Indonesian Journal of Electrical Engineering and Computer Science
Vol. 7, No. 1, July 2017, pp. 9 ~ 17
DOI: 10.11591/ijeecs.v7.i1.pp9-17

Status Review on Gas Insulated Switchgear Partial Discharge Diagnostic Technique for Preventive Maintenance

Visa Musa Ibrahim*[1], Zulkurnain Abdul-Malek[2], Nor Asiah Muhamad[3]
[1,2]Institute of High Voltage and High Current (IVAT), Faculty of Electrical Engineering,
Universiti Teknologi Malaysia (UTM) Johor Bahru 81310 Malaysia
[3]School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM),
Corresponding author, e-mail: visaibrahim@gmail.com*, zulkurnain@utm.my, norasiah@utm.my

Abstract

Gas insulated switchgear (GIS) plays a vital role in high voltage transmission of electrical energy due to its advantages of high reliability and performance, compact in dimensions and outstanding compatibility with the environment. It uses sulphur hexafluoride gas as its insulant and coolant because of its high dielectric strength and excellent arc quenching ability. Gas insulated switchgear in operation suffers the challenge of its insulation decomposition and eventually failure due to the activities of partial discharge that arouses from defects. This failure is catastrophic and it will lead to entire power out stage that will affect all categories of human activities, so there is a need for Gas insulated switchgear condition monitoring and diagnoses in order to carry out preventive maintenance. This paper reviews diagnostic techniques and methods for Gas insulated switchgear insulation degradation caused by partial discharge for the purpose of carrying out preventive maintenance to avert its failure.

Keywords: *Gas insulated switchgear, Sulphur hexafluoride gas, Partial discharge, Decomposition products, Diagnostic technique*

Copyright © 2017 Institute of Advanced Engineering and Science. All rights reserved.

1. Introduction

In any modern society, the social welfare and economic good build and development depend solely on the availability of reliable and cheap supply of electrical energy. Extensive electrical power installation network at high voltage in industrialised countries have been build and in developing countries, they are being constructed at an ever increasing rate. A Large amount of electrical power that is generated, transmitted and distributed over a long distance is best accomplished using high voltage, thus high voltage equipment (GIS) is required and it serves as the backbone of Morden power system [1].

Gas insulated switchgear (GIS) is the combination of electrical switches, fuses, circuit breakers, current and capacitive voltage transformers that are used to control, protect and isolate electrical equipment. Switchgear is also used to de-energize equipment in power system network to enable fault of all types to be rectified [2]. GIS is used because of its high reliability and performance, compact in dimensions, low maintenance requirements, outstanding compatibility with the environment and ability to interrupt fault current in power system network. The increase in demand for electricity and the growing energy density in the metropolitan areas have made it necessary to extend the high voltage network in an economical manner to consumer unit while ensuring a high degree of supply reliability and quality. Gas insulated substations provide the best solution to the above challenge [3].

Gas Insulated Switchgear uses Sulphur hexafluoride gas (SF_6) as its insulant that has superior dielectric properties with excellent arc quenching properties compare to air and vacuum [4-6]. SF_6 gas is inert in nature, odourless, colourless, chemically stable, non-toxic, non-inflammable and has high vapour pressure (about 21 bar at ambient temperature) [7]. It can be used down to -35 ^{0}C without liquefaction occurring at a pressure of 5bar typical to GIS application. SF_6 gas is widely used in power equipment due to the fact that in addition to its high dielectric strength, it has good thermal transfer characteristics.

SF_6 gas has high dielectric strength three times that of air and at about 6 bar pressure

Received March 22, 2017; Revised June 3, 2017; Accepted June 17, 2017

its dielectric strength is approximately equal to that of transformer oil. If a critical field strength of about (89kv/cm) is exceeded in GIS medium, ionisation will build up very rapidly because of the brittleness of SF_6 gas. In practical application, this can happen in the vicinity of any small defects such as a metallic protrusion, free conducting particles, contamination on the surface of the spacer and gap at electrode/epoxy interface [3]. Depending on the nature of defect that occurs, the partial discharge (PD) at this local region of field enhancement may result in the breakdown of insulation system and will cause the GIS to fail. About eighty-five percent of GIS disruptive failure is caused by PD [8].

The failure of the live assets (GIS) is often sudden and catastrophic, with the release of large amounts of energy, leading to explosion and fire producing unrepairable damage on all the substation equipment, injury or death of personnel working in the substation, power outage that will paralyze economic, social, educational, military, security, medical activities and high cost of replacement.

