International Journal of Advances in Applied Sciences (IJAAS)
Vol. 14, No. 3, September 2025, pp. 784~792
ISSN: 2252-8814, DOI: 10.11591/ijaas.v14.i3.pp784-792

Sulphur corrosion in transformer insulating oils: its effects, detection methods, and mitigation strategies

Nur Izyan Husnina Zulkefli[1], Sharin Ab Ghani[1], Mohd Shahril Ahmad Khiar[1], Imran Sutan Chairul[1], Nor Hidayah Rahim[1], Nur Farhana Mohd Azlan[2]
[1]Electrical Asset Condition Monitoring Research Group (e-AMCM), Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Honda Malaysia Sdn. Bhd., Taman Perindustrian HiCOM Pegoh, Alor Gajah, Malaysia

Article Info

Article history:

Received Oct 24, 2024
Revised May 22, 2025
Accepted Jun 8, 2025

Keywords:

Additives
Antioxidants
Elemental sulphur
Metal passivators
Sulphur corrosion
Transformer insulating oil

ABSTRACT

Oil-immersed transformers are subjected to electrical, thermal, and mechanical stresses over time, which inevitably affect the insulating oil and paper insulation. The presence of sulphur corrosion also degrades the insulating oil and paper insulation. Sulphur corrosion in insulating oils has been a prevalent problem for many years, as it culminates in the failure of oil-immersed transformers. The longevity of oil-immersed transformers is dependent on the integrity of the insulating oil and paper insulation, which can deteriorate owing to sulphur corrosion. The occurrence and accumulation of copper sulphide (Cu_2S) can result in transformer malfunctions, which is a significant issue for transformer manufacturers and operators. This paper provides a concise overview of the effects of sulphur corrosion, its detection methods, as well as its mitigation strategies. It is believed that this paper will enhance the understanding of sulphur corrosion in insulating oils, provide the best practices for sulphur corrosion management, and serve as guidance on enhancing transformer reliability and performance.

Corresponding Author:

Sharin Ab Ghani
Electrical Asset Condition Monitoring Research Group (e-AMCM)
Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka
Durian Tunggal-76100, Melaka, Malaysia
Email: sharinag@utem.edu.my

1. INTRODUCTION

In general, there are two types of transformers: oil-immersed transformers and dry-type transformers. The parameters of these transformers are determined by their applications [1]. Oil-immersed transformers are used to transmit and supply electricity to electrical substations [1]–[3]. The insulating oil transfers heat from the cores and windings to the transformer’s naturally or artificially cooled exterior surfaces, making it more efficient as a cooling medium than air [4]. The insulation system has two parts: primary insulation and minor insulation. The primary insulation is located between the core and low-voltage windings, between the low-voltage and high-voltage windings, and between the top and bottom of the windings. Minor insulation covers the conductors, turns, layers, laminations, joints, and connectors. Kraft paper is used to insulate these components [5], [6].

Oil-immersed transformers are severely damaged by the presence and accumulation of corrosive sulphur [7], [8]. Sulphur corrosion in insulating oil creates a low-resistance path through the paper insulation, leading to potential transformer breakdowns. Dissolved copper increases dielectric losses in the insulating oil, while copper deposition can significantly increase the conductivity of the paper insulation. To ensure the insulating oil in large transformers and electrical equipment remains suitable for use, the electrical and chemical properties of the insulating oil are evaluated on a periodic basis. Filtration and treatment can sometimes improve the condition of the insulating oil. Corrosion-induced insulation failure can severely impact the safe and stable operation of oil-immersed transformers. Figure 1 shows the photographs of copper winding failures due to sulphur corrosion. Various factors may influence the progression of sulphur corrosion, such as the elemental sulphur concentration and ageing period [9]. Surface resistivity measurements have been conducted to investigate the effects of corrosion factors on the surface resistivity of the kraft paper, which is used to assess the occurrence of sulphur corrosion in insulating oils [10], [11].

The sulphur content of transformer mineral oils (TMOs) falls within a range of 0.001-0.500%. Sulphur is intentionally incorporated into TMOs as an antioxidant, namely dibenzyl disulphide (DBDS), to enhance the thermal stability of the TMOs [12]–[14]. Oxidation and copper dissolution are positively correlated because dissolved metal cations are potent oil oxidation catalysts. The sulphur corrosion issue was extensively debated in 1958. This is demonstrated from experiments in which the copper concentration in spontaneously oxidizing oils is measured over time [15]–[18]. In addition, various methodologies have been devised to detect sulphur corrosion in TMOs. Assessing the effects of sulphur corrosion is crucial to identifying the fundamental causes of corrosion and developing effective treatments. The development of sulphur corrosion detection techniques is essential as early detection can reduce severe damage and prolong the operational lifetime of oil-immersed transformers.

