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Article

The Dual Transition of Electrical Switchgear: Navigating SF6 Alternatives and the Rise of Predictive Maintenance

Ayman Alhijazi [1], Samer Diab [2] and Adil Adam [2,*]

[1] Faculty of Mechatronics Engineering, Al-Shamal Private University, Sarmadā, Idlib, Syria
[2] Engineering Department, Al-Zaytoonah International University, Azaaz, Aleppo, Syria
[*] Correspondence: adiladam080@gmail.com

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Abstract: Electric switchgear serves as the backbone of any power system; it protects, controls, and isolates electrical circuits. For decades, Sulfur Hexafluoride (SF6) gas has been the insulating and quenching medium of choice. SF6 gas has great dielectric properties, making SF6 gas-insulated switchgear (GIS) compact and highly dependable. However, SF6 gas is highly detrimental to the environment, having a global warming potential of 22,800 times that of CO_2. This makes it imperative that SF6 gas be phased out. At the same time, the rapidly developing complexity of power grids has outpaced the time-based maintenance systems. This article provides a summary of key research to examine the important changes that must be made when addressing the phasing out of SF6 gas and the alternatives for medium and high voltage applications. The article also addresses the shift from time-based maintenance to predictive and condition-based maintenance, as well as the impact of advanced analytics, Artificial Intelligence (AI), and Machine Learning (ML) on the future reliability and efficiency of switchgear. The article concludes by highlighting the importance of the emerging patterns and the need for sustainable and resilient electrical systems. Overall, the discussion highlights the need to prepare for innovation in the industry, as well as the need for sustainable and flexible electrical systems. Meeting these challenges will both reduce negative ecological impacts and protect the future viability of the network systems for power distribution.

Keywords: Electric Switchgear; SF6 (Sulfur Hexafluoride); Predictive Maintenance; Artificial Intelligence (AI); Machine Learning (ML); Gas-Insulated Switchgear

1. Introduction

The continuous generation of electricity is crucial in modern society [1], and one of the most important components of this system is electrical switchgear assemblies. These assemblies aid in the control, protection, and isolation of different pieces of electrical equipment. With the world's energy consumption continually growing, the power grids must incorporate various power generation alternatives. Because of this, the focus has shifted to the performance and efficiency of the switchgear [2]. In the past, SF6 gas insulated and extinguished the arcs at both the high- and medium-voltage switches. This is because SF6 is thermally stable and possesses great dielectric strength [3]. Because of these attributes, the use of gas-insulated switchgear (GIS) has been possible in many fields despite the reliable and compact nature of the equipment [4]. Unfortunately, S6 is a highly dangerous greenhouse gas and has a global warming potential (GWP) of 22,800 times that of carbon dioxide. SF6 can also remain in the atmosphere for over a thousand years [4]. These characteristics make it critical to remove SF6 from use [5]. Every day, the electrical grid gets more critical and more complex, and there is a change in maintenance methodology that is needed. Time-based maintenance (TBM) is ineffective, failing, and not taking advantage of the fault detection capabilities of the system. Smart grid and new sensor technologies have made condition-based maintenance (CBM) and predictive maintenance (PM) a viable strategy [6]. TBM, CBM, and PM all combine the use of real-time data and artificial intelligence (AI) to self-monitor, determine repair/replacement requirements, maintain optimal performance, and extend the useful life of the equipment. The goal of this paper is to analyze the switchgear industry and its various changes over the years. It will start with the fundamentals of switchgear and then move to the SF6 conundrum [7]. SF6 is a very useful gas but unfortunately very controversial in regards to its environmental impact and the regulations that go with it. This paper will analyze the SF6-free alternatives, the available mediums and high-voltage applications, as well as the surrounding complexities. It will analyze the switchgear reliability, the types of failures, and the maintenance challenges. This will also introduce state-of-the-art diagnostics. It will also tackle the challenges of predictive maintenance, and the results it is generating, especially in the intersection with machine learning and artificial intelligence. It will address the impact of the resilient electric grid and the environmental and operational impacts it creates. Although the trends concerning the moves from SF6 to predictive maintenance (PM) are well documented, the main innovation of this work is the fostering of the combined and simultaneous application of both as an integrated framework for next-generation switchgear. Such a framework is posited to promote synergistic outcomes for the goals of the systemic reduction of failures, the improvement of operational stability, and the prolonging of asset life on a decarbonized grid. This study presents a comprehensive analysis of the ongoing dual transition in electrical switchgear by integrating two critical developments: the replacement of SF6 gas with environmentally sustainable insulation alternatives and the adoption of predictive and condition-based maintenance strategies. The work systematically reviews available SF6-free technologies across medium- and high-voltage applications, evaluates their technical and environmental implications, and highlights how modern sensor technologies, artificial intelligence, and machine learning enhance asset reliability and operational efficiency. A key contribution of this paper is the demonstration of the synergistic relationship between SF_6-free switchgear designs and predictive maintenance frameworks, enabling improved diagnostics, reduced lifecycle costs, and increased grid resilience. The study further outlines practical challenges, implementation considerations, and future directions necessary for achieving sustainable, reliable, and data-driven electrical infrastructure.

2. Basics of Electrical Switchgear

Electrical switchgear is vital equipment in an electrical power system that manages, protects, and disconnects from electrical devices and circuits. Constructing an electrical power system requires ample switchgear, as it needs to be built in every electrical grid [8]. With sufficient switchgear, the electrical grid can be built and provide protection against electrical surges and faults. In the electrical grid, the main functions are control, protection, and isolation of the equipment [9]. Control refers to turning the power of circuits on and off. Protection is done by relay and circuit breaker coordination, and is the most vital function of switchgear. Protection is to detect and disconnect current flow during abnormal situations, such as failures in the system, to avoid a domino effect, which is a severe failure in the system [10]. However, a circuit breaker can only isolate a circuit by opening it. It cannot provide isolation by closing a circuit to a particular zone of the network. Without closing the circuit, a zone is left still energized, which is not the case when isolation is implemented. Protection is achieved through these relays and circuit breakers, as seen in **Figure 1**. For a functioning power system, sufficient amounts of switchgears are needed, and the voltage level is the main factor that decides the design, dimension, and level of insulation.

