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Insulation Coordination and Reliability in Modern Substations: Case Study of AIS and GIS in the Egyptian Grid

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ABSTRACT

This paper presents a comparative study among Air-Insulated Substations (AIS) and Gas-Insulated Substations (GIS) with a detailed focus on insulation coordination requirements. MATLAB-based simulations are used to assist the study's thorough examination of insulating characteristics, ionization and attachment coefficients, and surge impedance. In terms of dielectric-strength, dependability, and spatial efficiency, the results show that GIS technology performs noticeably better than traditional AIS while also distinctly defining the crucial electric field thresholds at which breakdown takes place. To put the theoretical discussion into context, a case study of the Magusa power substation in Minya Governorate, Egypt, is presented in this work to illustrate the realistic transition from the old 132/33 kV AIS system to a modern 220/66/11 kV GIS system. According to the study, GIS technology supports Egypt's national grid development ambitions by enhancing insulation reliability; environmental resilience, operational stability, and guiding technology selection in future network expansions.

1. Introduction

The philosophy of insulation coordination is not only a technical matter that is dealt with great interest by specialized researchers and engineers in the field of electrical-power-engineering, but it is also an extremely important economic matter due to the huge financial-losses that occur as a result of the interruption of electrical-supply service. The insulation-coordination offers a methodical framework for creating technically sound and cost-effective insulation levels in electrical-equipment.

Insulation coordination reduces the possibility of catastrophic failure and limits service interruptions by ensuring that each network-component has a predetermined withstand-level capable of handling transient-overvoltages, as opposed to oversizing insulation-arbitrarily [1-3]. The weakest spots in the insulation system, which are usually found close to the surge entry channel, are frequently stressed by transient-overvoltages brought on by switching operations, lightning-impulses, or system malfunctions [4]. If a breakdown is inevitable, it can be prevented by coordinating insulation across transmission lines (TLs), transformers, circuit breakers (CBs), and related equipment. This strategy promotes supply continuity, makes repairs simpler, and avoids widespread outages [5].

Because they combine the duties of generation, transmission, and distribution, substations are essential to this coordinating system. Substation-installed switchgear assemblies are in charge of isolating faults and containing them to specific areas of the system in addition to managing power-flow. This improves the grid's overall stability and stops cascade failures [6]. Therefore, in addition to insulation-requirements, the design of a high-voltage (HV) substation must take into account environmental-considerations, geological and thermal stressors, earthing, lightning protection, and equipment arrangement [7].

Engineers must weigh space, cost, and dependability while choosing an appropriate layout. Gas-Insulated Substations (GIS) and Air-Insulated Substations (AIS) are the two main technologies. Although they serve the same basic purpose, they differ greatly in terms of their insulating media, space needs, and operational features. While GIS offers a more compact-design and enhanced dielectric-strength, making it the better option in urban locations and difficult weather-circumstances, AIS installations continue to be appealing due to their cheaper initial-cost and simple maintenance [8, 9].

In Egypt where transmission networks must be expanded due to fast urbanization and load increase. Thus the choice between AIS and GIS has a big impact on system-dependability, cost, and environmental impact. This work helps to optimize future grid planning by offering a comparative analysis of the insulation coordinating requirements of AIS and GIS within the Egyptian framework.

2. Literature Review

Limitations in land availability may indicate GIS will be used more widely in the future. Nevertheless, the greenhouse effect of the insulating sulfur-hexafluoride gas (SF_6) makes this alternative less appealing despite the highly effective GIS space reduction [7, 10-12]. The IEC 60071 standards, which specify tolerance levels and methods for assessing overvoltages in substations, regulate insulation-coordination globally [13, 14]. The benchmark for guaranteeing uniformity in AIS and GIS designs is these standards. Numerous researches have examined the behavior of AIS insulation, demonstrating the impact of outside variables as temperature, humidity, and pollution. In this regard, Llovera-Segovia, Pedro [15]. showed that under severe conditions, the probability of flashover increases as the insulation-strength of AIS dramatically declines with pollution and surge-duration. According to CIGRÉ technical findings [16], GIS preserves insulating dependability even in coastal or highly-polluted-areas. However, because of its significant potential for global warming, SF_6 has raised concerns regarding sustainability over the long run. The trade-offs of AIS and GIS technologies are emphasized by comparative studies. When Kumar et al. [9] examined their insulation needs, they discovered that AIS is more susceptible to outside influences even though it is less expensive and simpler to install. Although GIS has a larger initial-cost and environmental-impact, Ahmed and Hassan [8] found that it delivers greater reliability and a smaller footprint.

