International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V71I4P207
Volume 71 Issue 4, 72-78, April 2023

Original Article

Analysis of Switchgear on Insulation Performance and Reliability in Malaysian Railway Double Track Project

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Received: 03 October 2022 Revised: 31 January 2023 Accepted: 12 April 2023 Published: 25 April 2023

Abstract *- Switchgears are the key component in protecting equipment in High Voltage (HV) settings. With the rise of railway projects in Malaysia, there will be an increase in demand for switchgear for the electrification project. Therefore, the type of switchgear that is better in terms of insulation performance and reliability needs to be determined. Then, a simulation model is developed in order to measure the Partial Discharge (PD) in the insulation medium of the switchgears. An analysis is conducted in order to compare which insulation medium is superior for switchgear. It is found that Sulfur-Hexafluoride (SF6) gas is seen to have lower values of peak voltage during PD inside the insulation medium compared to air. SF6 gas proves to be the better insulation medium compared to air in terms of insulation performance and reliability due to the lower values of peak voltage detected during the occurrence of PD. The finding of insulation performances will enhance the quality of Malaysian railways in order to decrease the breakdowns and disturbances related to the electrification system.*

Keywords *- Gas-insulated switchgear, Air-insulated switchgear, Partial discharge.*

1. Introduction

In the railway industry, electrified equipment would cost thousands of dollars. Therefore, it is important to protect the electrified equipment to avoid unnecessary losses and minimise the repair cost. Thus, this protection is provided in switchgears which consist of multiple electrical components such as circuit breakers, relays, disconnect switches, and fuses to operate, secure and separate electrical devices in an electric power system. The separation of circuits or electrical devices enables the isolation of electrical sections in the railway to enable maintenance activities, troubleshooting, and diagnostic activities to be conducted while maintaining operation at a minimum delay; in the reported accidents and incidents in Malaysian railways from years 2000 until 2020, where 42.86% of the incidents were caused by the breakdown of the power supply system, as depicted in Figure 1 [1].

Therefore, extensive research in the area of switchgear insulation performance and reliability has been done for many years. For instance, developing new insulation materials and techniques to improve the performance and reliability of switchgear. Many researchers have explored using new insulating gases, such as sulfur hexafluoride (SF6), which have high dielectric strength and can minimise switchgear's size and weight. Various techniques, such as partial discharge measurement, insulation resistance measurement, and infrared thermography, have been developed to detect insulation defects and identify potential failure modes.

Gas-insulated switchgear (GIS) uses sulfur hexafluoride (SF6) gas as an insulation medium. SF6 has excellent insulating properties, is non-flammable, and has high dielectric strength. Thus, making it ideal for use in high-voltage applications. Additionally, GIS is compact, requires less maintenance, and has a longer lifespan than air-insulated switchgear. The choice of insulation medium depends on the specific requirements of the application, as well as environmental and regulatory considerations. While SF6 gas-insulated, switchgear is generally considered superior for high-voltage applications. Air-insulated switchgear (AIS) and solid-insulated switchgear are suitable for lower voltage applications and offer benefits such as environmental friendliness, low maintenance requirements, and resistance to pollution and moisture.

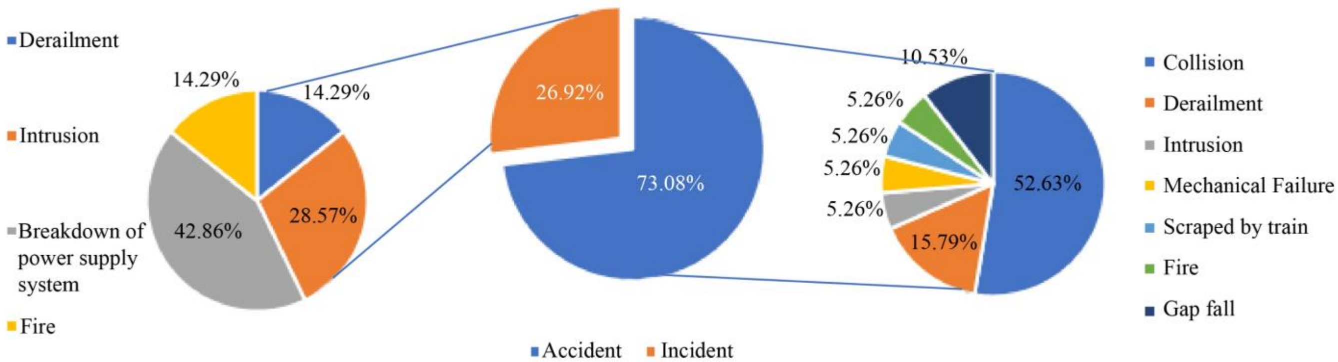

Fig. 1 Reported accidents and incidents in Malaysian railways from 2000 until 2020 [1]

