Gas-Insulated Substations is an all-inclusive reference guide to gas insulated substations (GIS) which takes account of its basic principles, technology, application, design specification, testing and ownership issues. Practical and theoretical aspects are handled by acknowledged GIS experts who have been involved with the technology from the start. They provide the reader with the knowledge needed to identify a project with GIS, manage the GIS process and then assemble and later maintain that system. This learning resource offers engineering students and manufacturing professionals a sound insight into this important technology at a time when application of GIS is spreading as fresh projects are being launched and more companies are becoming involved.

Key features:

- Written by leading GIS experts who have been involved in the development of the technology since its invention.
- Discusses both the practical and theoretical aspects of GIS.
- Details advanced and basic material, accessible for both existing GIS users and those planning to implement the technology.
- Chapters are written as tutorials and provide helpful references for further reading and study.
- Invaluable guide to practicing electrical, mechanical and civil engineers as well as third and fourth year electric power engineering students.
- A companion website hosting full colour versions of the figures in the book.

www.wiley.com/go/koch/substations
GAS INSULATED SUBSTATIONS
GAS INSULATED SUBSTATIONS

Edited by

Hermann Koch
Energy Transmission, Siemens AG, Germany
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Foreword

Though this book on GIS is new, there is quite a long history of how it all began. Initially, and many years back, the technical leads involved in developing GIS industry standards for IEEE assembled a tutorial and presented it at key IEEE meetings and conferences. The popularity with engineers and industry was quite inspiring so the presentations continued. After each occasion, the contributing authors purposely requested helpful feedback from the attendees. This way, the technical material and information flow was improved and finetuned before the next presentation.

After many years, with an effective, polished product in place, the demand arose to re-package this entire knowledge into one valuable book. And so these technical experts under the leadership of Hermann Koch have purposefully congregated and endeavored to assemble this excellent industry reference book for GIS. It is a comprehensive collection which expands on the knowledge and understanding well beyond any other GIS information currently available in industry books.

It begins with basic information on definitions, the physics of GIS, reliability, design principles, safety aspects, decision factors, and SF$_6$ gas. There is a substantive chapter on the technology of the design, modular components, manufacturing, specification development, instrument transformers and arresters, interfaces, and the bus system alternatives. Then it proceeds into detailed chapters on control and monitoring, testing, installation, and operation and maintenance. This is followed by a chapter providing numerous bus scheme applications, many installation examples, and a case study. This chapter closes with additional information on mobile and mixed technology switchgear (MTS) applications, and future developments. The final chapter addresses other valuable topics including environmental, lifecycle cost analysis, very fast transients, and electromagnetic fields.

This GIS book addresses an impressive amount of involved aspects of the GIS technology, design and application. I am very pleased this book is now available for all the existing power engineers utilizing the advantages of GIS installations, the concerned policymakers and utility leaders, and for students and the generations to come. And I’m also honored to have shared my engineering career with these GIS colleagues who have so generously volunteered their time and energy for the benefit of others.

John Randolph
Chair, IEEE PES Substations Committee 2011–2012
San Francisco, May 2014
Acknowledgements

This book on gas-insulated substations (GIS) is created by a group of expert engineers who have been working to gather in the GIS tutorial working group K2 of the substations committees of the Power and Energy Society (PES) of Institute of Electrical and Electronics Engineers (IEEE). For more than a decade, these experts prepared and presented the GIS tutorial in the USA and around the world. It is time to thank both authors and co-authors for their contributions to the book: Arun Arora, George Becker, John Boggess, Phil Bolin, John Brunke, Ravi Dhara, Arnaud Ficheux, Noboru Fujimoto, Peter Grossmann, Charles L Hand, Richard Jones, Jorge Márquez-Sánchez, James Massura, Venkatesh Minisandram, Pravakar Samanta, Devki Sharma, Dave Solhtalab, Charles L Hand, and Xi Zhu.

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Thank you, John Randolph, for writing this book’s Foreword.