When the dielectric failure occurs in the GIS, the arc will not be extinguished by the insulant (SF_6) gas, this will lead to internal pressure build up that will cause hole in the metal wall of the GIS due to the concentration of the arcing thereby causing SF_6 gas that is highly potential greenhouse gas to leak. Sulphur hexafluoride (SF_6), is a highly potent greenhouse gas with a global warming potential of about 23,900 times greater than CO2. SF_6 also has an atmospheric lifespan of about 3,200 years, so it will contribute to global warming for a very long time. One pound of SF_6 gas has the global warming equivalent of 11 tonnes of CO_2. [5], [9-10]. However, under high-temperature conditions, SF_6 gas decomposes into byproducts that are toxic and corrosive. The decomposition by-products can occur when SF_6 gas is exposed to spark discharges, partial discharges, and switching arcs. These byproducts that are in the form of gases or powders, can affect human health and cause the following conditions in humans: irritation to the eyes, nose, and throat, pulmonary oedema and other lungs damage, skin and eye burns, nasal congestion, bronchitis and body rashes [5], [11-13]. Therefore this critical asset (GIS equipment) should be monitored closely and continuously using a reliable and effective technique in order to assess its operating condition that will enable preventive maintenance to be carried out in order to ensure its maximum uptime [14].

2. Sulphur Hexafluoride Gas Insulation

Heavy gases (Chlorine and Fluorine) under experimental condition have a considerably higher dielectric strength about thrice that of air. Their high breakdown strength depends on their ability to take up free electrons thereby forming heavy negative ions. These gases are called electronegative gases. Sulphur hexafluoride gas is one of the electronegative gas among the many available gases. SF_6 gain its relevance as the dielectric gas of choice because it is chemically stable and has high breakdown strength which makes it effective in arcs extinction and as a result of that it is extensively used in gas-insulated switchgear, circuit breakers, gas insulated transmission lines and gas-insulated transformers [15-17].

2.1. Basic Properties of Sulphur Hexafluoride Gas

Sulphur hexafluoride gas is a highly electronegative gas that belongs to the seventh group of the periodic table. It is odourless, colourless, non-flammable, non-toxic and inert in nature with high dielectric strength [15-18]. SF_6 gas at about 14 bar in 0 ^{0}C liquefies whereas at about 3.5 bar in -40 ^{0}C, the gas liquefies which makes it difficult to be used at high pressure in the cold region. Detail properties of Sulphur can be seen from Table 1. SF_6 gas at atmospheric pressure is chemically stable up to 500 ^{0}C and it decomposes into by-products at a higher temperature. SF_6 under electrical discharge in the presence of water and oxygen will undergo oxidation and decomposition into some by-products such as SOF_4, SOF_2, SO_2F_2, S_2F_{10}, CF_4, CO_2, S_2F_2, SF_2, SF_8, SF_4, S_2OF_{10}, H_2S, HF, SO_2, SiF_4, ALF_2 (solid), CUF_2 and WF_6 (solid). Some of the by-products are toxic and corrosive [7, 19].

Table 1. Some important physical properties of SF_6

Molecular weight	146.6
Melting point	-50.8 ^{O}C
Boiling point	-63.0 ^{O}C
Critical temperature	45.6 ^{O}C
Sublimation temperature	-63.9 ^{O}C
Liquid density (at 25 ^{O}C / 50 ^{O}C)	1.33 / 1.98 g/ml
Gas density (at 1 bar and 20 ^{O}C)	6.2 g/l
Relative density	5.1
Critical density	0.735 g/ml
Critical pressure	35.56 bar
Vapour pressure (at 20 ^{O}C)	10.62 bar
Specific heat (at 30 ^{O}C)	0.599 J/g
Thermal conductivity	0.1407 W/m ^{O}C
Dielectric constant	1 – 1.07

2. Decomposition Mechanism of Sulphur Hexafluoride Gas under Partial Discharge

Decomposition mechanism of sulphur hexafluoride gas under partial discharge study was comprehensively conducted by American National Standard Institute researchers. The decomposition mechanism illustrating their zone model was shown in Figure 1 [20-22].