International Electrotechnical Commission (IEC) standards dictate the following voltage classifications: Low Voltage (LV), Medium Voltage (MV), High Voltage (HV), and Extra High Voltage (EHV). LV is below 1 kV for secondary commercial, industrial, and residential distribution. MV is between 1 kV and 52 kV and is necessary for primary and secondary distribution, connecting local transformers and substations [11]. The MV range is of particular interest for SF6 alternatives and predictive maintenance. HV is from 52 kV to approximately 230 kV, used in primary distribution and transmission for large power flows. EHV is defined as being above 230 kV and is employed primarily for bulk power transfer in transmission systems [12], as shown in **Table 1**.

Applications are strictly divided by grid position. Transmission Substations is Handle EHV and HV, enabling bulk electricity transfer. Primary Distribution: Interface with transmission, transferring from HV to MV, usually in indoor substations [13], and Secondary Distribution: Supply MV networks into lower voltage transformers, generally in outdoor cabinets.

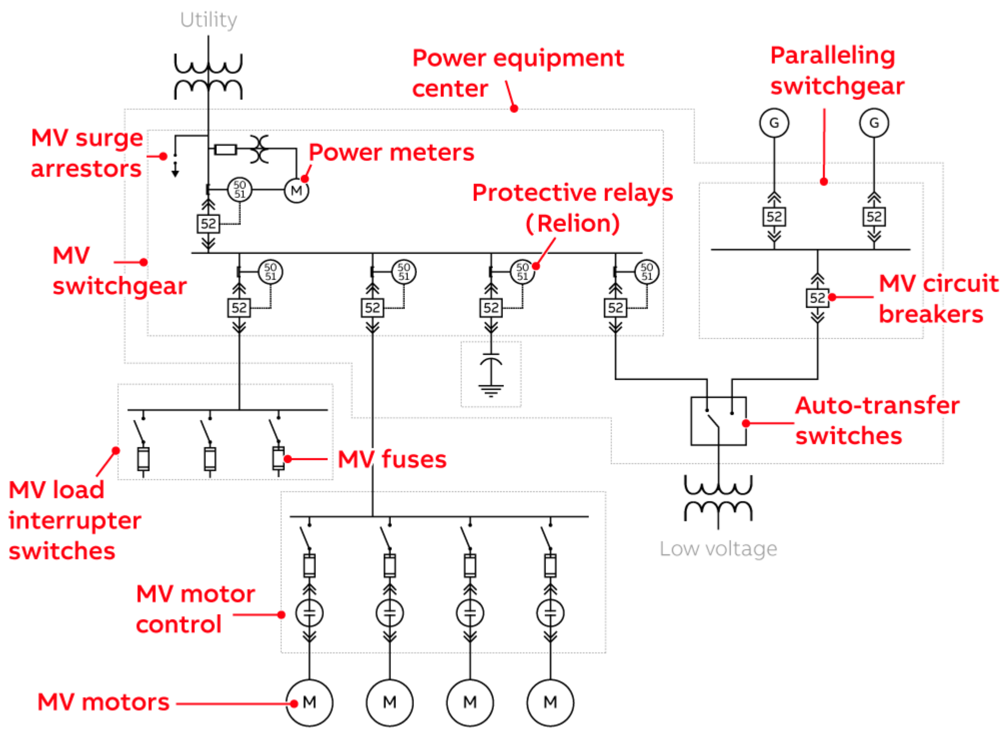

Figure 1. Single Line Diagram of Medium Voltage System.

Table 1. IEC standards voltage classifications.

Classification	Voltage Range
Low Voltage (LV)	below 1 kV
Medium Voltage (MV)	1 kV–52 kV
High Voltage (HV)	52 kV–230 kV
Extra High Voltage (EHV)	above 230 kV

The insulator for live electrical elements is crucial. Switchgear used in LV applications is primarily categorized into types: Miniature Circuit Breakers (MCBs), Moulded Case Circuit Breakers (MCCBs), Air Circuit Breakers (ACBs), fuses, contactors, and isolators. The common braking type in the LV system is a free gas (air) or vacuum interrupter (VI) [14]. Switchgear used in MV applications is primarily categorized into types: Air-Insulated Switchgear (AIS), Gas-Insulated Switchgear (GIS), Oil-Insulated Switchgear (OIS), and Vacuum Insulated Switchgear (VIS). The common braking type in the MV system is free gas (air), oil, Sulfur Hexafluoride (SF6) gas, or vacuum interrupter (VI). Switchgear used in HV applications is primarily categorized into types AIS, GIS, OIS, and VIS. The common braking type in the HV system is a free gas (air), oil, SF6 gas, or VI. Switchgear used in EHV applications is primarily categorized into types AIS and GIS. The EHV common braking types are free gas (air) and SF6 gas. The modular nature of sealed designs makes Ring Main Units (RMUs) widely used in MV systems. The Ambient Air Insulated Switchgear (AIS) is also comprised of ambient air, which is cost-effective but also footprint-heavy and environmentally sensitive. Therefore, it is suitable in applications without space restrictions, as current cutting technologies do allow for more compact designs. Gas-insulated switchgear (GIS) uses SF6 gas to insulate the medium voltage (MV), high voltage (HV), and extra high voltage (EHV) components of circuit breakers (CB) and disconnectors (DS), which makes them highly reliable, compact, and suitable for space-constrained areas. By replacing air with SF6, GIS provides superior insulation properties, protecting components from contaminants and requiring less maintenance than air-insulated systems. While having a higher initial cost, GIS offers a longer service life and lower life-cycle costs, especially in urban environments. Solid-Insulated Systems (SIS): Combine solid insulation with air in a hermetically sealed enclosure, allowing environmental protection. SIS secondary distribution is commercially available, with a comparable footprint to SF6 products up to 24 kV, and is currently marketed as equal to that of solutions using SF6 [15]. Existing interrupting technology includes Circuit Breakers (CBs), which interrupt normal load and high fault currents. They work by rapidly splitting contacts, with the arc being interrupted by media such as air, SF6, or a vacuum, as shown in **Figure 2**.