Table 1. Technical Specifications for Siemens 8DA [13]

Electrical Data	Ratings
Nominal voltage according to IEC 60850	25 kV
Rated insulation voltage	27.5 kV
Rated frequency	50/60 Hz
Rated short-duration power-frequency withstand voltage	95 kV to earth and across open contacts 110 kV across isolating distance
Rated lightning impulse withstand voltage	200 kV to Earth and across open contacts 220 kV across isolating distance
Rated short-circuit breaking current	31.5 kA or less
Rated short-time withstand current	31. 5 kA or less for 3 seconds
Rated short-circuit, making current	80 kA or less
Rated normal current	3150 A or less for busbar 2500 A or less for the feeder

Other than that, a sum of RM180 billion was invested into the Malaysian railway industry, funded by the government and announced by the Chairman of Suruhanjaya Pengangkutan Awam Darat (SPAD) in 2013 [2-4]. This will produce higher demand for electrical switchgears to protect the railway's electrification systems. This study aims to focus on switchgear which is superior in terms of insulation performance and reliability for Malaysia railway. Therefore, the parameters involved for air and gas-insulated switchgear must be identified to determine the insulation and reliability performance. Then, a simulation model is developed to conduct the case studies. An analysis is performed to compare the insulation performance between AIS and GIS. The findings will enhance the quality of the Malaysian railway due to fewer breakdowns and disturbances related to the electrification system.

1.1. *Gas-Insulated Switchgear (GIS)*

This study focuses on using Gas-Insulated Switchgear (GIS) for 25 kV AC 50 Hz applications inside a railway feeder station. Only collisions with neutral particles on the applied electric field determine how electrons flow in gases. In the electric field, electrons are increased and gain kinetic energy between collisions. A considerable fraction of inelastic collision processes in molecular gases allows for a more significant dissipation of the electron's kinetic energy [5-10]. In GIS, SF6 is widely used in the industry as the insulation medium due to the specific properties that are present in SF6 proved to be beneficial for the applications. These properties are excellent insulation as it has high strong dielectric resistance and superior arc quenching properties due to their high stability and high heat dissipation [11]. However, SF6 is a potent greenhouse gas. It is chemically stable, with a lifetime of 3200 years in the atmosphere [25]. A case study for Gemas-Johor Bahru Electrified Double Track Project using a GIS from Siemens is utilised, specifically the 8DA11/12 model—the technical specifications for the switchgear as shown in Table 1 [13].

1.2. *Air-Insulated Switchgear (AIS)*

Air-Insulated Switchgear (AIS) is designed with air as the primary dielectric medium for insulation. Even though the air has the lowest dielectric strength properties compared to other alternative insulation within the industry, it is still widely used because of its low initial cost. Furthermore, it needs large spaces and is unsuitable to be built in dense areas because it is significantly larger than GIS equipment. However, the system's simplicity in the utilisation of ambient air to do the insulating works attracts customers to resort to the AIS applications. An arc is formed by strong thermal convection effects and electromagnetic force to stretch across splitter plates whenever switching occurs. This stretching will cause elongations, which assist in cooling the insulation medium. The long arc resistance also improves the power factor and ends in the extinction of the arc [14].

Nevertheless, the AIS is an open-air design which causes insulation degradation from an environmental condition, whether it be natural or man-made pollutants [15]. The AIS can be utilised for the same application of 25 kV 50 Hz supply. The AIS uses UniGear ZS2, the ABB mainline switchgear, for primary distribution up to 36 kV, 3150 A, and 31.5 kA—technical specifications for the ABB Unigear ZS2 as depicted in Table 2 [16].