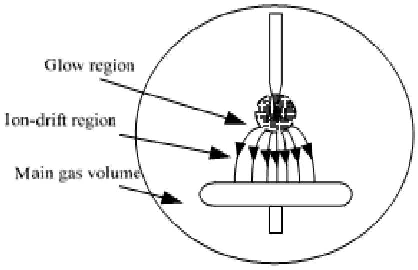

Figure 1. Decomposition mechanism of sulphur hexafluoride gas under partial discharge zone model

The reaction zone in the gas chamber is divided into three according to the zone model namely the glow region, the ion-drift region and the main gas volume. The glow region is the region which the excitation and ionization by electron collision of the molecules takes place and the molecules split into low fluorine sulphide (SF, SF_2, SF_3, SF_4, and SF_5). These substance react with H_2O which splits into O and OH generating vast products as HF, SO_2, SO_2F_2, SOF_4, SF_4, SF_2, and S_2F_{10} as shown in equation (1) - (12). The ion drift region is in between the glow and the planar anode where the charge is transported by negative ions as shown in equation (13) – (15). The main gas volume region is surrounded by point to plain gap in which the surface reaction or slow gas phase reaction occurs as shown in equation (16) – (19). In the discharge region CO_2 and CF_4 will be generated in the presence of stainless steel electrode and organic insulation through the reaction of O_2 and fluorine atoms (F) as shown in equation (20) – (23). [13], [20- 24].

$$e + SF_6 \rightarrow SF_x + (6 - X)\,F + e,\ X = 1 \sim 5 \quad (1)$$

$$e + O_2 \rightarrow O + O + e \quad (2)$$

$$e + H_2O \rightarrow O = OH + e \quad (3)$$

$$SF_5 + OH \rightarrow SOF_4 + HF \quad (4)$$

$$SF_5 + O \rightarrow SOF_4 + F \quad (5)$$

$$SF_4 + OH + F \rightarrow SOF_4 + HF \quad (6)$$

$$SF_3 + O \rightarrow SOF_2 + F \quad (7)$$

$$SF_3 + OH \rightarrow SOF_2 + HF \quad (8)$$

$$SF_2 + O \rightarrow SOF_2 \quad (9)$$

$$SF_2 + OH + F \rightarrow SOF_2 + HF \quad (10)$$

$$SF + O + F \rightarrow SOF_2 \quad (11)$$

$$SF + OH + 2F \rightarrow SOF_2 + 2HF \quad (12)$$

$$SF_6 + SF_4 \rightarrow SF_5^- + SF_5 \quad (13)$$

$$SF_6^- + SF_4 \rightarrow SOF_5^- + SF_5 \quad (14)$$

$$SF_6^- + SO_2 \rightarrow SO_2F^-SF_5 \quad (15)$$

$$SF_2 + O_2 \rightarrow SO_2F_2 \quad (16)$$

$$SF_4 + H_2O \rightarrow SOF_2 + 2HF \quad (17)$$

$$SOF_4 + H_2O \rightarrow SO_2F_2 + 2HF \quad (18)$$

$$SOF_2 + H_2O \rightarrow SO_2 + 2HF \quad (19)$$

$$\text{epoxy} + F \rightarrow CF_4 \quad (20)$$

$$\text{epoxy} + O_2 \rightarrow CO_2 \quad (21)$$

$$C + 4F \rightarrow CF_4 \quad (22)$$

$$C + O_2 \rightarrow CO_2 \quad (23)$$

Sulphur hexafluoride gas main decomposition products under the activities of partial discharge include SO_2F_2, SOF_4, SOF_2, CF_4, SO_2, HF and CO_2.

3. Genesis of Partial Discharge

Partial discharge is the breakdown that is localised which occur under high voltage stress in a small portion of solid, liquid or gas insulator that does not bridge completely the space between two conductor electrodes. These occur due to the defects of irregularities or protrusion on high voltage or earth electrode, free or floating metallic particles, contamination on the surface of spacer and void or gap at electrode/epoxy interface as a result of mechanical abrasion movement of conductor during load cycling, error in manufacturing of GIS and also vibration during shipment of GIS equipment as shown in Figure 2. Partial discharge is accompanied by the emission of energy as electromagnetic emission informs of radio wave, light and heat; acoustic emission inform of sound at ultrasonic ranges and also emission of ozone and oxide of nitrogen. Although the magnitudes of partial discharge are small (about 5eV-10eV) but it causes gradual progressive deterioration or degradation of insulation in gas insulated switchgear, then eventually lead to ultimate failure of the GIS. [3, 20, 24], [41-43], [51], [57-59]. About eighty-five percent of GIS disruptive failure is caused by PD [8], therefore there is need to employ an effective method to diagnose the activities of PD in GIS.

