finally, a fourth generation of transformer substations (Figure 2) has recently appeared [4][5], where the detailed technical specification has been replaced by functional specification [6][7].

A new design integrating the MV protection within the transformer will also be presented.

Basic requirements

Utilities and end user expectations from transformer substations are based on several attributes:
- Continuity of service,
- Low levels of maintenance and easier operation,
- Operational safety,
- Low levels of environmental impact,
- Low purchase costs.
• Supply availability is assured by the use of tested materials to reduce the risk of breakdowns and also control the internal temperature by means of effective ventilation.
• Safety is assured by the use of materials and designs that comply with the minimum protection indices, such as IP3X as per IEC 60529 for HV equipment, and IP2X for other equipment, including transformer substations. In addition, to minimise the effects of a rare, but possible, internal arc, units are fully internal arc tested. Safety is also assured by an earth circuit that is capable of dispersing the fault current.
• Low levels of environmental impact are assured by the use of containment volumes for liquid dielectrics, the prohibition of chlorinated dielectrics, and the low levels of noise emissions.
• Low purchases costs are assured by a design that limits the product qualification tests and by industrial manufacture.

New constraints

For the fourth generation designs functional specifications resulted in the emergence of additional requirements in the following areas:

• Reliability of supply improved as a result of the requirement to integrate the emergency supply function into the low-voltage distribution switchboard and integrating automation on the MV switchgear.
• Safety was strengthened by the general demands in terms of internal fault withstand, through limiting the touch voltage, the presence of an equipotential loop and the product’s fire behaviour. The equipment may also be seismically qualified.
• Environmental impact has been reduced by a reduction in the above-ground height and/or site-adapted aesthetics, the limitation of electromagnetic and electric field emissions and the use of waste recycling.

Evolution of the specifications and the functional approach.

Utility specifications have evolved, and they now define the true requirements of the Utility. When writing specifications, two knowledge bases are required, that of the core business of the Utility itself, and that of the manufacturer using a product manufacture and design methodology when designing and producing their products. Today, utilities focus on their own area of expertise, and therefore produce specifications that are better suited to their true requirements. This is the origin of functional specifications.

The functional specifications for a transformer substation are based on the supply of either a ring, a single feeder or a double transfer distribution network, the option to insulate parts of the network, the option to supply power from an emergency source, and the guarantee of personal safety and environmental protection. The characteristics attributed to the substations [8] make up part of the information contained in these specifications, including information relating to reliability.

Transfer of knowledge and responsibilities

These new specifications result in a transfer of knowledge. By conforming more closely to functional requirements, products become increasingly compact and more fully equipped. The components that make up a transformer substation are therefore less inter-changeable and utilities can no longer act independently when contacting manufacturers for replacement parts in the event of a breakdown. Additionally, substation manufacturers are becoming increasingly responsible for their products, notably the design and qualification of the product.

In the past in the event of disputes relating to design faults, it was easy for manufacturers to hide themselves behind the fact that the product had been qualified in accordance with a utility product specification. With this new functional approach, the manufacturer is now directly responsible for his technology, design and for ensuring that the product complies with international and local regulations.

Application of the “plug & play” concept

This concept is similar to that of computer products. Utilities wish to purchase products for less cost, and then connect them to their networks and operate them with minimum effort. Furthermore, the manufacturer must offer utilities support in order to minimise commissioning time and maintenance downtimes. The fourth generation substation incorporates these concepts (Figure 2).

DEVELOPMENT METHODOLOGIES

Principal rules

When designing a transformer substation from functional specifications, the constraints are fixed by applicable standards and market trends. In order to satisfy utility requirements, substations must therefore:

• Be as small as possible.
• Retain liquid dielectrics in the case of a leak.
• Withstand external and internal constraints,
• Evacuate thermal losses, essentially from the transformer,
• Guarantee minimal noise and field emissions,
• Guarantee mechanical stability in case of fire.
Be recyclable. These constraints must be integrated within shorter and shorter deadlines between the market demand and the product qualification phase.

Combination of volumes (Safety, Flexibility)

Market demand means that products have to be developed more rapidly than ever. For this, 3D design tools are particularly suited to transformer substation housings manufactured by moulding, allowing for the volumes and associated constraints to be better catered for. Transformer substations consequently integrate retention volumes, in accordance with standard IEC 61330 [8]. In ultra-compact substations, these same volumes are combined with gas expansion volumes in the event of an internal fault in the MV switchgear (Figure 3).

The drawback in mixing these two volumes presents itself when a fault occurs in the transformer resulting in transformer oil loss followed by an internal fault in the MV switchgear. This case is low probability based on the maximum failure rate concerning dielectric leaks, which is 1.10^-7 per hour of operation for the transformer and 1.10^-7 per hour of operation for the switchgear, is when the internal switchgear fault occurs after the transformer fault which is negligible.