1.3. Partial Discharge (PD)

Partial Discharge (PD) is closely related to the reliability of the equipment. It determines the ability of the equipment's insulation to withstand mechanical stresses as well as the electrical stresses put upon it. According to the IEEE Standard Terms, PD is defined as an electric discharge that only partially bridges the insulation and may or may not occur adjacent to a conductor [26]. According to the IEC Standard, PD is an electrical discharge partially bridging the insulation between conductors [18]. During equipment operation, a specific voltage level exists across conductors within an insulation medium. Suppose a defect exists within this insulation medium. In that case, the permittivity of that defect is less than the permittivity of the insulation medium, which will result in excess electric field strength in the defect [19]. This usually happens when there are microscopic air bubbles within the insulation medium. These air bubbles will produce a difference in dielectric strength within the insulation medium. This non-uniform dielectric strength causes a localized dielectric breakdown which introduces electrical stress within the insulation medium. If this phenomenon repeatedly occurs during switching, whether energizing or de-energizing, it can produce more microscopic air bubbles, further deteriorating the insulation medium.

1.4. Partial Discharge Measurement

PD measurements can be done either online (operating) or offline with the correct equipment. For medium voltage switchgears, usually, the measuring methods are Ultra High Frequency (UHF) method, radio frequency method, ultrasonic method and Transient Earth Voltage (TEV) method [20]. Whenever PD occurs, the transfer of positive and negative charges will follow. These charges are balanced during the transfer process, followed by a steep pulse current that radiates electromagnetic waves to the surroundings. These electromagnetic waves have a high frequency that can go up to the GHz range. From this, the UHF detection method can be used. From previous studies, it is observed that the steepness of the pulse is related to the frequency [27]. The steeper the pulse, the higher its frequency in an electromagnetic wave. The steepness of the pulse is relevant to partial discharge because it is related to the discharge gap that occurs. The discharge process duration and current pulse are faster and steeper when the discharge gap is smaller. The rising duration of the PD current pulse is noticeably short. Thus, these PD pulses cause many resonances in the GIS modules [22].

2. Methodology

In this study, a simulation model is developed using MATLAB, which can measure the PD inside the insulation medium for the Malaysia Railway Double Track Project. A test circuit model is developed in order to simulate the occurrence of PD inside a void. In this model, it is assumed that a cubical void is present in the switchgear insulation. This cubical void will be charged and undergo breakdown, which leads to PD. The schematic is developed to recreate the occurrence of PD inside insulation material for the switchgear in the feeder station. From the test circuit, the PD current and voltage can be obtained. The simulation is run for 0.06 seconds using the ode23tb solver. The test circuit is shown in Figure 2.

2.1. Test Circuit Parameters

In Figure 2, the test circuit is equipped with a measuring device with an integrated bandpass filter and peak detector. The bandpass filter will filter out signals from undesirable frequencies while providing the precise time of peak voltage. Then, the signal will pass through the peak detector to measure the highest voltage during the partial discharge occurrence. Hence, two case studies are carried out. The first case study will utilise the parameters for an air-insulated medium. Meanwhile, the other case study will utilise the parameters for an SF6 gas-insulated medium. In both cases, certain parameters will be kept constant such as the internal resistance (R_i), the internal capacitance (C_i), the coupling capacitance (C_k) and the load for measurement (R_m, L_m and C_m), as shown in Table 3 [28].

Table 2. Technical Specifications for ABB Unigear ZS2 [16]

Electrical Data	Ratings
Rated voltage	36 kV
Rated insulation voltage	36 kV
Rated power frequency withstands voltage	70 kV for 1 min
Rated lightning impulse withstand voltage	170 kV
Rated frequency	50/60 Hz
Rated short-time withstand current	31.5 kA for 3 sec
Peak current	80 kA
Internal arcs withstand current	31.5 kA for 1 sec
Main busbars rated current	1250/1600/2000/ 2500/3150 A
Branch connections rated current	1250/1600/2000 A