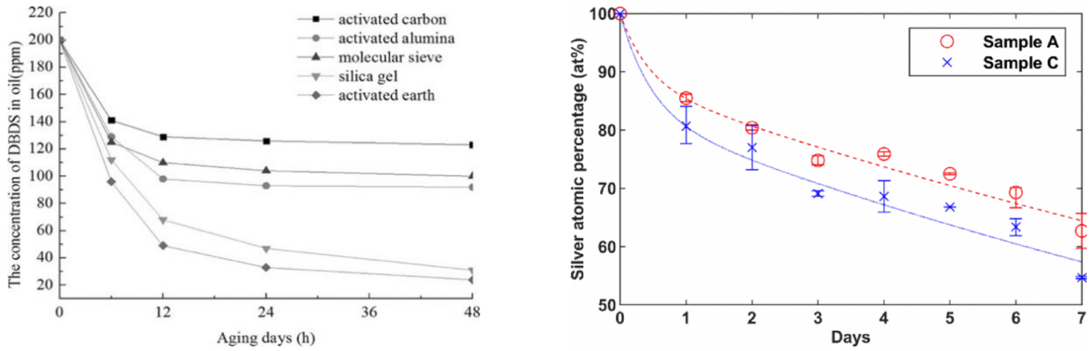
Figure 1. Failure of copper windings in oil-immersed transformers due to sulphur corrosion [9]

2. METHODS USED TO DETECT SULPHUR CORROSION IN TRANSFORMER MINERAL OILS

In the absence of overload or overheating in in-service transformers, the sulphur compounds present in the TMO can function as antioxidants. According to the IEC 60296 standard, the maximum permissible concentration of sulphur compounds in insulating oils is 5 ppm. Corrosion arises when sulphur molecules undergo a chemical reaction with the copper wires, resulting in the formation of copper sulphide (Cu_2S). The Cu_2S penetrates and degrades the paper insulation, reducing its efficacy. This eventually leads to deterioration of the coil insulation over time [19]–[21]. TMO manufacturers perform initial detection of corrosive sulphur to ensure compliance with industrial standards. The task is executed by the operators of the transformer system, who are in charge of continuously monitoring the quality of the TMO [22], [23].

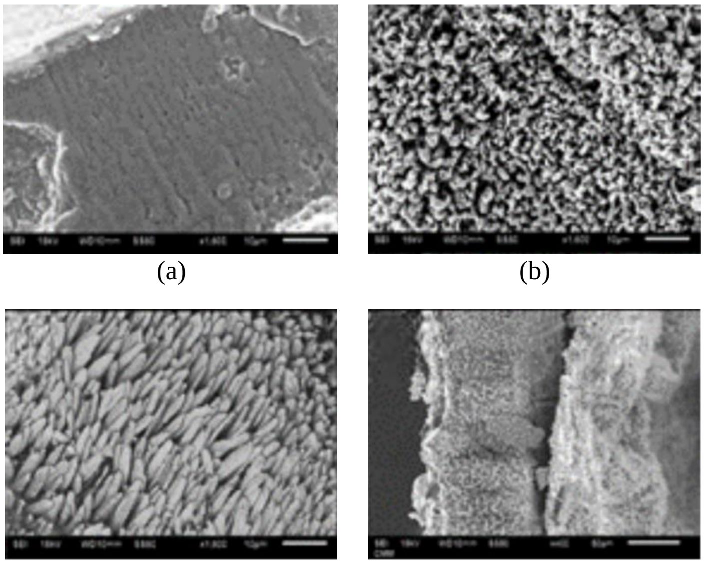
Accelerated ageing tests are conducted in conjunction with adsorption treatment to determine the presence of sulphur corrosion, as shown in Figure 2. Yang *et al*. [24] investigated the effects of DBDS in insulating oil and the level of corrosion on copper after adsorption treatment. Activated alumina, molecular sieve, and silica gel effectively inhibited the degradation of the insulating oil. Figure 2(a) shows the changes in the DBDS concentration in the insulating oil after adsorption treatment. The DBDS concentration significantly decreases as the adsorption period increases, particularly for the adsorption treatment using silica gel. Silica gel reduces the DBDS concentration from 24 to 200 ppm in ~48 h. This suggests that adsorption treatment can be used to detect sulphur corrosion in insulating oil. The results indicate that the DBDS activity decreases after adsorption treatment.