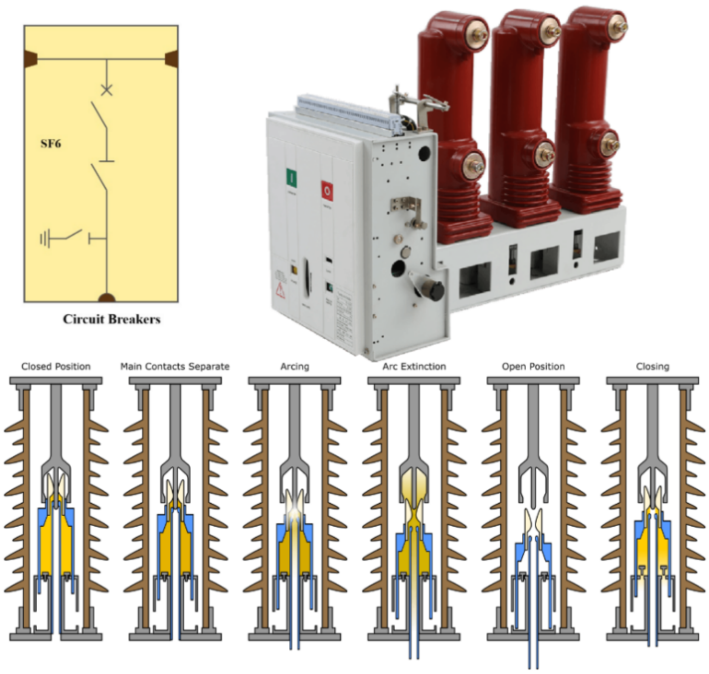

Figure 2. Circuit Breaker.

CB includes fault current interruption, especially in fault conditions, Relay: Trip signal sent to the CB by detecting abnormal conditions, Isolator (Disconnector): Provides visual isolation for maintenance; is not fault interruption rated, Current Transformers (CTs) and Potential Transformers (PTs): Step down currents and voltages to be used in relays and metering, Surge Arrester: Avoids transient over voltages, and Earthing Switch: Safely earths de-energized circuits. Additionally, Load Break Switches (LBS) are used to open standard load circuits, typically equipped with fuses to protect against short circuits—most traditional LBS utilize SF6 [16], as shown in **Figure 3.**

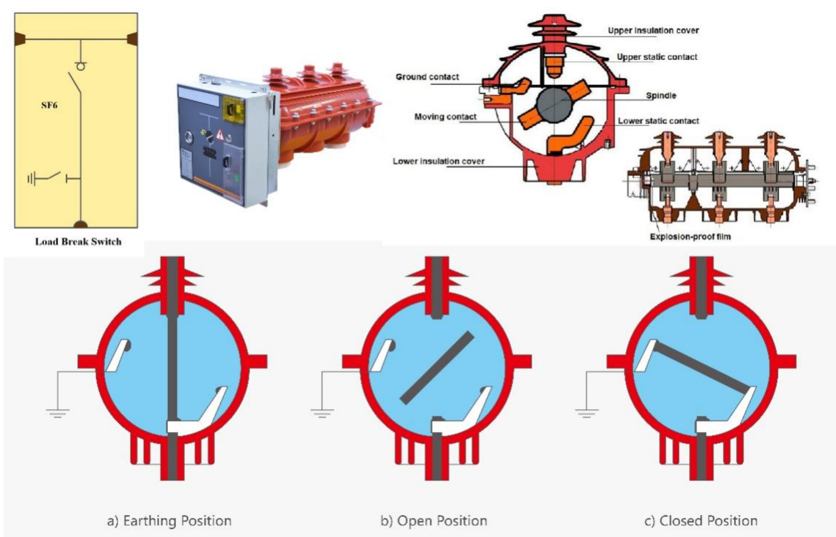

Figure 3. Load Break Switches.

3. The SF6 Challenge

Gas-insulated switchgear (GIS) construction and design have been dominated by the use of sulfur hexafluoride (SF6) gas for insulating and arc-extinguishing for over fifty years [17]. These attributes of SF6—extinguishing an arc (energy of the arc) and providing good insulation (thermally and electrically)—are overshadowed by its enormous environmental consequences. The international community recognizes the need for SF6 replacements. SF6 is an engineered, odorless, colorless, and transparent gas, which is non-toxic and non-flammable and possesses good electrical and thermal insulating qualities [18]. SF6 is much less combustible than air; for example, its dielectric strength is 2.5 times greater than that of air. This means that less clearance is needed, which results in an increase in the construction of SF6-packed Gas-Insulated Switchgear (GIS) (see **Figure 4**) [19]. The ability to pack GIS is essential in urban centers and areas of critical infrastructure. SF6 is also effective as an arc extinguishing medium. During a fault (overcurrent and arcing conditions), SF6 gas is responsible for dissipating the thermal energy of the arc, rapidly losing and then recombining (dissociating and recombining) SF6 gas molecules. This characteristic of SF6 enables the SF6-insulated GIS to interrupt fault currents, which improves the reliability of the grid and increases the safety [20]. Furthermore, SF6 is chemically stable, which contributes to long-lasting and low-maintenance characteristics of SF6 GIS. Even with all its advantageous attributes, SF6 has a massive negative impact on the environment. SF6 has the highest global warming potential (GWP) of 22,800 on a 100-year time frame, which makes SF6 the most potent greenhouse gas [21].

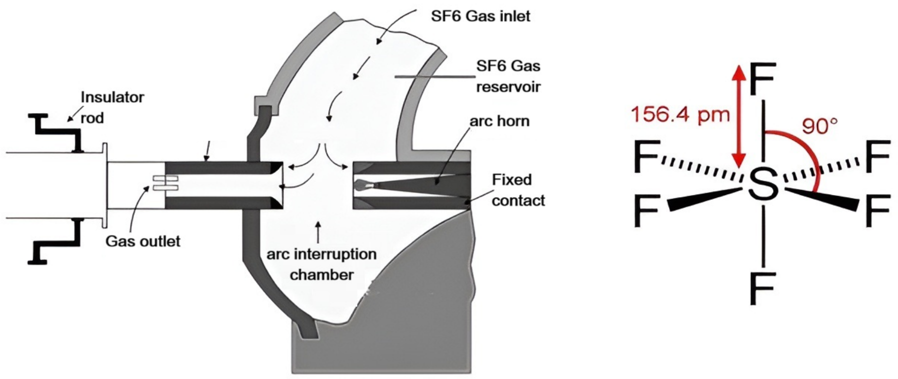

Figure 4. Sulfur Hexafluoride (SF6).