Few studies have been conducted in the Egyptian framework. According to reports from the Egyptian Electricity Holding Company (EEHC) [17], GIS has grown in popularity in Cairo and Alexandria, where pollution and land shortages demand compact and reliable solutions, but AIS continues to dominate in rural areas due to economic considerations.

According to this research, there is a lack of a comprehensive comparison of the insulation-coordination requirements of GIS and AIS systems in Egypt. By bridging this knowledge gap, engineers and decision-makers will be able to optimize future power substations, particularly in Upper Egypt, such as the case study we present in this article, through data-driven insights.

3. Substation Components, AIS and GIS Overview

A. Substation Components

There are often a variety of interior and outdoor switchgear devices at every electrical substation. Every piece of switchgear-equipment has specific functional needs. The equipment is either designed to be indoors or outdoors, depending on the local-environmental-circumstances and voltage-rating. In general, outdoor-switchgear is chosen for voltages greater than 33 kV, whereas indoor equipment is preferable for voltages up to 33 kV [5, 18].

However, in heavily polluted places, indoor equipment can also be employed for high voltages. Large areas have SF_6 - GIS installed at voltages of 33 kV and higher. While the indoor-substation is housed in a metal container known as metal-clad-switchgear, the outdoor-substation is built outdoors [9, 14]. The substation makes use of the switchgear listed below [19]:

- *Circuit breaker*: Is a device that switches and interrupts current. In essence, a CB is made up of both a movable and a fixed contact. An operational mechanism is used to separate the contacts. An arc is created when fixed and moving contact separate. A appropriate medium known as a dielectric (air, vacuum, oil, or SF_6 gas) [12] extinguishes the arc. In an AC sub-station, CBs are required at each switching-point.

- *Isolator (disconnector)*: This disconnecting switch is used to cut off the CB when there is no current flowing through it. Usually, the CB is placed with an isolator. The isolator will open after the circuit-breaker. Once the isolator is open, the earthing switch can be closed to release the trapped electrical charges to the ground.
- *Current transformer (CT) / Potential transformer (PT)*: For measurement, safety, and control purposes, the current and voltage are converted to a lower value.
- *Surge arresters / lightning arresters*: are used to safeguard substation-equipment from lightning and switching overvoltages by directing them to earth.

B. Air Insulated Substations

The conventional-switchgear-substations that have been in use for decades are known AIS. Air serves as the main dielectric-medium for insulation, as the title makes clear. AIS's design begins with the fundamental task of site selection, which covers a sizable land area and the environmental-circumstances for substation construction [20]. Connecting step-up systems to power plants and sizable transformer substations in extra HV (EHV) transmission systems are two of the AIS unit's primary functions.

When considering the substation's layout and operation, the AIS has several beneficial qualities. The main decision regarding the choice of space or area in AIS can be made based on the needs. This system's inexpensive switchgear and construction costs make it viable with a high-quality design. Additionally, it takes less-time to build an AIS system, and its ease of maintenance increases system dependability [7, 9]. Even yet, the AIS system has many drawbacks, such as the inability to endure malfunctions due to the equipment's exposure to environmental factors such pollution, human intervention, salt particle deposition, lightning strikes, and unusual weather [8, 18]. The installation of switchgear requires a lot of space, and regular maintenance raises the system's cost. In addition, the air's weak dielectric qualities and other elements like pollution, dampness, and humidity mean that more room is needed for effectiveness [21].

