Bibliometric review of emerging technologies in Gas Insulated Substations SF6

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Abstract. The gas insulated substations (GIS) are made up of a set of equipment submerged in SF6 gas and a metal enclosure in which all the equipment associated with the substation is located. The GIS are being widely used in the high voltage electrical sector, due to this, developments and a high degree of research corresponding to new trends or emerging technologies that allow advances in this equipment are being presented. For this reason, this report contains a documentary investigation on the subject of isolated gas substations, through which a bibliometric analysis was carried out that allowed observing the high interest that GIS present in the scientific community in different parts of the planet. The objective of this work is to provide information corresponding to GIS such as some technical characteristics, a regulatory framework and new emerging technologies.

1. Introduction

A gas insulated substation is the set of electrical devices and appliances immersed in the dielectric gas Sulphur hexafluoride (SF6), contained within an aluminum alloy enclosure [1]. These substations can be used in industrial areas to meet high demands for electrical power through a space-saving design with minimal cost in maintenance and operation. These technologies are typically modular in design and can be used both indoors and outdoors [2], [3]. The GIS have advantages such as small volume, less maintenance and good technical performance, being a type of advanced high voltage electrical distribution equipment that is developing rapidly [4].

In GIS, the two main insulating media used are SF6 gas and solid insulating supports called spacers. The most used materials for spacer insulation functions are alumina and epoxy resin. The preferred shapes of spacers are disc, pole and cone type [5].

The most important element for gas insulated substations is the SF6, which is used as a means of isolating GIS busbars and equipment, and in the switches it is used as a means of extinguishing the electric arc produced by the opening or closing of the interrupting device contacts [6], [7].

Considering that gas is an important factor in ensuring safety in both construction and operation, it is important to have constant monitoring of this element [8], through the use of measuring instruments capable of detecting lack of SF6 gas [9], because the gas in the presence of moisture has by-products that have a high degree of toxicity [10], being moisture one of the biggest problems in the presence of failures in the insulation systems of electrical equipment [11], which compromises the reliability of the substation, affecting the quality indicators of the electric service supplied [12]. The
substation operating conditions must be adapted to future changes in the regulations of the transmission networks, since they can generate a technical-economic impact in the sector [13]. In addition, this gas is also classified as a gas with high greenhouse potential by the KYOTO protocol [14]. Therefore, in this work a documentary search was carried out with respect to emerging technologies that consider regulatory frameworks and allow significant improvements in these equipments.

This document is organized as follows, Section II presents the concept of gas insulated substation, in Section III gas quality and leak prevention, in section IV the technical standards corresponding to encapsulated substations, section V presents a bibliometric review with respect to emerging GIS technologies, and section VI presents the conclusions of this paper.

2. Gas insulated substations

Gas insulated substations (GIS) consist of a compact set of several components, enclosed in a grounded metal enclosure in which the primary insulating medium is a compressed gas. Within this envelope are the busbar and equipment associated with the substation such as circuit breaker, disconnectors, busbars and instrumentation transformers [3], [15], [16], [17], [18].

A gas insulated substation uses a superior dielectric gas, SF6 Sulphur hexafluoride, at a moderate pressure for phase-to-phase and phase-to-ground insulation [19].

Gas insulated substations are used when little installation space is required or there is a high impact on the environment. Sulphur hexafluoride is the gas used as an isolation medium for this type of substations, because dielectric stiffness this atmospheric pressure gas is three times that of air, and the space required for installation is only 10% to 25% of those required in an air-insulated substation (AIS) [6], [20], [21]. Figure 1 illustrates the scheme of an isolated substation in ABB brand gas.

The gas insulated substation has the following main characteristics [2]:

- Units assembled and tested from manufacturing.
- Operational life over 50 years.
- Major inspection not before the age of 25.
- Self-lubricating motor-operated mechanisms.
- Minimum cleaning requirement.
- Corrosion resistant.
- Low probability of failure/high availability.
- Protected against aggressive environmental conditions.
- Seismic-resistant.

The GIS envelope must be electrically grounded. In the middle of the envelope is the conductor (bar) attached through cones called separators. The area between the bar and the driver is filled with SF6 gas at a pressure between three to 7 bar [6]. The basic design of the envelope is illustrated in figure 2.

Encapsulation is the main protection of electrical components against external influences such as environmental effects [21]. In addition, the metal envelope reliably prevents electrical parts under voltage from being touched, providing protection to service personnel from the direct consequences of the arches due to internal dielectric faults [22].
Figure 1. ABB's GIS. 1) busbar with high voltage switches combined and grounding switches, 2) circuit breaker, 3) current transformer, 4) voltage transformer, 5) combined high voltage switches and grounding switches, 6) high-speed grounding switches, 7) cable terminal, 8) control cabinet. By: [23].