According to Samarasinghe *et al*. [25], on-load tap changers (OLTCs) are a vital component used to regulate the output voltage of the transformer. The formation of silver sulphide on the OLTC tap selector is influenced by several factors, including the presence of elemental sulphur, moisture levels, and oxygen concentration in the insulating oil. Even at low concentrations, elemental sulphur is highly corrosive to silver, and the risk of corrosion increases with higher moisture content [26], [27]. The OLTC can fail due to the build-up of silver sulphide. Corrosive sulphur compounds such as elemental sulphur, mercaptans, and disulphides react with the silver coating on the surface of the OLTC tap selector. Figure 2(b) shows the silver atomic percentage for sample A (indicating only silver) and sample C (indicating both silver and copper). Based on the results, it can be deduced that the rate of silver sulphide deposition increases in the presence of copper. Scanning electron microscopy-energy-dispersive x-ray (SEM–EDX) spectroscopy reveals the formation of silver sulphide, as shown in Figures 3, where copper sulphide on copper surfaces is shown in Figure 3(a), silver sulphide (clump formation) is shown in Figure 3(b), silver sulphide (dendrite formation) is shown in Figure 3(c), and flakes of silver sulphide is shown in Figure 3(d). During the OLTC operation, the silver sulphide layer is exposed to compressive and frictional forces, causing flakes to detach and mix with the insulating oil.



(a) (b)

Figure 2. Tracking corrosion activity in transformer oil of (a) concentrations of DBDS in the insulating oil after adsorption treatment [24] and (b) atomic percentage of silver-on-silver metal strips obtained from SEM–EDX spectroscopy [25]



(a) (b) (c) (d)

Figure 3. Analyzing corrosion on OLTC by using SEM–EDX spectroscopy of (a) Cu_2S on copper surfaces, (b) silver sulphide (clump formation), (c) silver sulphide (dendrite formation), and (d) flakes of silver sulphide [25]

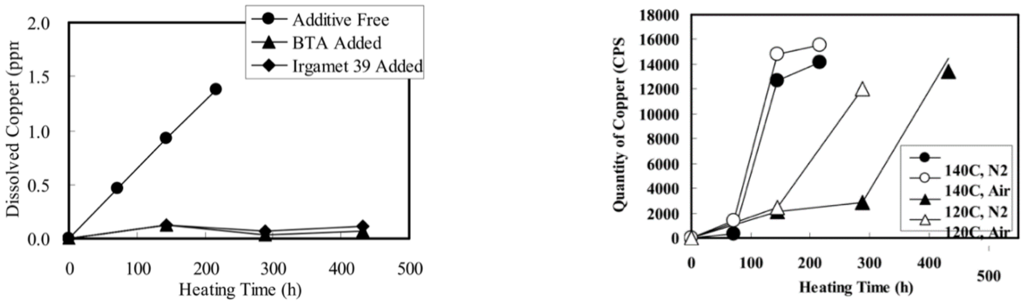
3. EXPERIMENTAL STUDIES ON SULPHUR CORROSION IN TRANSFORMER MINERAL OILS

Many experimental studies have been carried out regarding sulphur corrosion in oil-immersed transformers [28], [29]. These studies collectively focus on the effects of sulphur compounds on transformer components, such as copper corrosion, insulation degradation, and formation of corrosive by-products, as shown in Figure 4. The role of environmental factors (such as temperature), interactions between different additives, and efficiency of various detection and prevention techniques were also explored. Based on the study by Jaber *et al*. [30], qualitative measurements were conducted according to the IEC 62535 standard, and quantitative measurements were performed using liquid–liquid extraction pre-treatment and gas chromatography–high-performance liquid chromatography (GC/HPLC) to investigate the effects of using antioxidants 2,6-Di-tert-butyl-p-cresol (DBPC) and 2,6-Di-tert-butyl phenol (DBP) combined with a metal passivator benzotriazole (BTA) and corrosive sulphur DBDS [31]. The results were compared with those of the new TMO according to the IEC 60296 standard. The samples were aged at 150 °C over a period of 5 days. For each accelerated ageing interval, the liquid-liquid extraction process appeared to remove any additives that remain in the TMO, and it is sensitive to fractions as low as 1 mg/L [31], [32]. Figure 4(a) shows the concentration of dissolved copper with respect to the heating time over a period of 500 h. It is evident that the concentration of dissolved copper in the additive-free insulating oil (without metal passivator) shows a marked increase with respect to the heating time.

Studies have also explored the use of highly selective adsorbents (HSA) to remove elemental sulphur [33]. A kinetic model was used to explore the sorption mechanism and potential rate-controlling steps such as mass transport and chemical reaction processes [34]. The process involves modifying the raw material by combining it with HSA. This includes impregnating the raw material with silver ions on a silicon dioxide substrate, using an aqueous solution containing ammonia as a complexing agent [35]. The experimental results showed that the adsorbent could significantly reduce the presence of elemental sulphur and corrosive sulphur compounds (including DBDS) from the insulating oil. This ensures the oil retains its desirable qualities after treatment, making it suitable for reuse in power transformers. The purpose is to verify the efficiency of HSA in removing elemental sulphur from the insulating oil, better simulate on-site conditions, and assess the overall performance.