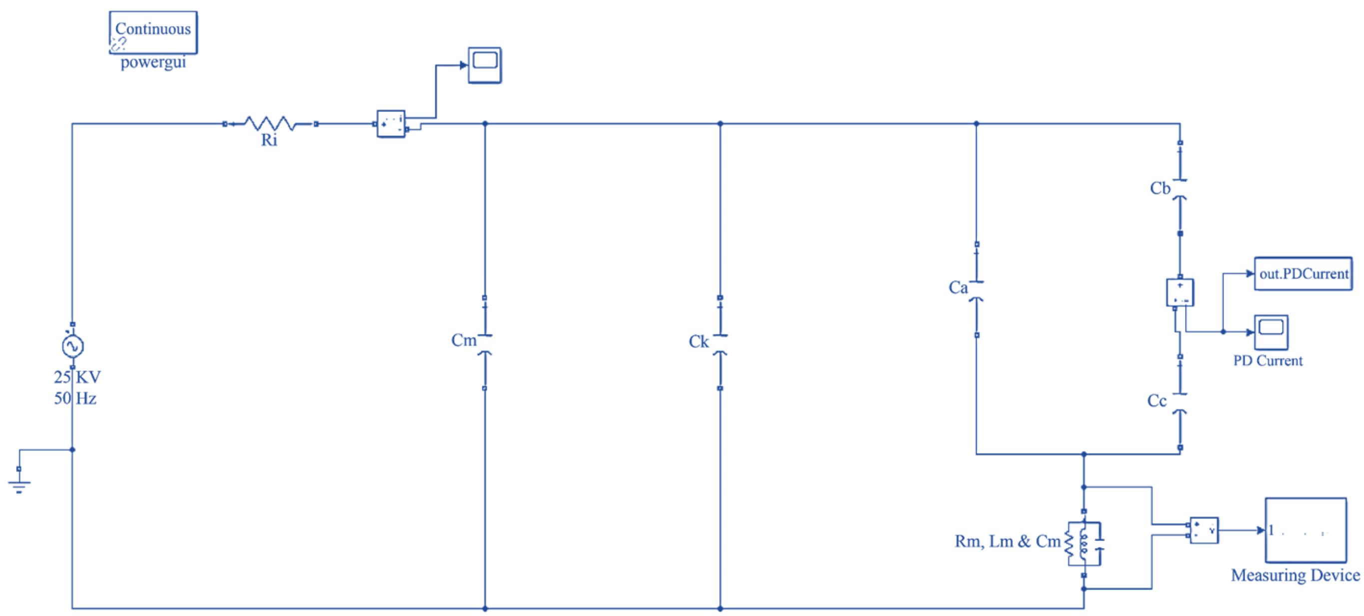

Fig. 2 Test Circuit for PD Measurement

Table 3. Constant Parameters in the Test Circuit [28]

Parameter	Value
Source	25 kV
R_i	20 Ω
C_i	1 nH
C_k	1 mF
R_m	50 Ω
L_m	0.6 mH
C_m	0.45 µH

In the meantime, the variable parameters include the capacitance values of the cubical void, which are the values of C_a, C_b and C_c, as illustrated in Figure 2—these capacitance values as presented in Table 4.

Table 4. Capacitance values for Air-Insulated Medium and Gas-Insulated Medium

Parameter	Value	
	Air-Insulated	Gas Insulated
C_a	1.107×10^{-14} F/m	1.109×10^{-14} F/m
C_b	1.230×10^{-14} F/m	1.232×10^{-14} F/m
C_c	3.164×10^{-14} F/m	3.168 10^{-14} F/m

3. Results and Discussion

The PD measurements involved two insulation mediums which are SF6 gas nd air insulation. The PD measurements involved the PD Current, PD Voltage, Bandpass Filer Output and Peak PD Voltage. The analysis focused on comparing the PD Current and the Peak PD Voltage. The bandpass filter is present to determine when the PD voltage peaked.

The frequency response of the bandpass filter is depicted in Figure 3. The frequency response was selected in accordance with IEC 60270: 2000 standard, which is for high voltage test methods specifically for partial discharge measurement. According to the standard, for wideband PD measurements, the lower limit frequency must be between 30 kHz to 100 kHz. However, the upper limit frequency must be less than 500 kHz. As a result, by subtracting the upper and lower limits frequency, the range fall between 100 kHz and 400 kHz [24]. Consequently, the better insulation medium in terms of insulation performance and reliability will be determined.