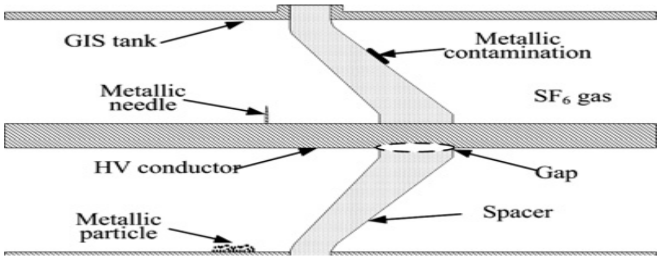

Figure 2. Typical defects in practical GIS [21]

3.1. Diagnostic Techniques for Partial Discharge Detection in GIS

Partial discharge measurement is usually implemented during GIS quality assurance in the factory, testing of high voltage to detect assembly and transportation fault on site and also for early detection of PD during GIS operation. [20], [25-26]. Several types of research of PD diagnostic technique of GIS was conducted and they are as follows.

3.1.1 Optical (Light Eemission or Output) Technique

This uses photomultiplier to detect the emission of light from partial discharge. It can detect the emission of an even single photon. The radiation which is primarily in UV band is strongly absorbed by both glass and SF_6, therefore for detection purpose, it is necessary to use quartz lenses and a reasonable short path length. Although to some extent, this method performed effectively, there are some difficulties (limitation) that will occur in detecting discharge anywhere in the GIS due to internal and external interference (noise and electromagnetic interference) and also many sensors are used [27- 30].

3.1.2. Acoustic Emission Technique

Acoustic signals arise from the gas chamber free moving particles bouncing on it and pressure wave caused by partial discharge. These signals in the GIS travel from source to the detector by multiple paths due to its broad bandwidth. Acoustic emission sensor attached to the outside chamber is used for the measurement of the signal. this method faces difficulties in measurement due to high attenuation of signal that occurs in acoustic emission which makes detection of PD not accurate and reliable; and also it require good location of sensor on the chamber thereby making it not suitable for permanently installed monitor because it will require many sensors and also internal and external interference (noise and electromagnetic interference) affects the measurement [20-21], [27-29], [31-35].

3.1.3. Electrical Discharge Technique

This uses coupling capacitor that is placed in parallel with the test object as the conventional method for detecting partial discharge. The discharge signals are measured across external detection impedance. The limitation of this technique is that the sensitivity is insufficient and it is incompatible for long length GIS and also internal and external interference (noise and electromagnetic interference) affects the discharge signal measurement [20-21], [27, 29, 31], [36-37].

3.1.4. Ultra-High Frequency (UHF) Technique

This adopts both internal and external coupler technique, and UHF sensors are used. It has the limitation of loss of sensitivity, the risk of breakdown if the UHF sensor is not a position in hatch cover. external interference(electromagnetic interference) affect the UHF measurement and a large number of the sensor from six to eight per three phase bay is to be used and also the discharge calibration and pattern recognition of UHF signal has not been completely resolved [1], [20, 21], [27, 29, 31].

3.1.5. Chemical by Product or Decomposed Gas Technique

Chemical by product diagnostic technique is used to monitor and detect the activities of PD in GIS through the use of gas chromatography, Fourier transform infrared spectroscopy, gas analyser and detector tube with high sensitivity down to 1 ppm_v [21-23], [26]. This technique is rarely affected by noise and electromagnetic interference present outside and inside the GIS, and this makes it more attractive than the other diagnostic techniques and has the potential of becoming the most powerful diagnostic technique in order to carry out preventive maintenance for GIS. The main decomposition product of SF_6 gas is sulphur tetrafluoride gas (SF_4), but this is a highly reactive gas [3, 17]. It reacts further with water vapour to form thionyl fluoride (SOF_2) and sulphuryl fluoride (SO_2F_2) a more stable compounds and also under the activities of PD caused by defects, SF_6 decomposes to form into many compounds such as SOF_4, $S2F_{10}$, CF_4, CO_2, S_2OF_{10}, H_2S, HF, SO_2,SiF_4, ALF_2(solid), CUF_2 (solid) and WF_6 (solid) [7, 19].

4. Decomposed Gas Detection Technique

Decomposed gas detection technique is also known as a chemical by-product or gas analysis technique is similar to that of dissolved gas analysis in the transformer which uses the method of gas chromatography, Fourier transform infrared spectroscopy, gas analyser and detector tube. These methods are not affected by internal and external interference (noise and electromagnetic interference) and it has the potential of becoming the most powerful diagnostic method to be used in GIS to ascertain its fault and condition in order to carry out an effective preventive maintenance [28-44].