In 2012, an abnormal dielectric loss (110 kV) occurred successively [36], [37]. The sulphur corrosion experiments were performed on a bushing model at 130 °C for different DBDS concentrations over a period of 40 days [38]. The aim of this study was to replicate a real-life bushing model by tightly winding a copper rod with five layers of paper insulation and one layer of aluminium foil. To secure the windings, the copper rod was wrapped with two layers of aluminium foil and secured with a cotton thread. The experiments involved three sequential steps. First, the paper insulation and TMO were dried at 90 °C and 50 Pa for 48 h. Second, DBDS was added into the TMO at different concentrations, the TMO and paper insulation were mixed and placed in containers at 40 °C and 50 Pa for 24 h. Finally, the containers were hermetically sealed and placed in a vacuum chamber at 130 °C and 50 Pa for 7-40 days.

Dissolved oxygen and copper play a critical role in the formation of Cu_2S. Since Cu_2S is produced from the reaction between copper and DBDS, a higher oxygen content can accelerate its deposition on transformer components [20], [39]. Figure 4(b) shows the effects of atmospheric conditions on copper deposition in the insulating oil. No changes were observed during the accelerated thermal ageing test at 140 °C. The model consisted of two coil windings, each with a length, thickness, and width of 16, 0.2, and 1.4 cm, respectively. The coil winding was divided into three sections, where the first section was a straight piece measuring 10 cm, and the second section was a 3 cm bent portion, forming an angle of 30° with respect to the horizontal [40].



(a) (b)

Figure 4. Monitoring corrosion activity in transformer oil of (a) progression of dissolved copper levels in response to air exposure [32] and (b) effects of atmospheric conditions on the Cu_2S deposition [39]

4. SUPPRESSION OF SULPHUR CORROSION USING METAL PASSIVATOR

The implementation of best practices is known to effectively mitigate sulphur corrosion; however, it is imperative to optimise the associated costs while ensuring that the reliability of transformers remains high [41]–[43]. Metal passivator serves as a sulphur corrosion inhibitor, where the metal passivator forms a protective film on the metal surface and protects it from sulphur corrosion. Although metal passivators are used to protect metal components from corrosive environments, they do not remove corrosive sulphur compounds already present in the insulating oil. The use of metal passivators facilitates decelerating the progression of sulphur corrosion. However, metal passivators do not stop sulphur corrosion entirely. The amount of metal passivator in the insulating oil decreases over time as it reacts with copper surfaces and degrades due to heat and oxygen [44], [45]. Table 1 summarizes the types of metal passivators used by other researchers and their effectiveness in inhibiting sulfur corrosion.

Table 1. Studies on the effectiveness of metal passivators in inhibiting sulphur corrosion

Type of metal passivator	Concentration	Findings
BTA	20-100 ppm	The effects of BTA were studied, where accelerated thermal ageing was conducted on the oil–paper insulation with and without BTA at a temperature of 130 °C [46]. The BTA concentration in the insulating oil was 100 ppm; however, a BTA concentration of 50 ppm ensures the safety of the oil-immersed transformer. The weights of the BTA to produce a BTA concentration of 100 and 200 ppm were measured to be 0.0885 and 0.177 g, respectively. One litre of TMO was used for the samples with and without BTA in order to perform comparative experiments [32], [47], [48].
Irgamet 39	100 ppm	Experiments were conducted to investigate the effects of adding 100 ppm of Irgamet 39 on the mitigation of sulphur corrosion [41], [49], [50]. The paper insulation and copper conductors were mixed with the insulating oil with and without a metal passivator, and the samples were exposed to a temperature of 140 °C for 1,400 h. The main purpose of these studies was to determine the maximum acceptable quantities of DBDS and mercaptans in the insulating oil before the insulating oil was used in in-service transformers.
Irgamet 30	100-300 ppm	A new additive (Irgamet 30) was discovered in recent years, which has a similar structure to Irgamet 39. The efficacy of Irgamet 30 on the oxidation stability and sulphur corrosion of insulating oil was investigated, and the results were compared with those obtained using Irgamet 39. The following conclusions were drawn. Irgamet 30 functions as a metal deactivator in the insulating oil, which prevents the oil from oxidising and improves the oxidation stability of the insulating oil. However, unlike Irgamet 39, Irgamet 30 did not provide any protection for copper surfaces. Due to its inability to function as a metal passivator in insulating oil, this undisclosed substance cannot generate protective layers on copper surfaces [51].
Extreme pressure additives (RC 8210, RC 4220)	0-1.0 wt.%	Extreme pressure additives form protective layers over surfaces when there is high friction. The additives include chlorine, sulphur, and phosphorous compounds that react tribochemically with metal surfaces throughout mechanical interactions. The sulphur in the extreme pressure additives reacts with the metal, forming a tribofilm that improves the wear and friction behaviour of the metal component [52], [53]. The solubility of sulphur present in the TMO is limited due to the addition of extreme pressure additives, where the additive concentration should be kept within a range of 0.25-1 wt.%. Even at the lowest concentration (0.25 wt.%), the copper strip showed discolouration, with different levels of tarnish [54]. Further experiments were carried out by adding corrosion inhibitors at different concentrations, ranging from 25 to 200 ppm. The results revealed that the Irgamet 39 and RC 8210 were effective at a concentration of 25 ppm.