Thus, 1 kg of SF6 is equivalent to 22,800 kg of CO_2 in terms of warming potential [22]. SF6 is particularly stable and has an atmospheric lifetime of about 3,200 years, meaning that once it is released into the atmosphere, it will impact the climate for thousands of years. Small emissions from electrical appliances can cause a disproportionately substantial climate impact due to the combination of their high global warming potential (GWP) and longevity [23]. SF6's superior and unique properties are the primary reasons it is used on a large scale in various electrical equipment.

SF6 was the first viable choice for GIS in MV and HV networks, facilitating the construction of compact substations in comparison to AIS, especially in locations with spatial limitations [24]. Besides GIS, SF6 is utilized in GIL, instrument transformers, and generator circuit breakers. Its long and established performance earned it an industry benchmark for decades [25]. Generation of Hazardous By-Products. It is true that SF6 is non-toxic in its original form, but due to the presence of toxic, corrosive, and arc by-products that decompose SF6, health hazards are associated with the maintenance of internal switchgear to H_2, SO_2, SO_2F_2, S_2F_{10}, and other toxic, corrosive components [26]. The presence of hazardous compounds is worsened by humidity, and for that reason, the presence and quality of the gas must be monitored and controlled tightly.

4. The Rise of SF6-Free Alternatives

SF6's impact on the environment has prompted the electrical industry to come up with innovative and viable SF6-free alternatives. These alternatives strive to match and/or exceed SF6 switchgear performance without the negative carbon emissions impact [27]. The alternatives vary depending on the application and associated voltage levels. SF6 substitution options are advancements on air-insulated systems (AIS), improved solid insulated systems (SIS), and gas-insulated systems (GIS) integrating other gases or gas mixtures [28]. The aim is also to achieve the same level of compactness, reliability, and operational efficiency without the environmental burden of SF6 [29]. The MV range has witnessed the development of immediate SF6-free technology, led by guidelines and diverse applications in distribution systems. Air-Insulated Switchgear (AIS) with Vacuum Breakers has never held SF6. AIS with vacuum circuit breakers holds a dominant market position in main distribution where space is not a constraint and environmental conditions are in control. Vacuum interrupters are effective, environmental-friendly, and totally embraced in MV switchgear up to 40.5 kV. AIS's major drawback is its larger size compared to GIS and susceptibility to environmental conditions unless properly housed, as shown in **Figure 5**.

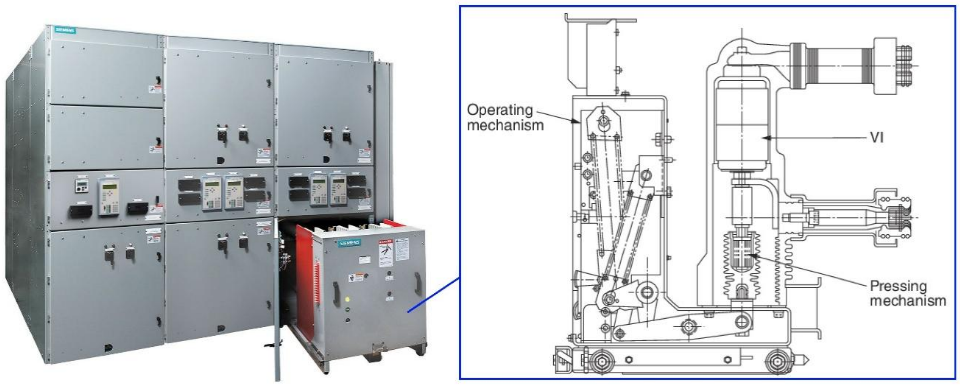

Figure 5. Air-Insulated Switchgear (AIS) with Vacuum Breakers.

Solid-Insulated Switchgear (SIS) is also a very well-established SF6-free technology, especially for secondary distribution. Solid dielectric material insulates these systems with air in a hermetically sealed tank and protects against environmental factors like dust and humidity. SIS units have been available for decades, with an equivalent footprint to SF6 devices for up to 24 kV, with long-term benefits far outweighing slightly higher initial costs. Innovation towards SF6 alternative in MV applications is mainly in new GIS designs with alternative gases or gas mixtures to ensure compactness and reliability with no environmental burden. They make use of naturally occurring, environment-friendly gases like nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2), supplemented by technical air. A typical commercial mixture for MV applications might contain approximately 4–6% fluoronitrile (C_4-FN) or 6–8% fluoroketone (C_5-FK) by volume, with the balance being CO_2 or a dry air (N_2/O_2) mixture. They have negligible or zero GWP and no special handling. To achieve SF6-equivalent insulation performance, the mixtures generally require moderate increases in gas pressure. Though early designs might be larger to some extent, ongoing optimization is improving compactness. Commercial products using technical air for insulation and vacuum interrupters are becoming increasingly popular up to 24 kV. Synthetic gas blends have low levels of fluorinated molecules (e.g., fluoronitriles like C4-FN or fluoroketones like C5 fluoroketone) blended with a carrier gas like CO_2. These kinds of molecules are optimized for maximum dielectric strength, often surpassing SF6 at similar pressures, making miniaturization possible. Their GWP is a small percentage of SF6's (1 to 500 CO_2 equivalent), showing a significant environmental benefit. SF6-free MV switchgear is increasingly feasible, with alternatives' physical size and electrical ratings similar to SF6 counterparts. Operating efficiency differences tend to be small. Take-up is prevented: initial capital expense can be 5% to 20% higher, although set to decrease. Some of the alternative mixtures have high boiling points, limiting operation in extremely cold temperatures without temperature compensation. Commercialization and market penetration rely on thorough development and type-testing for specific applications, e.g., RMUs. Full homologation by significant end-users is a requirement. Manufacturing processes must also be adapted by producers. While market readiness in general applications is estimated at two years, niche applications are expected to take longer. The new EU F-Gas regulation is expected to accelerate the process. Developing SF6-free technologies for HV switchgear above 52 kV involves greater technical challenges due to higher dielectric requirements. Nevertheless, there has been significant progress. For 52 kV to 145 kV HV switchgear, GIS with synthetic gas mixtures (such as fluoronitriles or fluoroketones) have achieved similar ratings and compact sizes to SF6 equipment. For HV applications, the concentration of the fluorinated component is often slightly lower (e.g., 2–4% C_4-FN) to manage decomposition and cost at higher voltages and pressures, with the remainder being predominantly CO_2. Pilot projects are successful, with hundreds of bays already on order, demonstrating growing confidence. Installation is forecast to rise significantly within two years. Natural gases (dry air, CO_2, nitrogen) for HV GIS would typically require larger sizes for necessary insulation strength and hence might be 20% to 30% more costly. Designs work towards curbing these penalties. SF6-free medium-based live tank breakers have also been conceived and pilot-tested. SF6-free switchgear for EHV applications (245 kV and 420 kV) is in development, building on current designs with increased pressure and/or pre-mixed blends. Development lead times are 2 to 5 years. Commercial introduction is GIS for 72.5 kV for offshore wind, demonstrating viability in harsh HV environments.