To the editing team, warmest thanks go to Angela Dietrich for the text and Ulrich Ballas for the graphics, both from Siemens AG, Germany. Without their great support, this book would not be possible under the dense working load of engineers mentioned above.

Thanks also to the professional work of the editorial and production staff of John Wiley & Sons who were a great help in organizing and setting up the book in a nice looking way.

And of course, I have to thank my wife Edith, my children Christian and Katrin, and their friends Britta and Christopher for giving me the time to work on the book.

May this book be a great help to all engineers active in the gas-insulated substation business and be an enjoyable read or reference to them as well.

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Hermann Koch

Gerhardshofen, Germany

May 2014
1

Introduction

Authors: Hermann Koch and John Brunke
Reviewers: Phil Bolin, Devki Sharma, Jim Massura, and George Becker

1.1 General

This book is based on the tutorial and panel sessions presented by the experts of gas insulated substations in the working group K2 of the IEEE Substations Committee. Gas insulated substations (GIS) were invented in the early 1960s with the first projects in the mid 1960s in the United States and Europe. In thousands of installed bays of GIS today, we can look back to a wide range of experiences gained in very different cases of applications.

The IEEE Substations Committee created GIS Subcommittee K0 more than twenty years ago and since then this subcommittee has continuously worked on standards and guides in the field of GIS technology and application. About twenty standards and guides related to the GIS have been published to-date, with continuous revision work in progress on all documents.

Around the year 2000 the experts of the GIS Subcommittee started to collect information on GIS and developed a tutorial on Gas Insulated Substations (GIS) and Transmission Lines (GIL). This working group is numbered as K2 in the GIS Subcommittee.

1.1.1 Organization

The organization of the Substations Committee has developed over the last decades with the focus on any equipment and systems related to substations. In Figure 1.1 the principal organization of the Substations Committee of today is shown.

In blue, the administrative level shows the chairman as the leader and the legislative administrative subcommittee B0, where all chairmen of the subcommittees of the Substations Committee are voting members. All decisions in the Substations Committee are taken here.

The green boxes are supporters of the chairman to help him carry out all the work by splitting tasks to the vice chairman, secretary, past chairman, standards coordinator, transaction editor,
awards nominator, and meeting planner. These functions are elected every two years but can be extended by re-elections.

The actual standards’ work is done in the working groups organized by the subcommittees, which cover:

C0: Data acquisition, processing and control systems with a focus on substation requirements as part of the overall network

D0: Transmission and distribution substation design for a medium voltage substation in the range of 1 kV up to and including 52 kV and a high voltage substation above 52 kV

E0: Transmission and distribution of substation operations for medium voltage substations in the range of 1 kV up to and including 52 kV and high voltage substations for above 52 kV

I0: High voltage power electronics stations for DC equipment above 1.5 kV to be installed in a substation or converter station like AC/DC converters, coils, filters, grounding, and software for control and protection

K0: Gas insulated substations for AC high voltage equipment above 1 kV of switchgear, disconnectors, and ground switches (GIS) and power transmission (GIL)

The responsibility for the GIS/GIL tutorial is with working group K2. In this working group the content of the tutorial has been worked out and discussed before the tutorials have been presented. Working group K2 has presented the content of the tutorial at IEEE meetings several times, sometimes as a half or full day tutorial or in other cases as a panel discussion, always with the focus to bring the information to the engineers participating from the electric power industry.

In the present case, the tutorial content will be revised and finally published as a GIS Handbook.
1.1.2 Experts over the Years

Over the years, a wide range of experts have left their footprint in the tutorial and enriched it with a wide range of information. The members of the tutorial working group K2 have, over the last decade, all contributed with their experiences and knowledge accumulated over many years in many executed projects as users of GIS, manufacturers, or consultants. The working group includes members from the United States of America (US), France (FR), and Germany (DE) to give an international outlook.

The active members are listed in Table 1.1 and the past members are listed in Table 1.2.

1.1.3 Content of the Tutorial

The tutorial is split into modules that cover many aspects of GIS in practical application. The focus of the content is to bring practical knowledge to the engineer to support his or her daily work.