5. CONCLUSION

To date, sulphur corrosion is the well-known cause of transformer insulation system failures. The rapid progression of sulphur corrosion in oil-immersed transformers needs to be examined. In this paper, a brief overview is provided on the methods used to detect sulphur corrosion, experimental studies related to sulphur corrosion in TMOs, and the use of metal passivators in inhibiting sulphur corrosion in TMOs. The findings provide insight into the major impact of sulphur corrosion on the performance of TMOs as well as the feasibility of various metal passivators in mitigating sulphur corrosion.

ACKNOWLEDGEMENTS

The authors wish to thank Ms. Nadia Abdullah from The Golden Touch Language-Editing Service for proofreading this paper.

FUNDING INFORMATION

The authors acknowledge the financial support provided by the Ministry of Higher Education Malaysia under the Fundamental Research Scheme (Grant no.: FRGS/1/2024/TK07/UTEM/02/19).

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nur Izyan Husnina Zulkefli	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Sharin Ab Ghani	✓	✓	✓		✓	✓		✓	✓		✓	✓		
Mohd Shahril Ahmad Khiar	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓		✓
Imran Sutan Chairul	✓	✓				✓			✓	✓	✓			
Nor Hidayah Rahim	✓								✓		✓			
Nur Farhana Mohd Azlan	✓								✓		✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] K. Shaarbafi, "Transformer modeling guide," *Alberta Electric System Operator*, 2014.

[2] P. K. Dooley, "A comparison of liquid-filled and dry-type transformers for industrial applications," *IEEE Transactions on Industry Applications*, vol. 34, no. 1, pp. 222–226, 1998, doi: 10.1109/28.658749.

[3] F. Scatiggio, V. Tumiatti, R. Maina, M. Tumiatti, M. Pompili, and R. Bartnikas, "Corrosive sulfur in insulating oils: its detection and correlated power apparatus failures," *IEEE Transactions on Power Delivery*, vol. 23, no. 1, pp. 508–509, 2008, doi: 10.1109/TPWRD.2007.911121.

[4] P. Wiklund and B. Pahlavanpour, "Properties of mineral insulating oils in service," *Journal of Iranian Association of Electrical and Electronics Engineers*, vol. 7, no. 2, pp. 65–73, 2011, [Online]. Available: https://jiaeee.com/article-1-215-en.pdf

[5] R. A. Raj, R. Samikannu, A. Yahya, and M. Mosalaosi, "Comparison of ageing characteristics of superior insulating fluids with mineral oil for power transformer application," *IEEE Access*, vol. 8, pp. 141111–141122, 2020, doi: 10.1109/ACCESS.2020.3012988.

[6] B. Gonzalez, O. Gasca, M. Juarez, and F. Bravo, "Effect of electric field at 150 °C on the formation of corrosive sulfur in mineral transformer oil," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 5, pp. 2449–2454, 2015, doi: 10.1109/TDEI.2015.004979.

[7] P. J. Griffin and R. Lewand, "An update on understanding corrosive sulfur problems in electric apparatus," in *75th Annual International Doble Client Conference*, 2008, pp. 1–27, [Online]. Available: https://www.doble.com/wp-content/uploads/IM-04_Corrosive_Sulfur_Griffin.pdf

[8] S. B. Garcia *et al.*, "Identification of elemental sulfur in mineral insulating oil-standard corrosive test (DIN 51353) vs. analytical approach," in *Proceedings of the 2020 IEEE 3rd International Conference on Dielectrics, ICD 2020*, 2020, pp. 740–743, doi: 10.1109/ICD46958.2020.9341889.

[9] CIGRE WG A2.40, "Copper sulphide long term mitigation and risk assessment," *Strategic Options for South Africa*, no. October, pp. 1–34, 2015, [Online]. Available: https://www.e-cigre.org/publications/detail/625-copper-sulphide-long-term-mitigation-and-risk-assessment.html.

[10] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Aging of kraft paper insulation in natural ester dielectric fluid," in *Proceedings of IEEE International Conference on Solid Dielectrics, ICSD*, 2013, pp. 541–544, doi: 10.1109/ICSD.2013.6619678.