The transition away from SF6 extends beyond electrical equipment to broader decarbonization efforts. Room temperature Gas Insulated Lines (GIL) using synthetic gas mixtures have been demonstrated for 420 kV voltage levels with a compact and better environmental solution for high power transmission. Alternatives for bushings up to 145 kV with extension to 245 kV are realistic. Fundamental research will, however, still be required for higher voltage levels and SF6-free solutions. Instrument transformers (CTs and PTs) utilize SF6 extensively in their production and emit very little residue. Steps are being taken to reduce these emissions, and SF6 replacement is possible for lower insulation levels in five years. SF6-free equipment for 245 kV has been erected and commissioned, and technology alternatives can be expected to expand. SF6-free technologies are emerging rapidly, driven by innovation and regulation. While there are still issues, the industry is making the transition to environmentally friendly, high-performance electrical equipment without SF6's environmental impact [30]. A comprehensive comparison of SF6 and the proposed alternative gas is presented in **Appendix A**, covering performance, environmental impact, and operational aspects.

5. The Synergistic Link, SF6-Free Alternatives

The move to SF6-free insulating media is more than an exercise in environmental compliance; it is a game changer in the world of predictive maintenance (PM) strategies from a technical and economic standpoint. SF6 alternatives and new monitoring technologies can help create a reliable predictive maintenance feedback loop.

1. Improved Technological Integration with Monitoring Tools and Improved Reporting. The chemical composition of SF6-free media is more limited, which is the case for a number of alternatives, including dry air (N_2/O_2) and CO_2 mixtures. As a result, there is likely to be less diagnostic signal "background noise" with these media than with SF6. Understanding of Gap Monitoring: One of the key pieces of the SF6 monitor is that it monitors compounds which, while in and of themselves more complex than solely rational, can be more difficult to rationally interpret. Monitoring the gas purity and pressure in a compartment where dry air and certainly CO_2 are present, is more rational and easier. A pressure drop is an unequivocal indication of a leak. The presence of moisture in a compartment filled with CO_2 is an unequivocal indication of seal failure or external contamination. All of these aspects contribute to greater simplicity in state assessment, decreased false alarm instances, and improved predictive and prescriptive maintenance reliability. Detection of Partial Discharge (PD): Some Solid Insulated (SI) and air-insulated designs related to SF6-free switch gears may allow more flexibility in the placement of Ultra High Frequency (UHF) or acoustic emission sensors. Since no sophisticated gas handling ports are needed and the signal-blocking SF6 gas is too dense, PD signals are more localized and clearer. This improves the ability of the machine learning algorithms to classify and score the location and severity of PD.
2. Removal of the "Ecological Fear Factor" and the opportunity for proactive data collection. The high Global Warming Potential (GWP) of SF6 and the tendency to understate ecological considerations have created a risk-averse mentality, where "zero-leak" policies have become the norm. In most cases, immediate containment is valued over data collection. When there is any gas loss, it warrants a physical breach of the containment to stop the loss, which then eliminates the opportunity to observe and document the failure mode. Novel PM Paradigm: Since low-GWP alternatives (GWP < 1,000, often <10) pose little ecological risk from even small monitored leaks, the PM paradigm can now afford to eliminate the ecological 'fear factor' from operational leaks. Controlled and safe operational degradation of a system is now permissible, and the system can con-

tinue to run while collecting valuable, continuous performance data. This data is invaluable for training AI models to predict the remaining useful life (RUL) of the system under real-world fault conditions, moving PM from merely diagnostic to fully prognostic. The next step for maintenance science is the ability to learn from purposeful degradation during maintenance cycles.

3. Material-Specific Failure Modes and Tailored AI Diagnostics The new SF6-free technologies provide new failure modes that are often more straightforward and easier to predict than the complex decomposition pathways of SF6. Fluorinated Mixtures: Certain fluorinated compounds, such as C_4-FN, have useful dielectric properties and, under high-energy arcing conditions, are known to generate a significant amount of corrosive reaction products, including hydrogen fluoride (HF). This arcing occurs in a predictable fashion, and PM systems can now incorporate electrochemical sensors that are low-cost and tuned to HF. Digital maintenance alerts for unambiguous HF detection are far better than interpretations of an SF6 byproduct mixture. Vacuum Interrupters (VIs): As the main switching technology in SF6-free MV gear, their end-of-life involves high, measurable contact wear, and low dielectric strength. PM can make use of timing analysis from actuator mechanisms and contact travel sensors. AI models can identify correlations from modulations in operational time and wear, resulting in predictions based on the physics of the mechanism and the time the VI can operate before falling below the specifications of the switching cycles.
4. Creating a Total Cost of Ownership (TCO) Model That Supports PM Investment. The high lifecycle costs of SF6, due to gas tracking, recovery, possible future carbon taxes, and complicated handling, have historically consumed maintenance budgets. Using SF6-free alternatives unlocks both capital and operational expenditures. Economic Reallocation: The predicted reduction in expenditures for gas management and the costs associated with compliance can be used to finance the installation of networks of distributed sensors, cloud-based analytics, and AI applications that comprise the infrastructure of a PM system. In addition, PM predicts longer maintenance cycles and fewer unplanned outages, resulting in improved protection for the initial outlay usually associated with new SF6-free technologies, thus enhancing their return on investment and speeding up their adoption.