- M1 – Overview. Gives an overview of the content and organization of the tutorial.
- M2 – GIS Basics. Here the basic knowledge of GIS is explained for practical applications.
- M3 – GIS Applications. Here a wide area of applications is given to show the large variations.
- M4 – GIL Basics. Here the basic knowledge of GIL for practical applications is given.

Table 1.1  Active members of the tutorial in 2012

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<td>Hermann Koch</td>
<td>Siemens</td>
<td>DE</td>
<td>Since 2002</td>
</tr>
<tr>
<td>Venkatesh Minisandram</td>
<td>National Grid</td>
<td>US</td>
<td>Since 2002</td>
</tr>
<tr>
<td>Ryan Stone</td>
<td>Mitsubishi</td>
<td>US</td>
<td>Since 2006</td>
</tr>
<tr>
<td>Peter Grossmann</td>
<td>Siemens</td>
<td>DE</td>
<td>Since 2008</td>
</tr>
<tr>
<td>Charles L. Hand</td>
<td>SCE</td>
<td>US</td>
<td>Since 2010</td>
</tr>
</tbody>
</table>

Table 1.2  Past active members

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Country</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lutz Boettger</td>
<td>ABB</td>
<td>US</td>
<td>2002 to 2006</td>
</tr>
<tr>
<td>Hugues Bosia</td>
<td>AREVA</td>
<td>FR</td>
<td>2002 to 2007</td>
</tr>
<tr>
<td>Wolfgang Degen</td>
<td>Consultant</td>
<td>DE</td>
<td>2002 to 2008</td>
</tr>
<tr>
<td>Mel Hopkins</td>
<td>CGIT</td>
<td>US</td>
<td>2002 to 2005</td>
</tr>
<tr>
<td>Deborah Ottinger</td>
<td>EPA</td>
<td>US</td>
<td>2002 to 2005</td>
</tr>
<tr>
<td>Joseph Pannunzio</td>
<td>AREVA</td>
<td>FR</td>
<td>2010 to 2013</td>
</tr>
</tbody>
</table>
• M5 – GIL Applications. Here many applications in typical surroundings and laying methods are explained.
• M6 – Mixed Technology Switchgear. Here the compact or hybrid types of partly gas insulated and air insulated technology is given.
• M7 – SF₆. Here the knowledge of handling, atmospheric impact, and recycling is given.
• M8 – GIS Overloading. Here the specific conditions and rules for overloading of GIS are explained.
• M9 – Theory. Here the physical theory and gas insulated systems with SF₆ is explained.
• M10 – Life Cycle Assessment. Here the impact for the lifetime of GIS is explained.
• M11 – Future Development. Here the next steps in development are explained for GIS.
• M12 – GIS Specification. Here the rules and conditions for correct specification of GIS are explained.
• M13 – GIS Monitoring. Here the monitoring systems for control and supervision are explained.
• M14 – Gas Handling. Here details of correct gas handling when dealing with SF₆ are given.
• M15 – Digital Communication IEC 62271-3. Here the impact of digital communication in substations is explained.
• M16 – Revision of C37.122 GIS. Here information of the latest revision of the GIS standard is given.

1.1.4 Tutorials and Panels Given

The tutorial and panel sessions have been given 22 times through 2011 at various locations in the United States of America, India, and South America (see Table 1.3). The tutorials have attracted over 700 participants in small (10 attendees) and larger (100 attendees) groups over the last ten years.

To present the complete set of the modules it would be necessary to have a tutorial lasting two or three days, which is considered to be too long and inconvenient for most of the engineers to attend. Thus, the decision was made to combine all the tutorial information in a GIS Handbook that can be consulted by the designers and users at their convenience.

1.2 Definitions

This GIS Handbook is based on definitions used in IEEE and IEC standards. Some of the most important definitions for better understanding of the book are listed below.