[11] N. Lelekakis, D. Martin, and J. Wijaya, "Ageing rate of paper insulation used in power transformers Part 1: Oil/paper system with low oxygen concentration," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 6, pp. 1999–2008, 2012, doi: 10.1109/TDEI.2012.6396958.

[12] S. Ren, XuYang, W. Yang, B. Xi, and X. Cao, "Research on insulation condition monitoring system for power transformers," *Proceedings of 2008 International Conference on Condition Monitoring and Diagnosis, CMD 2008*, pp. 1005–1007, 2008, doi: 10.1109/CMD.2008.4580451.

[13] M. S. A. Khiar, R. C. D. Brown, and P. L. Lewin, "Effect of temperature changes on tine film sacrificial copper strips due to sulfur corrosion," *Annual Report - Conference on Electrical Insulation and Dielectric Phenomena, CEIDP*, vol. 2018-Octob, pp. 490–493, 2018, doi: 10.1109/CEIDP.2018.8544883.

[14] C. Bengtsson *et al.*, "Oil corrosion and conducting CU2S deposition in power transformer windings," *41st International Conference on Large High Voltage Electric Systems 2006, CIGRE 2006*, pp. 1–10, 2006, [Online]. Available: https://www.e-cigre.org/publications/detail/a2-111-2006-oil-corrosion-and-conducting-cu2s-deposition-in-power-transformer-windings.html

[15] P. Wiklund, M. Levin, and B. Pahlavanpour, "Copper dissolution and metal passivators in insulating oil," *IEEE Electrical Insulation Magazine*, vol. 23, no. 4, pp. 6–14, 2007, doi: 10.1109/MEI.2007.386479.

[16] A. E. Papadopoulos and C. S. Psomopoulos, "Dissolved gas analysis for the evaluation of the corrosive sulphur activity in oil insulated power transformers," *IET Conference Publications*, vol. 2014, no. CP665, 2014, doi: 10.1049/cp.2014.1701.

[17] I. B. M. Taha, S. S. M. Ghoneim, and H. G. Zaini, “Improvement of Rogers four ratios and IEC code methods for transformer fault diagnosis based on dissolved gas analysis,” *2015 North American Power Symposium, NAPS 2015*, 2015, doi: 10.1109/NAPS.2015.7335098.

[18] S. Seifeddine, B. Khmais, and C. Abdelkader, “Power transformer fault diagnosis based on dissolved gas analysis by artificial neural network,” *2012 1st International Conference on Renewable Energies and Vehicular Technology, REVET 2012*, pp. 230–236, 2012, doi: 10.1109/REVET.2012.6195276.

[19] Y. H. Qian, Y. Wang, H. H. Hu, W. J. Yao, and Z. Li, “Analysis and treatment of transformer faults caused by corrosive sulfur,” *2008 China International Conference on Electricity Distribution, CICED 2008*, 2008, doi: 10.1109/CICED.2008.5211691.

[20] H. Kawarai *et al.*, “Role of dissolved copper and oxygen on copper sulfide generation in insulating oil,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 16, no. 5, pp. 1430–1435, Oct. 2009, doi: 10.1109/TDEI.2009.5293957.

[21] S. H. Gao and L. J. Yang, “Effects of sulfur corrosion on the properties of oil-paper insulation induced by dibenzyl disulfide,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 26, no. 4, pp. 1089–1097, 2019, doi: 10.1109/TDEI.2019.007866.

[22] M. S. A. Khiar, S. A. Ghani, N. A. Bakar, I. S. Chairul, and M. A. Talib, “Sulfur corrosion mechanism in power transformers and its detection techniques: a review,” *IEEE Transactions on Dielectrics and Electrical Insulation*, 2022, doi: 10.1109/TDEI.2022.3216847.

[23] M. Facciotti, “A surface analytical chemistry approach to copper corrosion and its inhibition with bezotriazole derivatives in oil-filled power transformers,” Doctoral Thesis, University of Southampton, pp. 1–245, 2015, [Online]. Available: http://eprints.soton.ac.uk/id/eprint/387346

[24] L. Yang, S. Gao, B. Deng, J. Zhang, W. Sun, and E. Hu, “Inhibition method for the degradation of oil- paper insulation and corrosive sulphur in a transformer using adsorption treatment,” *IET Generation, Transmission and Distribution*, vol. 10, no. 8, pp. 1893–1900, 2016, doi: 10.1049/iet-gtd.2015.1091.

[25] S. Samarasinghe, H. Ma, D. Martin, and T. Saha, “Investigations of silver sulfide formation on transformer OLTC tap selectors and its influence on oil properties,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 26, no. 6, pp. 1926–1934, 2019, doi: 10.1109/TDEI.2019.008232.