C. Gas Insulated Substations

While substation installation requires a significant amount of space, conventional AIS commissioning necessitates a far larger area. Because GIS must be small to install, they are more beneficial. The importance of GIS units as power-system assets is growing. In comparison to the traditional AIS, it is a competitive option. The basic idea behind a GIS is to completely enclose all of the live components in a metallic-encapsulation that is filled with compressed SF_6 [12, 22]. Excellent dielectric, physical, and chemical qualities are possessed by sulfur-hexafluoride. To replace SF_6 for insulation in the GIS unit, numerous scientists looked for an alternate gas. A blend of nitrogen gas and SF_6 gas, or SF_6/N_2, was discovered during the quest for an alternative [10]. Unfortunately, though, the mixture performs almost as well as pure SF_6 gas alone. So as to improve the GIS unit's performance, gases such as carbon-dioxide, nitrogen, and dry air were also taken into account. However, it was discovered that SF_6 gas was the most effective gas to improve the GIS unit's performance. 1968 saw the introduction of the first SF_6 HV GIS in history [23]. The GIS unit is protected from the weather by the enclosure. The SF_6 gas is a great insulator that can be employed between the GIS unit's electrified and encapsulated components. Encapsulated in an SF_6 enclosure, GIS consists of all electrified components, such as CBs, disconnectors, earth switches, instrument-transformers, surge arresters, and bus-bars [7]. Unlike traditional AIS equipment, which has the earth surface as its closest ground, a GIS unit has a grounded external shell encapsulating high voltage internal conductors [24]. The GIS unit surge impedance ($\simeq 75\,\Omega$) is higher than the one of regular-oil-filled cables, though not as high as that of OHTL ($\simeq 300{:}400\,\Omega$) [4, 25]. The basic-insulation-level (BIL) of a GIS unit differs from that of a traditional AIS-substation due to these characteristics as well.

The GIS system offers some advantages over the AIS, including safe operation because of the fully earthed metal shell. Due to the shorter distance between the system's active and non-active switchgear components, the GIS unit also takes up less space than a standard AIS unit. Because of its efficient design and defense against the weather, it requires less-maintenance [9]. Since SF_6 gas does not age or exhaust, there is no need to replenish the gas levels over the equipment's roughly ≃ 40-year lifespan [10, 12]. Even with all of the previously stated advantages of GIS system also has drawbacks like the high cost of installation as compared with the standard AIS system. SF_6 gas supply and acquisition become problematic, especially in off-site locations and rugged terrain, which raises the total cost even more.

4. Case Study: Magousa Substation, Egypt

In recent years, the Egyptian Electricity Transmission Company (EETC) has adopted a upgrading strategy to replace old AIS substations with advanced GIS substations [17]. Magousa substation, which is situated in Minia governorate, Egypt, is essential to the distribution and transmission of electricity in Upper Egypt. In the past, the station was run as Air-Insulated Substation AIS at $132/33$ kV equipped with 2×40 MVA transformers feeding the 33 kV network. Due to the aged insulation system, growing load demand, and poor reliability, this configuration-this has been in use for several decades-faces difficulties. Furthermore, operating stress and environmental elements like dust, humidity, and pollution in the immediate vicinity raise the chance of insulation failure. A Single line diagram (SLD) of Magousa substation in its existing 132/33 kV - AIS configuration is shown in Figure 1 (SLD has been modified but is originally based on the layout providing by EPP [26]).

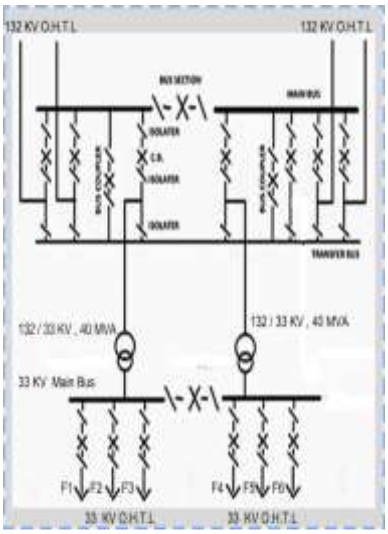

Figure 1: SLD of a 132/33 kV - AIS configuration

The substation is presently undergoing upgrades to a GIS with a voltage-level of $220/66/11\ kV$, as portion of the "Development of the Electric Transmission Grid – Phase II" project, according to the Arab Fund for Economic and Social Development (2022) [17, 27].

- 2×175 MVA transformers (220/66 kV)
- 2×40 MVA transformers (66/11 kV)
- 10×220 KV - GIS CBs
- Fifteen 66 kV bays

Figure 2 shows the main modifications that will be made to the old station to operate with the gas-spark-extinguishing GIS system, where a typical GIS - bay configuration showing isolators, CB, CTs, and earthing switches.