1.2.1 GIS

There are two definitions used in IEC “Gas Insulated Switchgear” and IEEE “Gas Insulated Substations.” The reason has an historical background, where IEC started in SC 17A to develop circuit breaker standards and later started a new subcommittee SC 17C on high voltage switchgear assemblies, so the link was made to switchgear. In IEEE, the substation committee developed standards on GIS in the substation subcommittee, so the link of GIS was taken to substations.

In IEEE C37.122:

Gas insulated switchgear (GIS): a compact, multicomponent assembly, enclosed in a grounded metallic housing in which the primary insulating medium is SF6 and which normally includes buses, switches, circuit breakers, and other associated equipment.
Table 1.3 Conferences where the tutorials have been presented

<table>
<thead>
<tr>
<th>Conference</th>
<th>Location</th>
<th>Year</th>
<th>Attendance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substations Committee Meeting</td>
<td>Sun Valley, USA</td>
<td>April 2003</td>
<td>20</td>
</tr>
<tr>
<td>T&amp;D Conference and Exhibition</td>
<td>Dallas, USA</td>
<td>Sept. 2003</td>
<td>50</td>
</tr>
<tr>
<td>Substations Committee Meeting</td>
<td>New Orleans, USA</td>
<td>April 2004</td>
<td>20</td>
</tr>
<tr>
<td>PES General Meeting</td>
<td>Denver, USA</td>
<td>July 2004</td>
<td>10</td>
</tr>
<tr>
<td>Switchgear Committee Meeting</td>
<td>Tucson, USA</td>
<td>Sept. 2004</td>
<td>40</td>
</tr>
<tr>
<td>Substations Committee Meeting</td>
<td>Tampa, USA</td>
<td>April 2005</td>
<td>20</td>
</tr>
<tr>
<td>PES General Meeting</td>
<td>San Francisco (Panel), USA</td>
<td>June 2005</td>
<td>30</td>
</tr>
<tr>
<td>IEEE Distinguished Lecturer Program</td>
<td>Dehli, Kolkata, Cheney, India</td>
<td>August 2005</td>
<td>50</td>
</tr>
<tr>
<td>Substations Committee Meeting</td>
<td>Scottsdale, USA</td>
<td>April 2006</td>
<td>15</td>
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<tr>
<td>PES General Meeting</td>
<td>Montreal, Canada (Panel), USA</td>
<td>June 2006</td>
<td>20</td>
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<tr>
<td>Substations Committee Meeting</td>
<td>Bellevue, USA</td>
<td>April 2007</td>
<td>15</td>
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<tr>
<td>PES General Meeting</td>
<td>Tampa (Panel), USA</td>
<td>June 2007</td>
<td>15</td>
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<tr>
<td>Substations Committee Meeting</td>
<td>San Francisco, USA</td>
<td>April 2008</td>
<td>20</td>
</tr>
<tr>
<td>T&amp;D Conference and Exhibition</td>
<td>Chicago (Panel), USA</td>
<td>April 2008</td>
<td>100</td>
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<tr>
<td>PES General Meeting</td>
<td>Pittsburgh (Panel), USA</td>
<td>July 2008</td>
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<tr>
<td>IEEE DLP</td>
<td>Lima, Peru and La Paz, Bolivia</td>
<td>August 2008</td>
<td>50</td>
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<tr>
<td>IEEE DLP</td>
<td>Pune, Kolkata and Kanpur, India</td>
<td>Sept. 2008</td>
<td>70</td>
</tr>
<tr>
<td>Substations Committee Meeting</td>
<td>Kansas City, USA</td>
<td>May 2009</td>
<td>15</td>
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<tr>
<td>PES General Meeting</td>
<td>Calgary, Canada</td>
<td>July 2009</td>
<td>10</td>
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<tr>
<td>UHV Test Base State Grid</td>
<td>Beijing, China</td>
<td>March 2010</td>
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<tr>
<td>T&amp;D Conference and Exhibition</td>
<td>New Orleans, USA</td>
<td>April 2010</td>
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<tr>
<td>PES General Meeting</td>
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<td>T&amp;D Conference and Exhibition</td>
<td>Chicago, USA</td>
<td>July 2012</td>
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<tr>
<td>ISGT Conference</td>
<td>Berlin, Germany</td>
<td>August 2012</td>
<td>15</td>
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<tr>
<td>IEEE PES ICPEN</td>
<td>Arunachal Pradesh, India</td>
<td>December 2012</td>
<td>45</td>
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<tr>
<td>IEEE PES Austrian Chapter</td>
<td>Graz, Austria</td>
<td>March 2013</td>
<td>45</td>
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<tr>
<td>IEEE PES Costa Rica Chapter</td>
<td>San Jose, Costa Rica</td>
<td>June 2013</td>
<td>35</td>
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<tr>
<td>IEEE PES El Salvador Chapter</td>
<td>San Salvador, El Salvador</td>
<td>June 2013</td>
<td>40</td>
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<tr>
<td>IEEE PES CATCON</td>
<td>Kolkata, India</td>
<td>December 2013</td>
<td>55</td>
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<tr>
<td>T&amp;D Conference and Exhibition</td>
<td>Chicago, USA</td>
<td>April 2014</td>
<td>63</td>
</tr>
</tbody>
</table>