Figure 2. Basic design of a GIS envelope.

3. SF₆ Gas Quality and leak prevention
The most important element for GIS technologies is the sulphur hexafluoride gas which is used as an insulator of busbars and equipment and as a means of arc extinction. Use requires a high degree of purity because otherwise the dielectric coefficient of the gas is reduced [6].

A gas with 100% purity has some physical and chemical properties such as thermal conductivity and sound propagation rate, properties that can be verified with portable instruments. Contamination causes changes in gas properties [9]. To determine contaminants, the comparison between contaminated gas and a pure SF₆ gas [15], [24].

When a leak occurs, it is important to find the exact location of each vanishing point, which in most cases is difficult to detect. To locate leaks an instrument that is used to perform SF₆ leak detection issued, after inspection the maintenance team can take the necessary steps to eliminate the problem [9]. GIS during construction and operation are closely monitored and regulated, but there is
always the possibility of accidents, because a dangerous situation could arise if SF6 gas escapes and effective measures are not given to eliminate contaminants on time [8]. While SF6 is a chemically stable gas (non-toxic, inert, non-flammable gas), it can cause suffocation when its concentration in the air exceeds $12 \text{ mg/m}^3$ [10], [25]. Leakage is due, in their normality to insufficient resistance of the GIS structure, caused mainly by defects in design and operation [26], [27].

Since Sulphur hexafluoride gas has high dielectric performance and interrupt capacity, it is widely used in the electrical energy industry [28]. When subjected to an electric arc and when the gas temperature exceeds 600 °C, it decomposes and recomposes extremely quickly when the temperature drops again, allowing the gas to regain its electrical resistance [29], [30]. This recovery property makes it suitable for high voltage switches. However, at 140°C, after operating for a period longer than 25 years, approximately 5% [25]. Can be broken down. It is known that some by-products are of high toxicity, particularly those that occur during discharges in the presence of moisture [10].

4. Regulatory framework
In this section the main rules applicable to gas-insulated substations are presented (table 1 and table 2).

### Table 1. Regulations applicable up to GIS.

| Source | Standard | Description |
|--------|----------|-------------|
| [31]   | IEEE Std. 1125-1993, IEEE Guide for Moisture Measurement and Control in SF6 Gas-Insulated Equipment | It describes guidelines for measuring moisture level, interpreting moisture data, and controlling moisture in gas-insulated transmission class equipment. |
| [32]   | IEEE Std. C37.123-1996, Guide to Specifications for Gas-Insulated, Electric Power Substation Equipment | Technical requirements for the design, manufacture, testing and installation of a gas-insulated substation (GIS) are described. |
| [15]   | IEEE Std. C37.122.1-1993, IEEE Std. Guide for Gas-Insulated Substations. | This guide provides information of special relevance for the planning, design, testing, installation, operation, and maintenance of substations and gas-insulated equipment (GIS). |
| [33]   | IEEE Std. 693-1997, IEEE Recommended Practice for Seismic Design of Substations | Recommendations for seismic substation design, including the qualification of each type of equipment, are discussed. |
| [34]   | IEEE Std. 1127-1998, IEEE Guide for the Design, Construction, and Operation of Electric Power Substations for Community Acceptance and Environmental Compatibility | Significant elements of community acceptance and environmental compatibility are identified and will be considered during the planning and design phases, the construction period and operation of power substations, and the document ways to address these concerns in order to obtain community acceptance and environmental compatibility. |
| [35]   | IEC 62271-1 2007, IEC High-voltage switchgear and control gear - Part 1: Common specifications | IEC 62271 applies to AC distribution devices designed for indoor and outdoor installation and for operation at service frequencies up to 60 Hz even in systems with voltages greater than 1000 V. |
| [36]   | IEC 62271-203:2003, IEC high-voltage switchgear and control gear - Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV | Specifies the requirements for gas-insulated substations, enclosed in metal where insulation is obtained, at least in part, by an insulating gas other than atmospheric pressure air, for alternating current of rated voltages greater than 52 kV, for indoor and outdoor installation, and for service frequencies up to 60 Hz. |
Table 2. Regulations applicable up to GIS.