4.1. Detector Tube

Detector tube is an SF_6 by-product measuring device which uses chemical reaction in a special test tube. The SF_6 by-products are identified by the changes in colour that occurs during the reaction and the detector tube can detect gases such as SO_2, SOF_2, SO_2F_2, and HF only. The detector tube precision can reach up to 1ppmv but its stability can be affected by temperature, humidity and cross interference problem [16, 26, 28, 36], [45-49].

4.2. Gas Analyser

The gas analyser is used to detect SF_6 decomposed components such as H_2O, SO_2 and O_2 only. It has the advantage of high efficiency and speed during operation but the sensor that is used in the gas analyser can be poisoned after a long period of used due to the chemical reaction between the gas sensor and the gas to be detected, thereby affecting the sensitivity and the detection precision of the gas analyser [16, 26, 28, 36], [45-48], [50, 51].

4.3. Gas Chromatography

Gas chromatography is a process of separating a mixture of gases into its individual components and is identified qualitatively and measured quantitatively. Gas chromatograph consists of the sample handling system, the chromatograph oven and the controller as its functional components. Sample handling system is used to preserve the composition of the gas and it acts as a filter for removing solid and liquid particles in the gas down to two microns size. Chromatograph oven consists of the columns, valves and detectors as its analytical components. The columns is the heart of the gas chromatograph and it is used to separate mixture of gases into its individual components using some physical characteristics of the gas (boiling points and molecular size) and the sample gas is carried through the columns by a carrier gas (Helium), the valve is used for the switching of the analytical flow path of the gas to enable the use of multiple columns and the detector is used to detect, and to measure the decomposed gas then pass the output to chromatograph controller for processing. The controller performs several functions including the control of the valve timing, oven temperature, analyse and store the detector output by calculating individual concentration and other physical properties of the gas sample and finally communicate to the outside world. This method can detect some type of gas such as SOF_2, SO_2F_2, CF_4,CO_2. etc. Detection time is long and the chromatographic column has to be clean regularly [16, 20, 26, 28, 31, 36], [45-49], [52].

4.4. Fourier Transform Infrared Ray Spectrometer

Fourier transform infrared ray (FTIR) spectroscopy is a workhouse technique in the laboratory that is used for quantitative analysis of different kinds of materials i.e. to identify unknown materials in a sample, to determine the quality or consistency of a sample and to determine the amount of component in the mixture. It consists of a source (glowing black body), Interferometer and detector. The source emits an infrared radiation (energy) inform of a beam that passes through an aperture (mirror) which controls the amount of energy that goes to the sample and detector. The beam enters the interferometer where spectral coding takes place resulting in interferogram signal, then it passes to the sample and some of the radiation is absorbed by the sample while some is reflected depending on the type of analysis to be accomplished, then the beam finally passes to the detector which is design to measure interferogram signal. The measured signal is digitised and sent to a digital computer where Fourier transformation takes place. The final infrared spectrum is then presented for interpretation [53, 54]. This method is very effective and efficient due to its high detection speed and precision, ability to detect numerous decomposed component and capacity to resist disturbances [17, 19, 45], [55-56], [60].

5. Conclusion

Modern gas insulated switchgear GIS plays a vital role of control, protecting and isolating electrical equipment in electrical power system network during the process of transmission and distribution of electrical energy. Sulphur hexafluoride gas SF_6 is used in GIS as an insulant because of its excellent characteristics of high dielectric strength and arc quenching properties.

GIS in operation suffers the challenge of degradation and eventually, failure due to the activities of partial discharge PD in the system and this failure is catastrophic and hazardous, hence there is a need for condition monitoring and diagnosis of the GIS asset in order to carry out preventive maintenance.

This paper presented a status review of gas insulated switchgear partial discharge diagnostic technique for preventive maintenance. Several diagnostic and monitoring technique was use which includes optical emission technique, electrical discharge technique, acoustic emission and ultra-high frequency UHF technique but all these techniques has deficiencies of internal and external interference that affects its sensitivity and reliability but chemical by-product technique is rarely affected by internal and external interference and also it is cost effective because through it the magnitude of insulation deterioration can be properly determined by the decomposition products and its concentration to know whether it can be recycled or not during maintenance. Therefore chemical by-product technique has the potential of becoming the most powerful GIS diagnostic technique for condition monitoring in order to carry out preventive maintenance to avert GIS failure.

Acknowledgements

The authors wish to thank the Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (Research Vote No. 4F828) for the financial aid and also appreciate the support of TNB research institute Kajang Selangor Malaysia for providing FTIR spectrometer for the test of SF_6 decomposed by products.