The transition to SF6-free alternatives means more than just replacing one piece of hardware with another. It is an opportunity to enable a more sophisticated and fully articulated, data-driven asset management strategy. The new materials offer improved diagnostic signals, safer data collection during minor fault events, and failure modes that contemporary sensor and AI systems are designed to quantify. By turning predictive maintenance from a hopeful concept into a practical, critical, and highly efficient tool for operating a sustainable and resilient electrical grid, we are able to do so much more.

6. Condition Monitoring through Sensor Infrastructure

Modern predictive maintenance technologies and systems utilize discrete sensor networks built into switchgear assemblies for continuous condition monitoring of these assemblies. The main types of sensors include:

- Partial Discharge (PD) Sensors: These comprise UHF (Ultra High Frequency) antennas or HF (High Frequency) current transformers that operate within the 300 MHz–3 GHz frequency range. This range enables the detection of localized thermal breakdown of insulation. The sensitivity of detection is determined by the level of breakdown, with levels of identification of 5 pC (picocoulombs) breakdown levels, facilitating the forecasting of insulation faults.
- Temperature Sensors: Resistance Temperature Detectors (RTDs) and thermocouples that are mounted proximate or adjacent to the busbars and contacts operate in the range of between −40 °C and +150 °C. They have an accuracy of ±1 °C and temperature differentiations of 0.1 °C, which are sufficient to provide the predetermined temperature for the establishment of hotspots that may develop as a result of contact resistance or overload conditions.
- Gas Pressure and Density Sensors: These sensors are utilized in the GIS compartments or chambers to monitor the insulation condition via the monitoring of the pressure within the range of 0–10 bar (and all pressure ranges have an accuracy of ±1% of the full scale). Pressure sensors may indicate a leak or deterioration of the insulation.
- Humidity Sensors: These sensors monitor the presence of moisture within the enclosed compartments and

operate within the 0–100% relative humidity range, with an accuracy of ±2%. High humidity levels in the compartments may indicate poor sealing.

- Vibration and Acoustic Sensors: These sensors provide early indications of mechanical faults. They include accelerometers with a detection frequency of 0–10 kHz. These sensors operate components that are loose in the mechanism system, and will enable the identification of faults that are mechanical in nature.

The degradation models based on analytics and machine learning extract patterns based on degradation from supervisory systems, which are continuously fed sensor data. In terms of system diagnostics and reproducibility, refined sensor characterization is beneficial.

7. Predictive Maintenance and Advanced Diagnostics for Switchgear

The transition to predictive maintenance (PM) is caused by the desire to exceed purely reactive and time-based maintenance; it seeks to prevent failures and avoid breakdowns on critical assets like switchgear. PM uses data to design maintenance actions that mitigate failures, decrease operational interferences, and prolong the life of assets. Such PM is economically justifiable. Economically viable PM uses one of the numerous condition monitoring mechanisms that inform the performance of the switchgear and diagnose abnormal performance. PD analysis is necessary to evaluate the condition of the insulation. PD is the discharge that is localized and signifies insulation breakdown. PD monitoring is suggested to be kept online without interruption for switchgear that is metal-clad and gas-insulated (GIS). Are the methods used? Phase-resolved partial discharge (PRPD) relates discharge pulses to the AC cycle, and it serves to categorize defects in insulation. The Three-Phase Amplitude Relation Diagram (3PARD) permits the simultaneous determination of PD in each phase and the differentiation of PD from noise. The Time-Frequency (T-F) Map algorithm separates PD of diverse origin based on time and bandwidth. Temperature is the indicator of the switchgear; its presence or absence reveals the level of contact resistance or overload.

Temperature sensors measure real-time thermal performance and detection of hotspots. Infrared thermography, which measures surface temperature deviations and overheating, helps avoid operational disruptions. Mechanical monitoring elements help avoid breakdowns during operational disruptions. Vibration analysis captures abnormal vibrations of loose and failing components, while acoustic sensors detect mechanical faults and offer early signals of deterioration. The composition and quality of gas in GIS are critical. Analysis of SF6 Decomposition Products shows internal arcing or partial discharges by recognizable by-products, while Alternative Monitoring of Gas Quality ensures gas retention of dielectric strength in SF6-free GIS. During the overhaul of switchgears, Classic electrical testing assesses the condition of the switchgears and includes: Insulation Resistance, which tests the insulation level of the switchgear versus leakage, and Contact Resistance, which assesses resistance across the contacts; high contact resistance is a sign of wear or contamination. AI and ML are redefining PM with the automated analysis of data, diagnosis, and prognosis from large monitoring systems data. Artificial Neural Networks (ANN) are applicable to Fault Detection and Classification, which is effective in pattern recognition. Artificial neural networks (ANNs) classify the health condition of switchgears by the input of sensors (PDs, thermometers), by classifying the sensor input data with the faults. A class of machine learning algorithms called Artificial Neural Networks (ANNs) is utilized in the automated detection and diagnosis of faults by analyzing data from multiple sensors in condition monitoring systems. For the established predictive maintenance system, the ANN model takes the following sensor data as inputs:

- Characteristics of partial discharge (PD) magnitude and PD pulse
- Critical contact point temperature readings
- Variation of gas pressure/density
- Humidity in insulation compartments
- Mechanical vibrations and/or operating time

The ANN model's output layer functions to classify the condition of equipment as either operating normally, insulation degradation, contact overheating, gas leakage, or mechanical wear. Furthermore, regression-based outputs of ANNs can predict the Remaining Useful Life (RUL) and/or the probability of a fault. The selected inputs correspond to the known failure mechanisms of switchgears, which enables the ANN to associate sensor data with degradation patterns. This improves predictive maintenance and supports maintenance by the data-based method.