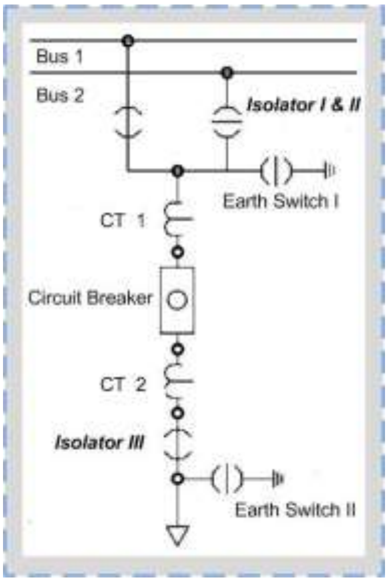

Figure 2: Representative GIS - bay configuration

However, Figure 3 displays a portion of the SLD for $66/11$ KV [26] for the suggested upgraded GIS architecture, emphasizing better insulation reliability and bus configurations.

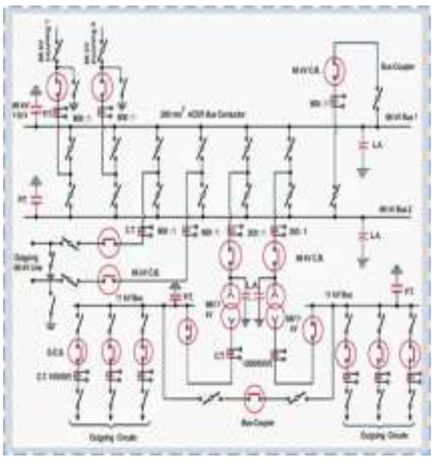
Figure 3: SLD for 66/11 KV for the suggested upgraded GIS station

This expansion demonstrates the widespread use of GIS technology and the notable rise in installed capacity. In addition to improving insulation-coordination, the renovated substation also increases dependability, lowers the amount of land needed, and guarantees steady operation in Upper Egypt's harsh environmental-circumstances. This modification also demonstrates how GIS technology outperforms traditional AIS systems in terms of electrical insulation-strength, ionization-characteristics, and reduced probability of insulation-failure.

5. Ionization Coefficient Curves for SF6 Gas and Air

The approximate mathematical relationships that define the ionization-coefficient $(\alpha - \eta)$ for Air and SF_6 as a function of the decreased-electric-field (E/p) are represented by the following equations. Plotting curves like those found in insulation-coordination studies frequently makes use of these relationships, which are based on experimental-observations [1, 3].

With the decreased electric-field, the ionization-coefficient $(\alpha - \eta)$ for air progressively rises until it approaches a positive growth at about $27 \frac{KV}{cm.bar}$. The following provides an approximate empirical relation [2, 14]:

$$(\alpha - \eta)\_Air \cong A \times e^{\left\{B \times \left(\frac{E}{p} - E0\right)\right\}}, \; for \; \frac{E}{p} > E0 \tag{1}$$

where, A , B are constants fitted from experimental-data,

$\mathrm{E0} = 27 \frac{\mathrm{KV}}{\mathrm{cm.bar}}$ (breakdown threshold).

Strong attachment is indicated by the ionization-coefficient $(\alpha - \eta)$ for SF_6 remaining negative for low E/p values. About $89 \frac{KV}{cm.bar}$ causes it to turn positive and climb sharply. The following is an approximate-empirical relation:

$$(\alpha - \eta)\_SF_6 \cong C \times \left\{\frac{E}{p} - E\_(crit)\right\}, \; for \; \frac{E}{p} > E\_(crit) \tag{2}$$

where, C is a proportionality-constant (steep slope), $\mathrm{E\_(crit)} = 89 \frac{\mathrm{KV}}{\mathrm{cm.bar}}$ (breakdown threshold).

The primary distinction between Air and SF_6 is that the former achieves positive ionization at a significantly lower decreased electric field than the latter. SF6 has a high attachment coefficient because it is a very electro-negative gas [3, 7]. Because larger E/p is needed before ionization takes over, it is hence a great insulating-medium as shown in Figure 4. This feature of SF_6 enables GIS to be significantly more compact than AIS in insulation-coordination.