Total 1018

In IEC 62271-203:

Metal-enclosed switchgear and controlgear: switchgear and controlgear assemblies with an external metal enclosure were intended to be earthed, and complete except for external connections. There is no specific definition of GIS.

1.2.2 Metal-Enclosed Switchgear and Controlgear

Switchgear and controlgear assemblies with an external metal enclosure were intended to be earthed and complete except for external connections, as defined in IEC 62271-203.

1.2.3 Gas Insulated Metal-Enclosed Switchgear

Metal-enclosed switchgear in which the insulation is obtained, at least partly, by an insulating gas other than air at atmospheric pressure, as defined in IEC 62271-203. This term generally
applies to high voltage switchgear and controlgear. Three-phase enclosed gas insulated switchgear applies to switchgear with the three phases enclosed in a common enclosure. Single-phase enclosed gas insulated switchgear applies to switchgear with each phase enclosed in a single independent enclosure.

1.2.4 Gas Insulated Switchgear Enclosure

Part of the gas-insulated metal-enclosed switchgear retaining the insulating gas under the prescribed conditions necessary to maintain the highest insulation level safely, protecting the equipment against external influences and providing a high degree of protection to personnel, as defined in IEC 62271-203.

In IEEE C37-122, a grounded part of the gas insulated metal-enclosed switchgear assembly retaining the insulating gas under the prescribed conditions necessary to maintain the required insulation level, protecting the equipment against external influences and providing a high degree of protection from an approach to live energized parts.

1.2.5 Compartment of GIS

A section of a gas insulated switchgear assembly that is enclosed except for openings necessary for interconnection provides insulating gas isolation from other compartments. A compartment may be designated by the main components in it, for example, circuit breaker compartment, disconnect switch compartment, bus compartment, and so on, as defined in IEEE C37.122.

A compartment of GIS as defined in IEC 62271-203 as part of a gas insulated metal-enclosed switchgear, is totally enclosed except for openings necessary for interconnection and control. A compartment may be designated by the main component contained therein, for example, circuit breaker compartment or bus bar compartment.

1.2.6 Design Pressure of Enclosures

The maximum gas pressure to which a gas insulated switchgear enclosure will be subjected under normal service conditions, including the heating effects of rated continuous current, as defined in IEEE C37.122.

1.2.7 Gas Monitoring Systems

Any instrumentation for measuring, indicating, or giving remote warning of the condition or change in condition of the gas in the enclosure, such as pressure, density, moisture content, and so on, as defined in IEEE C37.122.

1.2.8 Gas Leakage Rate (Absolute)

The amount of gas escaping by a time unit expressed in units of Pa m³/s, as defined in IEEE C37.122.