[26] S. Arnell and G. Andersson, “Silver iodide as a solid lubricant for power contacts,” in *Electrical Contacts, Proceedings of the Annual Holm Conference on Electrical Contacts*, 2001, pp. 239–244, doi: 10.1109/holm.2001.953217.

[27] J. J. Erbrink *et al.*, “On-load tap changer diagnosis-an off-line method for detecting degradation and defects: Part 1,” *IEEE Electrical Insulation Magazine*, vol. 26, no. 5, pp. 49–59, 2010, doi: 10.1109/MEI.2010.5585008.

[28] N. F. M. Azlan, S. A. Ghani, M. S. A. Khiar, I. S. Chairul, and M. N. M. Din, “Investigating the effects of corrosion parameters on the surface resistivity of transformer’s insulating paper using a two-level factorial design,” *International Journal of Applied Power Engineering*, vol. 13, no. 2, pp. 335–342, 2024, doi: 10.11591/ijape.v13.i2.pp335-342.

[29] Y. Zhao, Y. Qian, W. Su, and X. Chen, “Application of molecular probe to investigate surface structure of metal passivator on copper,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 2, pp. 1142–1147, 2016, doi: 10.1109/TDEI.2015.005409.

[30] A. M. Y. Jaber, N. A. Mehanna, G. A. Oweimreen, and A. M. Abulkibash, “The effect of DBDS, DBPC, BTA and DBP combinations on the corrosion of copper immersed in mineral transformer oil,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 4, pp. 2029–2035, 2016, doi: 10.1109/TDEI.2016.7556475.

[31] M. C. Bruzzoniti, R. Maina, V. Tumiatti, C. Sarzanini, and R. M. De Carlo, “Simultaneous determination of passivator and antioxidant additives in insulating mineral oils by high-performance liquid chromatography,” *Journal of Liquid Chromatography and Related Technologies*, vol. 38, no. 1, pp. 15–19, 2015, doi: 10.1080/10826076.2013.873875.

[32] T. Amimoto, E. Nagao, J. Tanimura, S. Toyama, and N. Yamada, “Duration and mechanism for suppressive effect of triazole-based passivators on copper-sulfide deposition on insulating paper,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 16, no. 1, pp. 257–264, 2009, doi: 10.1109/TDEI.2009.4784575.

[33] J. Jankovic, J. Lukic, J. Planojevic, D. Kolarski, and D. Janackovic, “Application of highly selective adsorbent in the removal of elemental sulfur and other corrosive sulfur compounds from mineral insulating oils,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 29, no. 1, pp. 54–61, 2022, doi: 10.1109/TDEI.2022.3148479.

[34] Y. S. Ho and G. McKay, “A comparison of chemisorption kinetic models applied to pollutant removal on various sorbents,” *Process Safety and Environmental Protection*, vol. 76, no. 4, pp. 332–340, 1998, doi: 10.1205/095758298529696.

[35] J. Jankovic and J. Lukic, “Method for production and use of highly selective adsorbent for simultaneous removal of amine derivative of tolyil tri azole and sulphur compounds corrosive to silver from mineral transformer oils,” RS Patent 59335 B1, 2019, [Online]. Available: https://patentimages.storage.googleapis.com/52/0b/0f/c6714af10befc8/WO2018190741A1.pdf

[36] F. Kato, T. Amimoto, E. Nagao, N. Hosokawa, S. Toyama, and J. Tanimura, “Effect of DBDS concentration and heating duration on copper sulfide formation in oil-immersed transformer insulation,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 6, pp. 1869–1876, 2011, doi: 10.1109/TDEI.2011.6118625.

[37] S. Toyama, J. Tanimura, N. Yamada, E. Nagao, and T. Amimoto, “Highly sensitive detection method of dibenzyl disulfide and the elucidation of the mechanism,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 16, no. 2, pp. 509–515, 2009, doi: 10.1109/TDEI.2009.4815186.

[38] G. Liu, Y. Yuan, Y. Jiang, J. Zhou, and R. Liao, “Sulfur corrosion in bushing and its effect on the property of oil,” *Annual Report - Conference on Electrical Insulation and Dielectric Phenomena, CEIDP*, vol. 2018-Octob, pp. 398–401, 2018, doi: 10.1109/CEIDP.2018.8544793.

[39] T. Amimoto *et al.*, “Identification of affecting factors of copper sulfide deposition on insulating paper in oil,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 16, no. 1, pp. 265–272, 2009, doi: 10.1109/TDEI.2009.4784576.

[40] N. Rudranna, V. Krishnan, and S. Rajan, “Application of FEM for understanding the electric field distribution in copper sulphide contaminated paper-oil insulation of power transformer,” *Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials*, pp. 73–76, 2009, doi: 10.1109/ICPADM.2009.5252501.