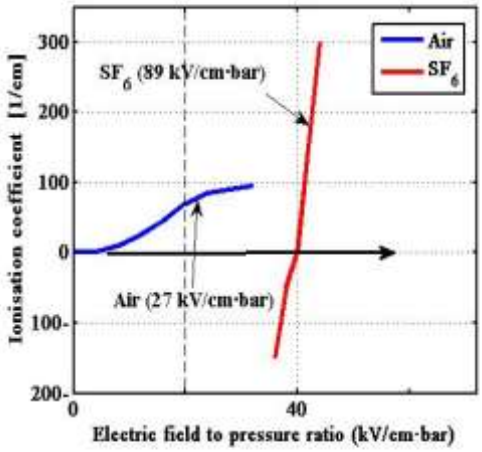

Figure 4: Air and SF6 ionization coefficient growth

6. Comparison between GIS and AIS Insulation Characteristics

Usage has mostly accepted the BIL evaluations for substations with conventional equipment, and standards have been set. However, because of certain characteristics specific to a GIS, these BIL values for conventional equipment cannot be directly applied to GIS equipment. The surge impedance ($\simeq 75\,\Omega$) of a gas-insulated bus is significantly lower than that of a typical overhead line ($\simeq 320 : 440\,\Omega$) and more comparable to an oil-filled cable [19, 25]. Furthermore, compared to a traditional station, a compact GIS typically has a significantly lower bus run. Also, there is no uncovered porcelain and no contamination issues because the GIS system is completely contained within a grounded-housing. Lastly, for the SF_6 -GIS, the BSL (Basic Switching Impulse Insulation-Level) to BIL ratio is nearly equal to unity [25].

Many studies and articles have addressed the insulation properties, but many of them have been focused on GIS and AIS separately [10-12, 20, 22, 24, 25]. Therefore, in this study, I attempt to facilitate this comparison for researchers and specialized engineers by creating these tables. The following table illustrates the main differences between GIS and AIS with regard to insulation properties and lightning response. These arguments are based on discussions of insulation properties, lightning resistance, and BIL.

TABLE 1: Comparison between AIS and GIS for Insulation and electrical properties

Property	AIS	GIS
BIL	Standard values are frequently used and well-established.	Cannot straight use AIS values due to different characteristics.
Surge Impedance	High: $\simeq 320:440\ \Omega$ (similar to O.H.T.L).	Low: $\simeq 75\ \Omega$ (like to oil-filled-cables).
Bus Run Length	Longer, due to superior physical station size.	Much shorter, since GIS is compact.
Insulation and Construction	Exposed, uses porcelain-insulators prone to contamination.	Fully enclosed in grounded metal housing (no contamination or exposed porcelain).
BSL/BIL Ratio	Typically less than 1 (switching impulse withstand is weaker than lightning-impulse).	$\approx$ 1 (switching and lightning-impulse withstand are nearly the same).

Equaion (3) show a formulathat can be used to determine the surge impedance of the $242\ kV$ SF_6 - bus with an average inner-diameter of 8.9 cm [19, 25].

$$Z = 138 / \sqrt{\varepsilon_r}\ \log_{10}\left(\frac{r_2}{r_1}\right) \qquad (3)$$

where, $Z =$ surge impedance in Ω, $r_1 =$ radius of inner conductor, $r_2 =$ inner radius of outer sheath, and $\varepsilon_r =$ dielectric relative permittivity ($\cong 1\ for\ SF_6$).

For a typical GIS - bus at $242\ KV$ [25]:

$$r_1 \simeq 4.45 \text{ cm},\ r_2 \simeq 15.25 \text{ cm},$$
$$\varepsilon_r \cong 1\ for\ SF_6$$

Thus the surge impedance becomes

$$Z = \frac{138}{\sqrt{1}} \log_{10}\left(\frac{15.25}{4.45}\right) = 73.8\ \Omega \simeq 75\ \Omega$$

As a result, the surge impedance of an average $242\ kV$ - GIS - bus is roughly $\simeq 75\ \Omega$, which is the order of magnitude of the surge impedance of oil-filled-cable. It will be assumed that the ratio of $\frac{r_2}{r_1}$ will largely remain constant for the different voltage levels taken into consideration, even though the precise values of the inner conductor and outer sheath diameter will change along the voltage range from $72.5\ kV$ to $765\ kV$ [19, 25].