1.2.9 Gas Leakage Rate (Relative)

The absolute leakage rate related to the total amount (mass or volume) of gas in each compartment at the rated filling pressure (or density). It is expressed in percentage per year, as defined in IEEE C37.122.
1.2.10 Gas Pass Through Insulator
An internal insulator supporting one or more conductors specifically designed to allow the passage of gas between adjoining compartments, as defined in IEEE C37.122.

1.2.11 Gas Zone
A section of the GIS, which may consist of one or several gas compartments that have a common gas monitoring system. The enclosure can be single-phase or three-phase, as defined in IEEE C37.122.

1.2.12 Local Control Cubicle (or Cabinet) (LCC)
A cubicle or cabinet typically containing secondary equipment including control and interlocking, measuring, indicating, alarm, annunciation, and mimic one-line diagrams associated with the primary equipment. It may also include protective relays if specified by the user.

1.2.13 Support Insulator
An internal insulator supporting one or more conductors, as defined in IEC 62271-203.

1.2.14 Partition
Part of an assembly separating one compartment from other compartments. It provides gas isolation and support for the conductor (gas barrier insulator), as defined in C37.122.
A partition as defined in IEC 62271-203, which is a support insulator of gas insulated metal-enclosed switchgear separating one compartment from other compartments.

1.2.15 Power Kinematic Chain
A mechanical connecting system from and including the operating mechanism up to and including the moving contacts, as defined in C37.122.

1.2.16 Design Pressure of Enclosures
Relative pressure used to determine the design of the enclosure. It is at least equal to the maximum pressure in the enclosure at the highest temperature that the gas used for insulation can reach under specified maximum service conditions. The transient pressure occurring during and after a breaking operation (e.g., a circuit breaker) is not to be considered in the determination of the design pressure, as defined in IEC 62271-203.

1.2.17 Relative Pressure across the Partition
Relative pressure across the partition is at least equal to the maximum relative pressure across the partition during maintenance activities. The transient pressure occurring during and after a breaking operation (e.g., a circuit breaker) is not to be considered in the determination of the design pressure, as defined in IEC 62271-203.

1.2.18 Operating Pressure of Pressure Relief Device
Relative pressure chosen for the opening operation of pressure relief devices, as defined in IEC 62271-203.
1.2.19 **Routine Test Pressure of Enclosures and Partitions**

Relative pressure to which all enclosures and partitions are subjected after manufacturing, as defined in IEC 62271-203.

1.2.20 **Type Test Pressure of Enclosures and Partitions**

Relative pressure to which all enclosures and partitions are subjected for type test, as defined in IEC 62271-203.

1.2.21 **Rated Filling Pressure** $p_{re}$

Insulation and/or switching pressure (in Pa), to which the assembly is filled before putting into service. It is referred to at the standard atmospheric air conditions of $+20\,^\circ\text{C}$ and 101.3 kPa (or density) and may be expressed in relative or absolute terms, as defined in C37.122.

1.2.22 **Bushing**

A device that enables one or several conductors to pass through a partition, such as a wall or a tank, and insulate the conductors from it, as defined in IEC 62271-203.

1.2.23 **Main Circuit**

All the conductive parts of gas insulated metal-enclosed switchgear included in a circuit that is intended to transmit electrical energy, as defined in IEC 62271-203.

1.2.24 **Auxiliary Circuit**

All the conductive parts of gas insulated metal-enclosed switchgear included in a circuit (other than the main circuit) intended to control, measure, signal, and regulate. The auxiliary circuits of gas insulated metal-enclosed switchgear include the control and auxiliary circuits of the switching devices, as defined in IEC 62271-203.

1.2.25 **Design Temperature of Enclosures**

Maximum temperature that the enclosures can reach under specified maximum service conditions, as defined in IEC 62271-203.

1.2.26 **Service Period**

The time until a maintenance, including opening of the gas compartments, is required, as defined in IEC 62271-203.

1.2.27 **Transport Unit**

Part of gas insulated metal-enclosed switchgear suitable for shipment without being dismantled, as defined in IEC 62271-203.