This fault probability already exists in numerous transformer substations in service. These substations evacuate the gas produced from an internal fault in the transformer compartment but frequently just above the relevant liquid dielectric retention levels. This assumes that, as is common only a certain percentage of transformer oil, rather than the maximum oil volume, is in the retention volume.

Internal and external constraints

In view of the constraints they are faced with, transformer substation housings are sized on the basis of software-based calculations that assume the fabrication of buildings from reinforced concrete (Figure 4: Type A). The results do, in fact, require adaptation in order to apply them to “Steel Fibre Reinforced Concrete” (Figure 4: Type B) or “Glass Reinforced Concrete” (Figure 4: type C) both of which are used in the construction of transformer substation housings.

There is a large gap in the cost/strength compromise between type B and type C concrete. We have therefore developed a type D concrete, the performance of which is set out in the table below (Figure 5).

This understanding of the different materials allows us to combine them, thereby achieving an optimum cost/performance ratio when producing a substation that is based on several components (Figure 6).

Calculations that include external constraints (snow, wind, earthquakes etc.) are integrated into the software, which provides an indispensable tool when designing for the different permanent or working load combinations.

The occurrence of an internal fault requires the integration of an additional constraint. Its value will depend on the pressure generated by the MV switchgear in the event of an internal arc, which is obtained either by calculation or by testing. This allows us to optimise the strength of the substation building and the materials chosen on the basis of
technical-financial criteria. A simulation tool (Figure 7) has been developed in order to predict the pressures to which the transformer substation will be subject. This tool is based on thermodynamic calculations, using the perfect gas equation of state in the case of air [7] and/or in the case of SF₆ [8].

![Figure 7: Lists of external factors and adjustments of values](image)

Without re-defining the equations concerning the internal arcing behaviour of the switchgear, already referred to in various other research works [9], an overview of the results is set out in Figure 8. Such research must be pursued in order to account for the metallization of the components inside the MV/LV switchgear and leaks from the second expansion volume.

![Figure 8: 1 Predicted curve 2 Curve after testing](image)

**Material control using heat treatment**

In order to achieve a suitable balance between the strength of the material and productivity, it is sometimes necessary to produce several concrete parts per day. For this, we can optimise productivity by subjecting the concrete to heat treatment. A tool has therefore been developed which allows us to simulate the heat treatment phases required to deduce the equivalent age of the concrete (Figure 9). The equivalent age in hours permits us, as a function of the concrete reference curve (Figure 10), to determine the estimated strength at the end of the heat treatment. Concrete therefore shows sufficient strength for initial handling operations.

![Figure 9: Heat cycle creation tool](image)

![Figure 10: Sample concrete reference curve](image)

**Evacuation of thermal loss by natural ventilation.**

An identical approach to that of the preceding chapter is also used for the phenomena to be contemplated when sizing natural ventilation for transformer substations led us to develop a special tool. This allows us to achieve a calculation/measurement deviation that is less than 2°C [10].
Transformer substation emissions

Emissions produced from transformer substations can be broken down into noise, electric and electromagnetic fields. The maximum admissible noise levels for a transformer substation are stipulated by local regulations, or decided upon the basis of an agreement between the utility and the manufacturer. Limit levels are either as an absolute value or a relative limit of several decibels with respect to ambient noise. In all cases, measurements are in accordance with the current IEC standard [11]. The emission of electromagnetic fields requires special attention, above all on the basis of numerous research reports [12] that can be accessed via WHO (World Health Organisation). The European limits [13] of 1999 contain values that are already applied in Germany, as per the regulation 26.BImSchV de 1996 (5kV/m for electric fields and 100μT for electromagnetic fields, measured in accordance with standard DIN VDE 0848-1). In all cases, the research carried out with a view to measuring the fields emitted by transformer substations should be carried out in accordance with the IEC document in force [14].

FUNCTION GROUPING

The Self Protected Transformer

The Self Protected Transformer [15] is the most notable evolution of substation design over the last ten years. This concept has contributed to increased safety of personnel and the protection of the local environment. This protection is obtained from the self-diagnostic system in the transformer, meaning that it can disconnect itself from the power distribution network in the event of a fault. Manufacturers are now working on the basis of this concept, using specifications drawn up by Electricité de France [16]. An IEC working group has also produced a document on this concept “IEC 60076-13 Self Protected Transformer”.