| Source | Standard | Description |
|--------|----------|-------------|
| [37]   | IEC 60137: 2017, Insulated bushings for alternating voltages above 1 000 V | Specifies the characteristics and tests for insulated bushings. This standard applies to bushings, as defined in Clause 3, intended for use in electrical appliances, machinery, transformers, substations and installations for three-phase AC systems, which have the highest voltage for equipment above 1000 V and power frequencies of 15 Hz. up to 60 Hz. |
| [38]   | IEC 60376:2018, Specification of technical grade sulphur hexafluoride (SF6) and complementary gases to be used in its mixtures for use in electrical equipment. | Defines the quality of technical grade Sulphur hexafluoride (SF6) and complementary gases such as nitrogen (N2) and carbon tetrafluoride (CF4) for use in electrical equipment. |
| [24]   | IEEE Std 1416-1998, IEEE Recommended Practice for the Interface of New Gas-Insulated Equipment in Existing Gas-Insulated Substations | Recommendations for connecting a gas-insulated substation to a gas-insulated substation of a different brand are described. |
| [37]   | IEC 60137: 2017, Insulated bushings for alternating voltages above 1 000 V | Specifies the characteristics and tests for insulated bushings. This standard applies to bushings, as defined in Clause 3, intended for use in electrical appliances, machinery, transformers, substations and installations for three-phase AC systems, which have the highest voltage for equipment above 1000 V and power frequencies of 15 Hz. up to 60 Hz. |

5. Bibliometric review

5.1. Bibliometric analysis

The methodology applied consisted of the analysis of 576 documents in the subject of study, obtained through the search in the Web of Science database, using as a keyword "gas insulated substations", with this input were proposed bibliometric indicators, allowing to analyze the temporal evolution of the subject between 2011 and 2020.

The countries with the greatest scientific contribution to gas-insulated substations are illustrated in Figure 3. Where it can be seen that China is the country that stands out the most because it has the highest number of publications with a total of 276 publications between 2011 and 2020, followed by Japan with 117 publications in the same time period. Figure 3 illustrates the number of country publications in the 2011-2020 period.

![Figure 3. Number of publications by country in the 2011-2020 period.](image)
In Figure 4 shows the publications recorded in the 2011-2020 period, allowing to identify that the years with the highest number of publications were 2017 with 75 and 2018 with 71 publications, respectively.

![Figure 4](image)

**Figure 4.** Number of publications per year in the 2011-2020 period.

Figure 5 shows the publication register of the 10 universities with the highest number of publications regarding GIS in the world, among which Xi an Jiaotong University stands out the most with the highest number of publications, with a total of 14 publications regarding GIS.

![Figure 5](image)

**Figure 5.** Number of publications by institutions in the 2011-2020 period.
Table 3 features the 10 authors with the highest number of publications between 2011-2020, including the author Okabe S. with a total of 14 publications.

| Authors            | Nº publications |
|--------------------|-----------------|
| Okabe S.           | 49              |
| Ueta G.            | 34              |
| Zhang XX.          | 29              |
| Xiaoxing Zhang     | 28              |
| Chen WJ.           | 26              |
| Thang j.           | 26              |
| Ju Tang            | 24              |
| Li CR.             | 24              |
| Wada J.            | 22              |
| Liu WD.            | 20              |

Table 4 shows the number of publications in the different IEEE journals indexed on The Web of Science. In which the high contribution of IEEE in terms of the research trend regarding gas-isolated substations can be identified, the journal IEEE transactions on dielectrics and electrical insulation is highlighted for having the highest number of publications in the 2011 to 2020-time period.

| Journal                                         | Nº publications |
|------------------------------------------------|-----------------|
| IEEE transactions on dielectrics and electrical insulation | 182             |
| IEEE transactions on power delivery              | 61              |
| IEEE transactions on plasma science              | 17              |
| IEEE electrical insulation magazine              | 11              |
| IEEE access                                      | 10              |
| IEEE sensors journal                             | 5               |
| IEEE transactions on components packaging and manufacturing technology | 5              |
| IEEE transactions on industry applications       | 4               |
| IEEE transactions on electromagnetic compatibility| 3               |
| IEEE transactions on magnetics                   | 3               |
| IEEE industry applications magazine              | 2               |
| IEEE transactions on applied superconductivity   | 2               |
| IEEE transactions on instrumentation and measurement| 2             |
| IEEE antennas and wireless propagation letters   | 1               |
| IEEE electron device letters                     | 1               |
| IEEE transactions on electron devices            | 1               |
| IEEE transactions on power electronics           | 1               |

5.2. Emerging technology for gas insulated substations
Gas insulated substations present a strong research trend in different parts of the planet, opening a door to the search for emerging technologies for the improvement of these equipment. In table 5, some emerging technologies for the improvement of GIS can be seen.
Table 5. Regulations applicable up to GIS.