3.1. Partial Discharge in Air-Insulated Medium and Gas-Insulated Medium: Current and Voltage

The simulation was run for 0.06 seconds, and the measurements were recorded. The analysis for the PD current going through the cubical void present in the insulation medium. The comparison of PD current between both insulation mediums is depicted in Figure 4. The y-axis shows the PD current measured in amperes, while the x-axis shows the time in seconds. There is no significant difference in the PD current going through the cubical void for both gas-insulated and air-insulated mediums. This is because the same source is fed to the test circuit, which is 25 kV 50 Hz. Thus, there are no differences in the performance for both insulation mediums with regard to PD current. For both test circuits, the current amplitude of about 1.095×10^{-8} A.

However, when SF6 gas and air insulation were compared for peak PD voltage recorded by the test circuit, the outcomes were found to be different.

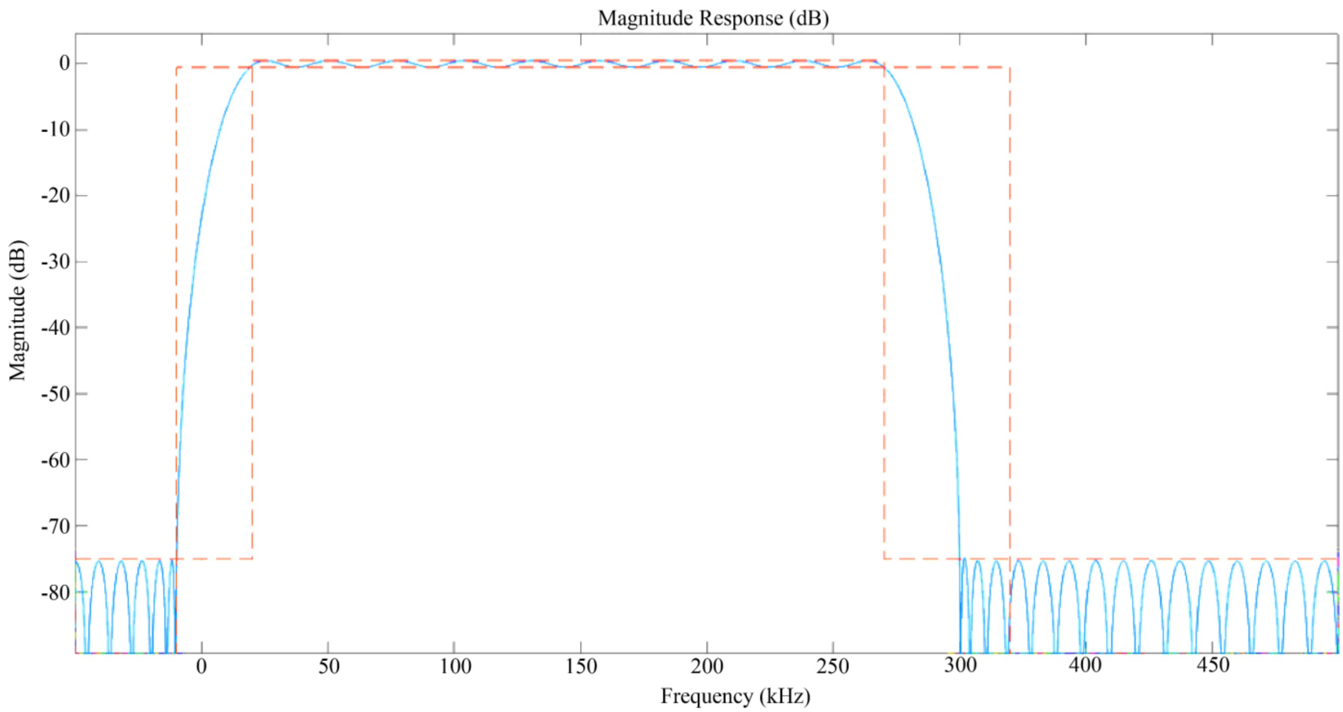

Fig. 3 Frequency Response of Bandpass Filter

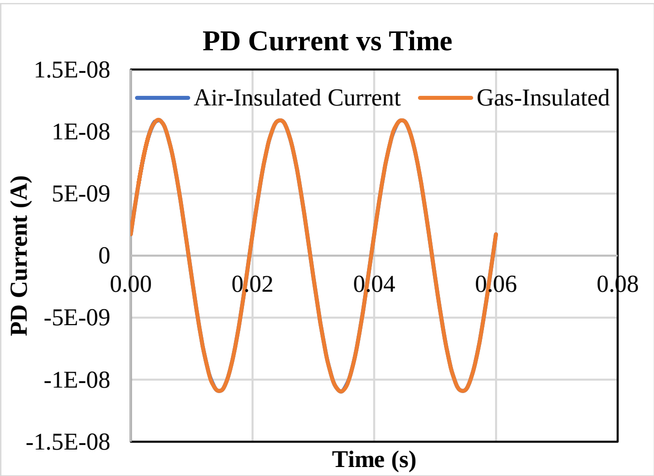

Fig. 2 Comparison of PD Current between Air-Insulation and Gas-Insulation

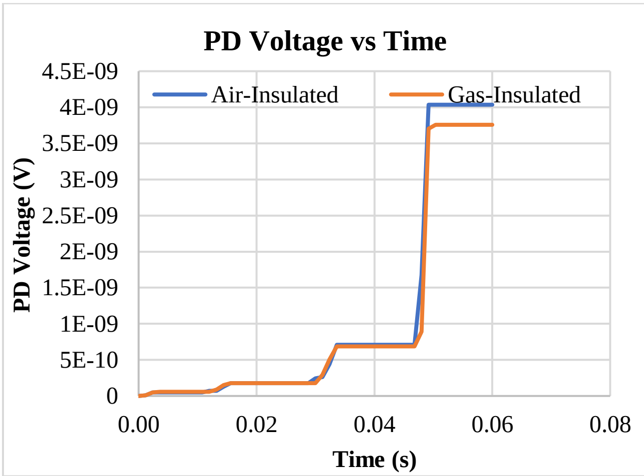

Fig. 3 Comparison of peak PD Voltage in Air-Insulation and Gas-Insulation

Figure 5 shows the output of peak PD voltage measured by the peak detector from the measuring instrument. The graph's y-axis shows the PD voltage, while the x-axis shows the time in seconds from 0 to 0.06 seconds. The figure shows that the PD voltage of the air-insulation medium reached a higher peak voltage than the gas-insulation medium. The highest PD voltage recorded for the air-insulation medium was 4.035×10^{-9} V compared to 3.757×10^{-9} V for the gas-insulated medium. The total differences are 2.78×10^{-10} V or approximately 7.14%. It shows that the gas-insulation is a superior insulator compared to air insulation based on the peak voltage measured during PD from the test circuit.