References

[1] MS Naidu, V Kamaraju, “High Voltage Engineering textbook” Third edition, Tata Mc Graw, Hili publishing company limited, New Delhi. 2005 pp. 1–19.
[2] M. Chauhan, U. Joshi, and D. Asija, “features and design concepts of gas", 2014 vol. 8354, no. 3, pp. 60–67.
[3] V. Aaradhi and K. Gaidhani, “Special problems in gas insulated substations (GIS) and their effects on indian power system,” *IEEE Int. Conf. Power Syst. Technol. Powercon.* 2012, pp. 1–5.
[4] C. Liu, S. Palanisamy, S. Chen, P. Wu, and L. Yao, “Mechanism of Formation of SF 6 Decomposition Gas Products and its Identification by GC-MS and Electrochemical methods : A mini Review2015.,” vol. 10, pp. 4223–4231,
[5] B. Lisa and S. Blackburn, “WHITE PAPER : SF 6 Is No Longer a Necessary Evil : The Human Health and Environmental Dangers of SF 6 Gas-Filled Switchgear,” 2015. no. 2002, pp. 1–6,
[6] M. Averyt and I. C. F. International, “SF 6 Gas Properties,” 2006.
[7] Y. Wang, “SF_6 Byproducts in High-Humidity Environment: an Experimental Evaluation between 200^oC and 500^oC,” *J. Electromagn. Anal. Appl.*, 2011. vol. 03, no. 06, pp. 179–183'
[8] EA Technology innovators in Power Engineering. Partial Discharge, “for 24/7 Gas Insulated Switchgear monitoring system,” pp. 1–8.