To exemplify the application at $220\ kV$ (Egyptian grid level), assume a GIS-bus-architecture with a radius ratio similar to typical $220–245\ kV$ schemes such as., $r_1 = 4.2\ cm$ (inner-conductor radius) and $r_2 = 14.5\ cm$ (inner-sheath radius), with $\varepsilon_r \cong 1\ for\ SF_6$. Accordingly the surge impedance becomes $Z = \frac{138}{\sqrt{1}} \log_{10}\left(\frac{14.5}{4.2}\right) = 74.3\ \Omega \simeq 75\ \Omega$.

Designs in the $72.5–245–300\ kV$ range frequently provide similar surge impedances if the ratio is maintained close to constant since Z is primarily dependent on the ratio of $\frac{r_2}{r_1}$ [2]. Therefore, compared to examples of $245\ kV$, adopting $220\ kV$ in the Egyptian framework does not significantly alter the typical Z value. Figure 5 compares representative surge impedances of different systems.

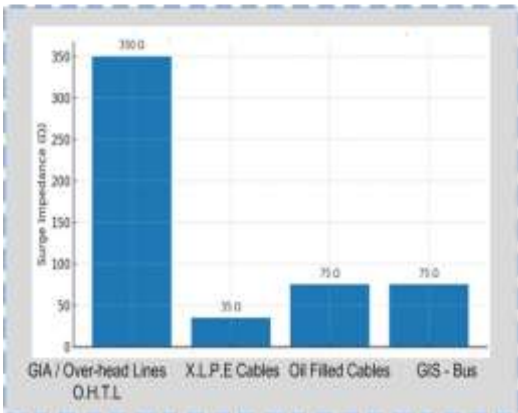

Figure 5: Surge impedance comparison of different power system components

In AIS - substations, the BSL to BIL ratio is usually between $0.6 : 0.86$, which is significantly less than unity. This suggests a reduced ability to tolerate switching surges versus to lightning surges. A nearly uniform withstand feature with BSL/BIL $\simeq$ 1.0 [7], on the other hand, indicates that switching and lightning surges are equally tolerated by GIS - substations that use SF_6 insulation.

$$\begin{cases} AIS\ :\ \frac{BSL}{BIL} \approx\ 0.6 : 85 \\ GIS\ (\ SF_6)\ :\ \frac{BSL}{BIL} \approx\ 1 \end{cases} \qquad (4)$$

While GIS retains values nearly equivalent to BIL, the AIS exhibits greater sensitivity for chopped wave tests ($2-3\,\mu s$ chopped-wave-levels are 1.29 and 1.15 times BIL) [25]. As a result, GIS offers better and more consistent insulation performance during surges.

Based on existing experimental data and IEC standards [4, 7], MATLAB was used to predict the insulation withstand properties of Air and SF_6 shown in Figure 6.

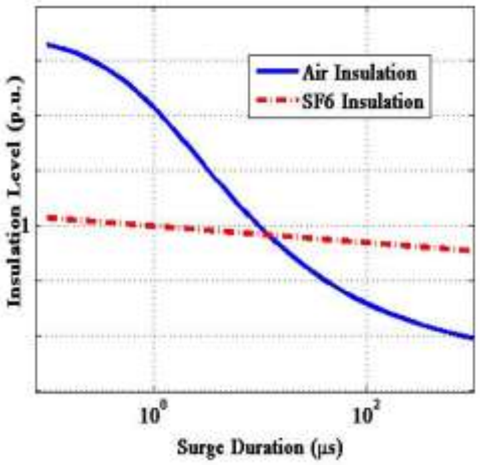

Figure 6: Insulation levels of SF_6 gas and Air (MATLAB simulated results).

The obtained curves replicate the usual pattern seen in laboratory studies, where SF_6 insulation stays rather constant while air insulation drastically drops with surge duration. The qualitative differences between the insulation behavior of AIS and GIS under different surge situations are well visualized by such a simulation.