| Source | Title                                                                 | Year | Scientific contribution                                                                                                                                                                                                                                                                                                                                 |
|--------|------------------------------------------------------------------------|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [39]   | Research and experiments on an external miniaturized VFTO measurement system | 2020 | A. P. Purnomoadi, A. Rodrigo Mor, and J. J. Smit propose a miniature sensor system that uses a capacitive voltage system and a differentiation-integration circuit to increase the bandwidth of the very fast front transient surge measurement system (VFTO), so that researchers can reduce the damage of equipment caused by VFTO.                                                                                       |
| [40]   | Emerging technologies in high voltage gas insulated switchgear-clean air gis and NCIT | 2019 | The authors propose a new unconventional instrumentation transformer, which offers an advantage over the conventional instrumentation transformer, because it has less copper wiring and therefore allows to open the door to digital substations, presenting better functionality in both measurement and protection.                                                                                     |
| [41]   | Highly Sensitive Acoustic Emission Sensor Based on Polarization-maintaining and Absorption-reducing Polarization-maintaining Fiber | 2018 | X. Li, Y. Zhang, H. Cao, X. Zhang, and R. Shen propose a new type of acoustic emission sensor (AE) based on a polarization maintenance fiber (PANDA) that maintains polarization (PANDA) to detect ultrasound information induced by partial discharge accurately in GIS.                                                                                   |
| [42]   | Electric field computation of epoxy- nano and micro composite conical spacer in a gas insulated bus duct | 2018 | The authors propose an alternative for existing insulating materials, based on the mixture of nano and micro composite polymers that exhibits excellent electrical, thermal, and mechanical properties.                                                                                                                                                                      |
| [43]   | Application of a multi-parameter sensor system for monitoring dielectric insulation of gas mixtures | 2017 | M. Porus, T. A. Paul, and A. Kramer propose a robust, low-cost method for deriving concentration into a binary gas mixture using simultaneous pressure, temperature, and density measurement to detect perfluorinated ketones.                                                                                                                                  |
| [44]   | Research on the microscopic state parameters of SF6/N2 and SF6/CO2 circuit breaker in arc formation process | 2017 | The authors L. Jing, Z. Hao, C. Yundong, L. Shuxin, and Y. Longbin propose to complete a process of formation of SF6/N2 and SF6/CO2 mixtures as an electrical insulation gas.                                                                                                                                                                                                                   |
| [45]   | Comparison of CF3CHCl2 Gas with SF6 Gas as an alternative substitute for gas insulated switchgear equipment | 2017 | Authors T. Juliandhy, T. Haryono, Suharyanto, and I. Perdana say cf3CHCl2 has a high potential as an insulating gas because it has a higher insulation capacity than SF6 gas and is recommended by the KYOTO protocol.                                                                                                                                  |
| [46]   | Development of 72/84 kV dead-tank VCB with rated normal current of 3000 A | 2013 | Author H. Saito et al says that insulated dead tank has been developed in dry air of 72/84 kV type VCB with a nominal normal current of 3000A, which is shown as a feed because the rated normal current of the conventional type is limited to 2000 A.                                                                                                                      |
| [47]   | A survey on the potential of CF3I gas as an alternative for SF6 in high voltage applications | 2010 | Authors M. S. Kamarudin, M. Albano, P. Coventry, N. Harid and A. Haddad say trifluoroyodomethane (CF3I) has recently been considered as a candidate to replace SF6. Because it has been used as a fire suppressor and many researches is being conducted to assess its capacity in high voltage applications.                                                                                                  |

5.3. Patents in the optimization of gas-insulated substation technologies

Taking into account the importance of isolated gas substations and the impact that SF6 generates due to its potential as greenhouse gas, the scientific community and companies dedicated to the invention of these technologies have developed new patents capable of providing alternatives for the use of sf6. Table 6 and Table 7 shows some patents for the optimization of GIS technologies.

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Table 6. Patents in the optimization of gas-insulated substation technologies.