3.2. Insulation Performance and Reliability of Air-Insulated Medium and Gas-Insulated Medium

From the analysis, it concludes that SF6 gas is a better insulation medium compared to air. This is related to dielectric strength for both insulation mediums inside the switchgears. Since the dielectric strength of SF6 gas is higher than the air, it explains why the peak voltage of PD measured in the gas-insulation medium is lower compared to the peak voltage of PD measured in air-insulation. Additionally, SF6 gas is considered to have three times higher dielectric strength than the air at 0.1 MPa. Furthermore, from the results, SF6 gas possesses 7% better insulation performance compared to air.

It also relates to the reliability of the equipment that possesses these insulation mediums. Since air-insulated mediums will amount to a larger peak PD voltage than gas-insulated mediums, this will affect the reliability of switchgears that utilise air-insulation. This is because higher PD voltages will cause a larger breakdown of the insulation medium. Consequently, an increase in maintenance costs may cause damage to the switchgear quicker compared to GIS.

4. Conclusion

In conclusion, the GIS is the better alternative for a 25 kV 50 Hz source. This is due to GIS having a lower peak voltage during PD compared to AIS. Using SF6 will cause higher insulation performance than air due to the higher dielectric strength possessed by SF6. In the long term, GIS proved more reliable because of the lower peak voltage obtained during PD occurrence. This will result in a lower insulation breakdown compared to AIS.

Acknowledgement

The authors gratefully appreciate the Universiti Tun Hussein Onn Malaysia (UTHM) for supporting this research work under the TIER 1 grant vot H859.

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