7. Comparison of GIS and AIS Major Failures (CIGRE-Surveys)

A problem that many established utilities face is the asset replacement of AIS substations by GIS at all levels. A thorough summary of the development of GIS reliability over several decades may be found in the four CIGRE reliability surveys. International data from utilities and operators covering various time periods and voltage levels ($\geq 60\,kV$) was gathered for each survey. With major failure rates per 100 bay-years dropping from over 1.0 in the early 1990s [28] to just 0.0807 in the most recent 4th survey (2014–2017) [28-31], it is evident that GIS dependability has been steadily improving over time.

TABLE 2: Comparison of GIS and AIS Major Failures per 100 bay-years (CIGRE Surveys)

CIGRE Survey	Service period	GIS $\geq 60\,kV$	AIS $\geq 60\,kV$
1st Survey	up to : 1990	1.0015	1.73
2nd Survey	up to : 1995	0.7504	1.1
3rd Survey	2004–2007	0.3655	0.55
4th Survey	2014–2017	0.0807	0.33

When compared to AIS, the data demonstrates a striking decrease in significant failures for GIS technology. For instance, AIS went from 1.73 : 0.33 and GIS failures decreased from over 1.00 failures per 100 bay-years in the first survey to just 0.08 in the most current one. The results unequivocally demonstrate that both GIS and AIS have steadily improved in reliability over time, with GIS continuously surpassing AIS. For scholars and practitioners interested in GIS performance and reliability trends, Table 2 is a comprehensive resource that includes the most recent CIGRE survey (4th survey).

A thorough analysis of the GIS insulation-coordinating was also provided by the CIGRE [32]. According to this survey, nominal voltage accounted for 61% of failures, while AC-overvoltage and/or switching accounted for 39%. There has only been one lightning-related failure documented.

8. Artificial Intelligence in HV Substations

Substation automation is being revolutionized by artificial intelligence (AI), especially in the fields of operation improvement, predictive maintenance, and problem detection. The study of artificial neural networks (ANNs) is where the idea of deep learning (DL) first emerged. Since 1958, when Frank developed the perceptron model, neural network (NN) research has been gaining momentum. However, multilayer NN training is not possible at that time due to the limitations of computer-performance. When Hinton's team used DL to win the Image Net-Classification Competition in 2012, it was the most significant development in the field of computer-vision. This achievement caused a huge shock in the field and led to a surge in DL [33]. Another way to describe DL is as a branch of machine learning (ML). Its goal is to create and model a NN for human-brain analysis and learning that mimics the brain's process for interpreting text, audio, and images. The feature and classifier are the two components of a traditional-pattern recognition system. Classifier and feature-optimization are done independently. The potential for collaboration between the classifier and feature representation can be fully realized by collaborative optimization within the Deep-NN framework. Through multi-layer-nonlinear-mapping, DL may translate picture information into straightforward linear relations, which can then be integrated with the classification process to accomplish end-to-end learning [33–34]. Substations are now able to switch from reactive to predictive and prescriptive-maintenance tactics thanks to recent developments in ML, DL, and data-driven-modeling.

Conclusion

According to a comparison of AIS and GIS substations, GIS-technology has a number of benefits when it comes to land use, insulating-performance, and dependability. Magousa case study in Egypt shows how switching from an AIS to a GIS configuration improves the transmission network's overall effectiveness and operational security, especially under harsh-environmental-circumstances. Higher investment costs and environmental-issues with SF_6 gas, however, continue to be significant obstacles that need to be overcome. To balance technical performance, financial viability, and environmental sustainability, the research shows the importance of insulation-coordination and reliability-evaluations for the future development of contemporary HV substations. Finally, the comparison tables in this work are not an exact replication of any scientific study, but rather a composite overview based on data from CIGRE, IEC, and IEEE publications. Therefore, they can be considered a novel contribution, supported by respected and recognized scientific references and surveys.

Future Work

In future research, more emphasis will be placed on the integration of AI-techniques into insulation-coordination and reliability assessments. Advanced ML and DL models will be specifically examined for predictive maintenance methods in both AIS and GIS-substations, as well as for the detection and categorization of partial-discharges. It is anticipated that these methods will improve the failure-predictions accuracy, lessen unplanned-outages, and facilitate the shift to more intelligent and dependable electricity-grids.

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