The Self Protected Transformer developed by ALSTOM disconnects using mechanical, electrical or electro-mechanical fault detectors acting on a three-phase short circuiting device that causes the MV fuses to melt. The fuses are mounted, in series, between the bushing and the high-voltage coils. This three-phase disconnection can be provided in two ways, either by means of three MV fuses and a three phase disconnector, or, innovatively, by two MV fuses and a disconnector fitted to the unfused phase of the MV circuit. In this the disconnector is tripped after the MV fuses have melted. Research, validated by tests, has demonstrated that the probability that three fuses of a given grade (eg. 25 A) would melt and break simultaneously for a 24 kV 6 kA Isc network is 75 %. In the case of the remaining 25%, only two fuses functioned perfectly. This percentage of 25% increases, using the same fuse grade, for larger Isc networks. [18]

In view of this data, our investigations indicated that a two fuse solution with integrated disconnector for the third phase would give a satisfactory performance. Therefore the range of Self Protected Transformers developed by ALSTOM between 1996 and 2000 was fitted with two MV fuses. Versions using two and three MV fuses are currently available. Another innovative feature of the two phase MV fused solution is based on its design, which permits it to operate in a leak-tight enclosure containing the transformer dielectric. The disconnection and contact separation movements take place in a zero voltage environment, thereby preventing the creation of electric arcs that could damage the dielectric strength of the liquid insulant.

In this configuration, with the self protecting system having performed its function, only the high-voltage bushing, the electrical connections between two high-voltage bushings and the two associated MV fuses and the connection between the third high-voltage bushing and the corresponding disconnector contact will be completely insulated.

In all cases the fault detectors determine the occurrence of possible faults, such as:

- Dielectric leak with pre-determined admissible levels of liquid insulant loss in order to reduce the risk of accidental environmental pollution
- Maximum dielectric temperature ( > 120 °C ) due to an overload, resulting in the deterioration of the seals and insulators of the windings
- Large currents controlled by two micro fuses associated with the MV fuses. These micro fuses are calibrated on the basis of the power of the transformer and the supply voltage. These remove the need for MV back up fuses in a non-break zone.
- Overpressure due, for example, to a turn-to-turn fault of one of the high or low-voltage windings, resulting in an ultra-rapid increase of pressure through an explosive gas release.

Other functionalities may be added, such as the detection of a zero phase-sequence fault through the circulation of a current between the magnetic circuit and its armature or the addition of a third micro fuse in the phase not fitted with the MV fuse.

ECO-DESIGN

Transformer substations that are located in the near vicinity of the public, as in the case of urban substations, require environmental protection to be incorporated from the initial design phase. The eco-design approach is therefore used...
during the different development phases. The first of the phases consists in identifying the different masses of each of the materials used. An example of mass distribution for a fourth generation substation is set out below (Figure 11).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sum</th>
<th>% of total mass</th>
<th>Recycling ways</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>4030</td>
<td>62.02</td>
<td>Second use by grinding</td>
</tr>
<tr>
<td>Steel</td>
<td>920</td>
<td>14.06</td>
<td>Recycling</td>
</tr>
<tr>
<td>Aluminium</td>
<td>733</td>
<td>11.21</td>
<td>Recycling</td>
</tr>
<tr>
<td>Oil</td>
<td>530</td>
<td>8.10</td>
<td>Regeneration</td>
</tr>
<tr>
<td>Organics</td>
<td>213</td>
<td>3.26</td>
<td>Recycling</td>
</tr>
<tr>
<td>Reuse</td>
<td>44</td>
<td>0.67</td>
<td>Second use by grinding or incineration</td>
</tr>
<tr>
<td>Others</td>
<td>7.46</td>
<td>0.11</td>
<td>Disparate recycling ways</td>
</tr>
<tr>
<td>Plastic</td>
<td>2.8</td>
<td>0.04</td>
<td>Recycling</td>
</tr>
<tr>
<td>S/Pb</td>
<td>1.14</td>
<td>0.02</td>
<td>Regeneration</td>
</tr>
</tbody>
</table>

The greatest mass percentage is that of concrete, a material for which large-scale industrial recycling procedures have been used for many years. Materials other than concrete relate to the switchgear and the transformer. For these materials, manufacturers have been incorporating eco-design processes for some years [17].

CONCLUSION

The constantly evolving transformer substation market requires the understanding of various key areas ranging from electrical engineering, environmental engineering, as well as civil and thermal engineering. The combination of all of these skills allows us to develop increasingly compact substations that are delivered as turnkey solutions that can be connected immediately to networks. The design tools that are adapted to these different areas, allow us to optimise the product while observing cost constraints and prioritising operational and environmental safety. The enclosure, where used, has evolved from a simple brick building to a fully technical product complying with International standards as for example for MV switchgear.

REFERENCES