| Source | Title                                                                 | Year | Scientific contribution                                                                                                                                                                                                 |
|--------|----------------------------------------------------------------------|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [48]   | Switchgear having earth switch.                                       | 2019 | A sideboard is provided that includes: a fixed electrode that is arranged inside a cabinet; a moving electrode that is provided corresponding to the fixed electrode and rotates between a first position that is in contact with the fixed electrode and a second position that is separated from the fixed and grounded electrode. |
| [49]   | Use of a linear octafluorobutene as a dielectric compound in an environmentally safe dielectric insulation or arc-extinction fluid. | 2019 | A combination, comprising: a linear octafluorobutene used as a dielectric compound in an arc-extinguishing fluid or environmentally safe dielectric isolation for a device for the generation, transmission, distribution and/or use of electrical energy, where the ratio of the linear octafluorobutene dielectric compound in dielectric or arc-extinguishing isolation fluid is at least 3%. |
| [50]   | Transformer for measuring currents in a gas-insulated substation.     | 2019 | An electronic current transformer for measuring currents, comprising: a Resistive Magnet Tunnel sensor (RMT); a driver; an amplification circuit; an armour structure; a circuit board; where the RMT sensor and amplification circuit are arranged on the circuit board; where the circuit board is arranged between the conductor and the shielding structure; and where the RMT sensor is configured to receive driver data and transmit the data to the amplification circuit, which is configured to amplify the data and release the data as a transformer output. |
| [51]   | Closed loop interferometric sensor using loop gain to determine interference contrast. | 2018 | Sensor to measure interference contrast in an interference-based closed-loop phase modulation optical sensor device, the gain of the feedback circuit is evaluated on a feedback controller. This gain is found to be a measure for contrast. Contrast evaluated in this way can be used, for example, for periods to change when determining the measurement and sensor device. The sensor device can be, for example, a high voltage sensor or a current sensor. This device can be used in HVDC in GIS. |
| [52]   | Apparatus containing a dielectric insulation gas comprising an organofluorine compound. | 2017 | The present invention refers to a device for the generation, transmission, distribution and/or use of electrical energy. The appliance comprises a housing enclosing an insulating space and an electrical component arranged in the insulating space. The insulating space containing a dielectric insulation gas comprising an organ fluorinated compound. The appliance also comprises a desiccant ready to meet the insulating gas. The desiccant contains or consists essentially of lithium bromide, ideal for gas encapsulated substations. |
### Table 7. Patents in the optimization of gas-insulated substation technologies.

| Source | Title | Year | Scientific contribution |
|--------|-------|------|-------------------------|
| [53]   | Temperature measurement in switchgear stations. | 2017 | The model refers to a device for measuring temperature at a high-voltage part of a power station, which is characterized by comprising: at least one temperature sensor located at one point in the high-voltage serving of which the temperature must be monitored, at least one antenna connected to at least one temperature sensor, a control module located in a low voltage part of the switching station and at least one antenna connected to the control module. This invention refers to temperature measurement in high voltage switching stations, type AIS (Isolated Air Substation) or GIS (Isolated Gas Substation) |
| [54]   | Method of extracting a jacket of a gas insulated substation (GIS) under a metal casing. | 2017 | This method refers to a removable stabilizer for a spacer housing of an electrical installation of the GIS type, the spacer housing comprising a first opening as well as a conductor fitted with a hole, the removable stabilizer comprises a plug configured to be inserted through the first opening in the separator housing, being designed the stopper to penetrate the driver's drill to block that conductor against translation movement after such housing spacer has been put under atmospheric pressure. The model of a spring controller for high or medium voltage electrical appliance, with the controller having a freewheel coupling device between a crank or motor and the drive shaft to operate a switching contact of the appliance and respectively providing coupling while loading the springs and decoupling while releasing the springs. The mechanical freewheel device is incorporated into a controller sprocket and includes at least one ratchet that engages or does not engage with an internal set of sprocket teeth. The invention applies more particularly to high or medium voltage switches and particularly to high or medium voltage automatic switches, either for those used in gas-insulated substations (GIS) or those used with air insulation. |
| [55]   | Control of spring(s) type for a high- or medium-voltage breaker furnished with a pawled free wheel coupling device. | 2017 |  |

### 6. Conclusions

Electrical substations play an important role within electrical power systems, thus having to meet safety and reliability requirements within the system, because of this since 1960 the isolated substations with SF6 gas were resulted, to meet the demand for electrical energy reliably and safely, also providing advantages such as little space for installation and lower operating and maintenance costs. These substations have a higher insulation medium than air-insulated substations because it employs a gas with excellent dielectric properties within a metal envelope, ensuring easy operation and greater safety for personnel engaged in installation activities.

However, it is necessary to have constant monitoring of the state of the GIS metal envelope to check that there are no dents, also, constant monitoring should be carried out through the use of sensors or gas measuring instruments SF6 to detect the existence of gas leaks, which may cause accidents in the facility by suffocation if the gas exceeds a concentration and their of $12 \text{mg/m}^3$ [10], [25]. For this reason, we must be persistent in the search for new technologies that can identify these problems quickly and effectively, through scientific research.

On the other hand, SF6 gas is a gas with high greenhouse efficiency according to the KYOTO protocol [14], so there is a need to look for alternatives that can replace the use of SF6 in high voltage applications, with environmentally friendly elements.
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