Machine learning approaches provide system self-awareness and adaptability by analyzing temperature measurements of the system macroscopically to identify small changes, such as loosening or tightening of the bolts, prior to a fault. The main obstacles are the unification of heterogeneous sensor data, the creation of sophisticated machine learning models, and the acquisition of high-caliber labeled datasets. The main sticks are cutting-edge machine learning, the unobstructed synthesis of real-time data, and the establishment of accurate digital twins to compute the remaining useful life (RUL). Predictive maintenance is most effective with a clear, logical, and structured approach, such as FMECA integrated with cost-benefit analysis, which cuts across virtually all of the components of a system. FMECA (Failure Mode, Effects, and Criticality Analysis) is a procedure to describe likely failing mechanisms and the related criticality. Simultaneously, the cost-benefit analysis estimates the economic impact, making it possible to achieve the right trade-off between reliability and cost. In the electrical grid, the most critical elements for improved reliability, efficiency, and sustainability are predictive maintenance and diagnostics, along with sensor technology and AI/ML.

8. Trends and Future Outlook

Technological advancement, environmental boundaries, and evolving energy profiles have influenced and shaped the electric power market, particularly how the power sector uses and integrates technology. The future of electrical switchgear will be more sustainable, innovative, and resilient. The shift toward alternatives to SF6 switchgear is irreversible. Innovation will be introducing economically feasible substitutes for high dielectric performance across all voltage classes used at the EHV unit. Natural Gas Blend Optimization: The development of dielectric gas mixtures (e.g., dry air, CO_2) tailored to achieve SF6 compactness and performance (synthetic additive-free) and operational improvements. Synthetic Gas Blend Development: Enhanced environmental profiles and operational characteristics of synthetic gases (e.g., fluoronitriles, fluoroketones) with additional GWP reduction and improvement of operating temperature extremes. Hybrid Solutions: Development of new hybrid insulation systems with solids, liquids, and gases as dielectrics for sustainable and efficient switchgear. The Design of New Technologies: To enhance market acceptance and utility, the confidence to develop, standardize, and regulate new technologies.

Significant changes in the ways that switchgears can be monitored will occur. This will occur with the use of digital twins and the Internet of Things (IoT). Sensors will be able to pinpoint real-time discharge, temperature, gas quality, and vibration. Maintenance that is predictive will be enhanced. More precise forecasting with regard to the health of equipment and predictive analytics of useful life (RUL) will be at hand. Digital twins will serve to integrate real-time information from sensors with the aid of simulation models to provide visibility into the performance of switchgears, thereby minimizing unforeseen and excessive maintenance and downtime. Remote access to monitoring and control: Adding operational flexibility and response time, especially in grids with distributed energy resources. As switchgears become more interconnected, robust defences will be required to protect critical infrastructure. Regulatory policies, such as the EU F-Gas Regulation, will have to become more stringent, with more ambitious targets and wider scopes. This will drive global adoption of SF6-free technology and developments.

The switch is able to provide a lot of positive and beneficial things. Reduction of Greenhouse Gas Emissions: Contains the potential to assist in the mitigation of climate change, Reduced Lifecycle Costs, Simplified end of life, reduction of environmental levies, and maintenance from reduced life cycle costs. Enhanced maintenance, improved reliability and resilience of the grid: More unplanned outages, the network is more stable, and restoration of faults is more rapid. Enhanced Safety: The removal of SF6 and toxic sub by-products and more monitoring from operational. The forthcoming grid will be decentralized, digital, and fully decarbonized. The future of resilient and sustainable electric infrastructure is built on smart maintenance and SF6-free solutions. The challenges and technological potential to integrate won't be possible without the collaboration of manufacturers, utilities, researchers, and policymakers.

9. Conclusions

The shift into more environmentally friendly and reliable grid sustainability has greatly changed the Switchgear Market. SF6 (Sulfur Hexafluoride) has been the go-to for gas insulation and will continue to be used, but the need for SF6 has to be reduced due to the high global warming potential of SF6. Reducing SF6 in switchgear is an ongoing environmental concern across the global market. The application of SF6 has environmental concerns, and so regulations have been placed to reduce the reliance on SF6. The market is beginning to shift with the application of SF6-free technologies across all voltage levels, and most importantly, high voltage switchgear. There are strong environmental substitutes such as Air Insulated Switchgear (AIS) with vacuum breakers, Solid Insulated Switchgear (SIS) systems, and Gas Insulated Switchgear (GIS) systems, as well as in high voltage switchgear (synthetic gas). The alternatives tend to have the same (or similar) levels of performance. The most significant concern of switchgear will always be reliability, and advanced alternatives to SF6 are proving themselves. Analyses of Failure Modes, especially insulation failure, have resulted in the need for a change of paradigm from reactive and time-based maintenance to Predictive Maintenance (PM) and Condition-Based Maintenance (CBM). With the fusion of PD (Partial Discharge) analytics, thermal monitoring, and gas testing with AI (artificial intelligence) and ML (machine learning), the maintenance of assets can optimally be performed while predicting faults and improving the longevity of the assets. The use of Artificial Neural Networks (ANN) allows for better diagnostics by effectively correlating sensor data to potential fault scenarios. The prospects of electrical switchgear in the near future are the continued advancement of technologies devoid of SF6, greater incorporation of the IoT (Internet of Things) and digital twin technologies for real-time monitoring, evolving regulatory frameworks, and the F. The economic and environmental benefits are paramount since there is reduced greenhouse gas emissions, lowered lifecycle costing, improved reliability of the grid, and enhanced safety. The need for a resilient and sustainable electric grid calls for collaboration among all stakeholders to ensure that energy supply is efficient, reliable, and sustainable to the environment, and that there is no pollution.