[9] M. Maiss and C. A. M. Brenninkmeijer. Atmospheric SF6: Trends sources and prospects. *Environmental Science and Technology*, September 1998 Vol 32, No 8:3077– 3086,
[10] ABB, Preussen Elektra Netz, RWE Energie, Siemens and Solvay Fluor und Derivate. Electricity supply using SF6 Technology: Life Cycle Assessment Report. Slovay Fluor und Derivate Technical Brochure. 1999.
[11] IPCC. Climate Change 2001: A Scientific Basis. Cambridge University Press, Cambridge, UK, 2001
[12] S. Wartmann, J. Harnisch, and E. Gmbh, "Reductions of Sf6 Emissions From High and Medium Voltage Electrical Equipment Final Report to CAPIEL Sina Wartmann and Jochen Harnisch All views expressed in this report are those of the authors and do not necessarily represent the views of the organisat," 2005.
[13] H. A., Stuckless, J. M. Braun and F. Y. Chu, "Degradation of silica-filled epoxy spacers by arc contaminated gases in SF_6-insulated equipment", *IEEE Trans. Power Apparatus Syst.* 1985. Vol. 104, pp. 3597-3602,
[14] K. Sueo, I. Shunichi, T. Yoshihide, M. Hisao, M. Setuyuki and T. Kohji,"Diagnostic technique of gas insulated substations by partial dischargedetection", *IEEE Trans. Power Apparatus Syst*., 1980.Vol. 99, pp. 4196-4206,
[15] R. Sarathi and R. Umamaheswari, "Understanding the partial discharge activity generated due to particle movement in a composite insulation under AC voltages," *Int. J. Electr. Power Energy Syst.*, Jun. 2013 vol. 48, pp. 1–9,.
[16] X. Zhang, H. Liu, J. Ren, J. Li, and X. Li, "Fourier transform infrared spectroscopy quantitative analysis of SF6 partial discharge decomposition components," *Spectrochim. Acta - Part A Mol. Biomol. Spectrosc.*, 2015.vol. 136, no. PB, pp. 884–889,
[17] F. Liu, D. Gan, S. Zhou, C. Hu, P. Liu, and X. Zhang, "Analysis of infrared spectrum characteristic and variation trend of SF 6 PD decomposition," *Int. Conf. High Volt. Eng. Appl. ICHVE 2010*, no. 2, pp. 409–412,
[18] Working Group B3.25, SF_6 analysis for AIS, GIS and MTS Condition Assessment. Cigre report February. 2014
[19] U. S. Epa, "Byproducts of Sulfur Hexafluoride (SF 6) Use in the Electric Power Industry," January 2002.
[20] J. Tang, F. Liu, X. Zhang, Q. Meng, and J. Zhou, "Partial Discharge Recognition through an Analysis of SF 6 Decomposition Products Part 1 : Decomposition Characteristics of SF 6 under Four Different Partial Discharges *EEE Trans. Dielectr. insul.* 2012." vol. 19, no. 1, pp. 0–7,
[21] J. Tang, F. Liu, X. Zhang, X. Liang, and Q. Fan, "Partial discharge recognition based on SF6 decomposition products and support vector machine," *IET Sci. Meas. Technol.*, 2012.vol. 6, no. 4, p. 198, '
[22] Vanbrunt, R.J., Herron, J.T.: 'Plasma chemical-model for decomposition of SF_6 in a negative glow corona discharge', *Phys. Scr.,* 1994, T53, pp. 9 – 29
[23] R. J. Van Brunt, "Physics and chemistry of partial discharge and corona - recent advances and future challenges", *IEEE Trans. Dielectr. Electr. Insul.,* 1994.Vol. 1, pp.761-784,.
[24] Y. Wang, N. Wei, S. Ji, W. Ding, and K. Ma, "*Study on SF_6 gas decomposition products of typical GIS defect models by infrared detection,"* 1st Int. Conf. Electr. Power Equip. - Switch. Technol. *ICEPE - Proc.*, 2011. no. 5, pp. 496–499,
[25] J. . Rayon, a Girodet, J. F. Penning, D. Gautschi, F. Aitabdelmalek, W. Weidmann, P. Juge, and G. Granelli, "B3-208 CIGRE 2012 Monitoring and condition assessment for GIS substations and GIL ALSTOM Grid, Aix-les-Bains France ALSTOM Grid, Lyon France ALSTOM Grid AG , Oberentfelden," *Cigre*, report 2012.
[26] R. Baumgartner, B. Fruth, W. Lonz, K. Pettersson, Partial discharge. Part X. PD in gas-insulated substations-measurement and practical considerations, *IEEE Electr. Insulat. Mag*. 8 (1) (1992) pp 16–27.
[27] I. a. Metwally, "Status review on partial discharge techniques in gas-insulated switchgear/lines," *Electr. Power Syst. Res.*, 2004 vol. 69, no. 1, pp.25-36.
[28] J.S. Pearson, O. Farish, B.F. Hampton, M.D. Judd, D. Templeton, B.W. Pryor, I.M. Welch, Partial discharge diagnostics for gas insulated substations, *Electr. Insulat.* 2-DEI (5) (1995) 893–905.
[29] Farish, O, Judd, MD, Hampton, BF & Pearson, JS 'SF6 insulation systems and their monitoring'. in AM Haddad & D Warne (eds), *Advances in high voltage engineering.* IET Power and Energy Series, 2004, no. 40, pp. 37-74.
[30] M. Ren, M. Dong, and J. Liu, "Statistical Analysis of Partial Discharges in SF6 Gas via Optical Detection in Various Spectral Ranges," *Energies*, 2016.vol. 9, no. 3, p. 152,
[31] J. Tang, F. Liu, Q. Meng, X. Zhang, and J. Tao, "Partial Discharge Recognition through an Analysis of SF 6 Decomposition Products Part 2 : Feature Extraction and Decision Tree-based Pattern Recognition, *IEEE Trans. Dielectr. insul.*, 2012," vol. 19, no. 1, pp. 37–44,
[32] L.E. Lundgaard, K. Ljokelsoy, W. Hansen, A. Schei, L. Hofstad, Acoustic insulation analyzer for periodic condition monitoring of insulation systems such as GIS, cable terminations and joints ETS, Technical Report published by TransiNor As, Norway, 1997.

[33] CIGRE Joint Working Group 33/23.12, Insulation coordination of GIS: return of experience, on-site tests and diagnostic techniques, Electra (1998) (176) 67–97.
[34] CIGRE Task Force 15/33.03.05 of Working Group 15.03, Partial discharge detection system for GIS: sensitivity verification for the UHF method and the acoustic method, Electra (1999) (183) 75–87.
[35] H.D. Schlemper, K. Feser. *Characterization of moving particles in GIS by acoustic and electric partial discharge detection*, in: Proceedings of the 10th International Symposium on High Voltage Engi- neering, Montréal, Canada, 1997.
[36] IEC Publication 60270, Partial Discharge Measurements, third ed. 2000.
[37] W. Jiajun, H. Bin, and W. Hongmei, “Electric Insulation Detection Method for High-voltage Insulators,” *TELKOMNIKA Indonesian Journal Electrical Engineering.* 2013;11(7): 4086–4090.
[38] S. Li, “Study of Dissolved Gas Analysis under Electrical and Thermal Stresses for Natural Esters used in Power Transformers,” 2012.
[39] N. M. Testing, “Dissolved Gas Analysis for Transformers, 2010.” pp. 2009–2011,
[40] A. C. Nishant, “Failure Analysis of a Power Transformer Using Dissolved Gas Analysis – a Case Study.2014.” pp. 2319–2322,
[41] E. Lee and W. Meng, “Dissolved Gas Analysis (DGA) of mineral oil used in transformers, 2009,” vol. 1, no. May, pp. 4–5,.
[42] S. Saranya, U. Mageswari, N. Roy, R. S. International, and R. Sudha, “Comparative Study Of Various Dissolved Gas Analysis Methods To Diagnose Transformer Faults. 2013,” vol. 3, no. 3, pp. 592–595,.
[43] J. B. Digiorgio and N. T. T. Copyrighted, “Dissolved Gas Analysis of Mineral Oil”, 2013 no. 916,.
[44] N. K. Sharma and P. K. Tiwari, “Review of Artificial Intelligence Techniques Application to Dissolved Gas Analysis on Power Transformer, 2011” vol. 3, no. 4
[45] J. J. Shea, “Advances in High Voltage Engineering [Book Review],” *IEEE Electr. Insul. Mag.*, 2007 vol. 23, no. 1, pp. 53–53,.
[46] I.J. Kemp, *Partial discharge plant-monitoring technology: present and future Developments*, Sci. Meas. Technol. IEE Proc. 142 (1995) 4–10.
[47] Cigré Working Group WG B3.25, *SF6 Analysis for (AIS, GIS and MTS) Condition Assessment February 2014*. ISBN : 978-2-85873-262-3
[48] 1.60480-2004. Guidelines for the checking and treatment of sulphur hexafluoride (SF6) taken from electrical equipment and specification reuse. 2004.
[49] I. J. Kemp. *Partial discharge plant technology: present and future developments*. Sci. maeas. Technol. IEE Proc. 142 (1995) 4-10.
[50] J Suehiro. G.B. Zhou. M. Hara Detection of partial discharge in SF_6 gas using carbon nanotube-based gas sensor. *Sens Actuators B- Chem.* 105 (2005) 164-169.
[51] J. Suehiro, G.B. Zhou, M. Hara, Detection of partial discharge in SF6 gas using a carbon nanotube-based gas sensor, Sens. Actuators B – Chem. 105 (2005) 164–169.
[52] Emerson, “Fundamentals of Gas Chromatography,” *85th Annu. Int. Sch. Hydrocarb. Meas.*, 2010. vol. 43, pp. 1–8,
[53] O. Instruments, “Introduction To Ft-Ir Spectroscopy, 2000.” vol. 49, no. 0, pp. 1–10,
[54] T. Nicolet and C. All, “Introduction to Fourier Transform Infrared Spectrometry,” *A Thermo Electron Bussines*, 2001 pp. 1–8,.
[55] O. Soppart, J.I. Baumbach, S.M. Alberti, D. Klockow, *On-site quality assessment of SF6 using ion mobility spectrometry*, in: Proceedings of the 10th International Symposium on High Voltage Engineering, Montréal, Canada, 1997.
[56] Y. Wang, N. Wei, S. Ji, W. Ding, and K. Ma, “*Study on SF6 gas decomposition products of typical GIS defect models by infrared detection*,” 1st Int. Conf. Electr. Power Equip. - Switch. Technol. ICEPE - Proc., 2011.no. 5, pp. 496–499,
[57] L.E. Lundgaard, G. Tangen, B. Skyberg, K. Faugstad, Acoustic diagnoses of GIS field experience and development of expert system*, IEEE Trans. Power Deliv. 7-PWRD* (1) (1992) 287–294.
[58] Z. Weixia, Z. Xianping, Z. Shutao, Y. Hong, and W. Dada, “Study on Partial Discharge Detection of 10kV Power cable,” *TELKOMNIKA Indonesian Journal Electrical Engineering.* 2012.;10(7):1795–1799,
[59] M. H. Ahmad, N. Bashir, H. Ahmad, A. A. A. Jamil, and A. A. Suleiman, “An Overview of Electrical Tree Growth in Solid Insulating Material with Emphasis of Influencing Factors Mathematical Models and Tree Suppression,” *TELKOMNIKA Indonesia Journal Electrical Engineering.* 2014;12(8): 5827 - 5846
[60] Y. Zhao, X. Wang, D. Dai, Z. Dong, and Y. Huang, “Partial discharge early-warning through ultraviolet spectroscopic detection of SO_2,” *Meas. Sci. Technol.*, 2014.vol. 25, no. 3, p. 035002.