Author Contributions

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Abbreviations

Abbreviation	Full Form
SF6	Sulfur Hexafluoride
GIS	Gas-Insulated Switchgear
GWP	Global Warming Potential
TBM	Time-Based Maintenance
PM	Predictive Maintenance
CBM	Condition-Based Maintenance

AI	Artificial Intelligence
ML	Machine Learning
IEC	International Electrotechnical Commission
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
EHV	Extra High Voltage
MCB	Miniature Circuit Breaker
MCCB	Moulded Case Circuit Breaker
ACB	Air Circuit Breaker
VI	Vacuum Interrupter
AIS	Air-Insulated Switchgear
OIS	Oil-Insulated Switchgear
VIS	Vacuum Insulated Switchgear
RMU	Ring Main Unit
CB	Circuit Breaker
DS	Disconnector
SIS	Solid-Insulated System
CT	Current Transformer
PT	Potential Transformer
LBS	Load Break Switch
GIL	Gas Insulated Line
EU F-Gas	European Union Fluorinated Gas (Regulation)
PD	Partial Discharge
PRPD	Phase-Resolved Partial Discharge
3PARD	Three-Phase Amplitude Relation Diagram
T-F Map	Time-Frequency Map
ANN	Artificial Neural Network
FMECA	Failure Mode, Effects and Criticality Analysis
RUL	Remaining Useful Life
IoT	Internet of Things
DER	Distributed Energy Resources

Appendix A

Table A1. Comparison of SF6 and alternative gases for high-voltage switchgear applications: Performance, environmental impact, and operational considerations.

Aspect	SF6 (Baseline)	Technical Air/Dry Air (N_2/O_2 mix)	CO_2 (Pure or Carrier)	Fluorinated Gas Mixtures (e.g., C4-FN/CO_2 or C5-FK/CO_2)
Composition	Pure Sulfur Hexafluoride.	Dry, clean air (~80% N_2, 20% O_2).	Pure carbon dioxide, or as a carrier gas.	Low % (2–8%) of fluoronitrile (C_4-FN) or fluoroketone (C_5-FK) mixed with CO_2 or air.
Dielectric Strength (Relative to SF6)	1.0 (Baseline). Exceptionally high (≈2.5 × air).	~0.3–0.4. Requires significantly larger gap or higher pressure for equivalent insulation.	~0.3–0.35. Similar limitations to air.	~1.0 to 1.2. Can match or exceed SF6 at similar pressure, enabling compact design.
Arc Quenching Ability	Excellent. Rapid recombination of dissociated molecules.	Moderate. Standard air-blast or vacuum interruption is typically used alongside.	Moderate to Good. Used with vacuum interrupters; CO_2 itself has decent quenching properties.	Good. The fluorinated component enhances arc quenching, but design often relies on vacuum interrupters for current breaking.
Global Warming Potential (GWP_{100})	22,800 (Extremely high). The most potent greenhouse gas known.	0 (Negligible).	1 (Defined baseline).	<1 to ~500. Varies by fluorinated component and concentration. Drastically lower than SF6.
Atmospheric Lifetime	≈3,200 years. Extremely persistent.	Not applicable (natural atmospheric constituents).	Varies (50–200 years for excess CO_2, but considered part of natural/biogenic cycle in this context).	Days to ~30 years. Much shorter-lived than SF6. The fluorinated molecules break down relatively quickly.

Table A1. *Cont.*

Aspect	SF6 (Baseline)	Technical Air/Dry Air (N_2/O_2 mix)	CO_2 (Pure or Carrier)	Fluorinated Gas Mixtures (e.g., C4-FN/CO_2 or C5-FK/CO_2)
Toxicity & By-products	Non-toxic in pure form. Decomposes under arc into toxic by-products (e.g., S_2F_{10}, SOF_2, HF). Requires handling.	Non-toxic. No hazardous decomposition by-products.	Non-toxic at operating concentrations. May produce trace CO or O_3 under intense arcing.	Low toxicity of base mixture. Decomposition products (e.g., HF, COF_2) can be corrosive but are produced in minimal quantities and contained.
Operating Temperature Range	Very wide (typically −40 °C to +40 °C for sealed GIS). Low liquefaction temperature.	Excellent. No liquefaction concerns.	Good, but higher pressure required for performance. CO_2 liquefies at moderate pressures around room temperature.	Limited by boiling point. Fluoroketones (~26 °C) and fluoronitriles (~−4 °C) may condense in cold climates, requiring heaters or blend adjustments.
Pressure Requirements	Low to moderate (typically 3–7 bar abs).	High (often 8–15+ bar abs) to compensate for lower dielectric strength, impacting tank design.	High (similar to air).	Moderate, comparable to or slightly higher than SF6 (4–8 bar abs) to achieve superior dielectric strength.
Material Compatibility	Excellent. Inert with most metals and elastomers used in GIS.	Excellent. Standard industrial materials.	Good. Non-reactive with metals; may require specific seals.	Requires evaluation. Fluorinated molecules can have solvency effects, requiring compatibility-tested seals (e.g., Perfluoroelastomer (FFKM)) and lubricants.
Leakage & Handling	Critical concern due to high GWP. Requires strict leak detection, recovery, and reporting protocols.	No special handling or recovery needed. Leakage is environmentally benign.	Low concern. Leakage has minimal direct climate impact (GWP = 1).	Medium concern. While GWP is low, leakage of the fluorinated component should be minimized; handling procedures simpler than for SF6.
Technology Readiness & Cost	Mature, Benchmark. Low initial cost for proven, compact designs. High lifecycle cost due to gas handling and potential future taxes.	Mature for AIS, Emerging for GIS. Lower gas cost. Higher initial cost for pressurized GIS due to larger size/stronger tanks.	Developing. Gas is cheap. System cost similar to air-based GIS due to high-pressure design.	Commercial for MV, Piloting for HV. Higher gas cost per kg, but used in small quantities. Initial equipment cost premium (~5–20%), decreasing with scale.
End-of-Life & Recycling	Complex and costly. Mandatory gas recovery and destruction (incineration > 1,200 °C) to prevent emissions.	Simple. Venting is permissible (non-toxic, natural air).	Simple. Can be vented (GWP = 1) or captured.	Requires controlled recovery. The fluorinated component should be captured and sent for specialized destruction/recycling.

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