[41] F. Scatiggio, M. Pompili, and R. Bartnikas, “Effects of metal deactivator concentration upon the gassing characteristics of transformer oils,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 3, pp. 701–706, 2011, doi: 10.1109/TDEI.2011.5931055.

[42] R. C. R. Neto *et al.*, “Thermo-oxidative stability of mineral naphthenic insulating oils: combined effect of antioxidants and metal passivator,” *Industrial and Engineering Chemistry Research*, vol. 43, no. 23, pp. 7428–7434, 2004, doi: 10.1021/ie049645o.

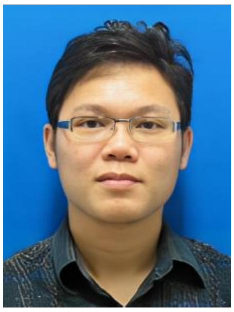
[43] K. J. Rapp, A. W. Lemm, L. A. Orozco, and C. P. McShane, “Corrosive sulfur phenomena mitigation by using natural ester dielectric fluids-field experience in Latin America,” *2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America, T and D-LA*, 2008, doi: 10.1109/TDC-LA.2008.4641707.

[44] S. Rehman *et al.*, "Maximum acceptable concentrations of DBDS, sulphur mercaptan and optimal concentration of passivators for safe and prolonged operation of power transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 4, pp. 2438–2442, 2016, doi: 10.1109/TDEI.2016.7556523.
[45] N. F. M. Azlan, S. A. Ghani, and M. S. A. Khiar, "Effects of corrosion factors on sulphur corrosion activity in transformer insulating oil using two-level factorial design," *2023 IEEE 21st Student Conference on Research and Development, SCOReD 2023*, pp. 514–519, 2023, doi: 10.1109/SCOReD60679.2023.10563832.
[46] S. H. Gao, X. S. Zeng, and G. W. Zhang, "Effects of metal passivator degradation on the dissolved gases characteristics of oil in oil-immersed transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 5, pp. 1735–1742, 2021, doi: 10.1109/TDEI.2021.009524.
[47] IEC, "IEC 60422 Mineral insulating oils in electrical equipment - Supervision and maintenance guidance," *IEC*, no. February, p. 13, 2014.
[48] P. Wiklund, "Chemical stability of benzotriazole copper surface passivators in insulating oils," *Industrial and Engineering Chemistry Research*, vol. 46, no. 10, pp. 3312–3316, 2007, doi: 10.1021/ie061570w.
[49] J. S. Rajan, C. J. Naidu, and K. Dwarakanath, "Influence of metal passivator on the corrosion of copper conductors due to sulphur in oil," *Proceedings of the International Symposium on Electrical Insulating Materials*, pp. 487–490, 2008, doi: 10.1109/ISEIM.2008.4664593.
[50] M. A. G. Martins, A. R. Gomes, and B. Pahlavanpour, "Experimental study of a passivated oil corrosiveness, after depletion of the passivator," *IEEE Electrical Insulation Magazine*, vol. 25, no. 6, pp. 23–27, 2009, doi: 10.1109/MEI.2009.5313707.
[51] A. Schaut, S. Autru, A. D. Rop, and S. Eeckhoudt, "Effects of Irgamet 30 as additive in transformer oil" *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 1, pp. 175–180, 2012, doi: 10.1109/TDEI.2012.6148516.
[52] S. M. Alves, R. B. Schroeter, J. C. Dos Santos Bossardi, and C. L. F. De Andrade, "Influence of EP additive on tool wear in drilling of compacted graphite iron," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 33, no. 2, pp. 197–202, 2011, doi: 10.1590/S1678-58782011000200011.
[53] T. Wan, H. Qian, Z. Zhou, S. K. Gong, X. Hu, and B. Feng, "Suppressive mechanism of the passivator irgamet 39 on the corrosion of copper conductors in transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 2, pp. 454–459, 2012, doi: 10.1109/TDEI.2012.6180238.
[54] B. N. Malinović, A. Borković, and T. Đuričić, "Copper strip corrosion testing in hydrocracked base oil in the presence of different inhibitors," *Hemijska Industrija*, vol. 76, no. 3, pp. 159–166, 2022, doi: 10.2298/HEMIND220113012M.

BIOGRAPHIES OF AUTHORS

Nur Izyan Husnina Zulkefli was born in Terengganu, Malaysia, in 1998. She finished her Foundation in Engineering at UiTM Dengkil in 2017. She earned both her Bachelor of Engineering (Hons) in Electrical Engineering and Master of Science in Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) in 2021 and 2024, respectively. She is currently pursuing her Ph.D. at UTeM, with a research focus on the application of natural ester as a retrofilling oil in transformer insulation systems. She can be reached via email at p112410001@student.utem.edu.my.

Sharin Ab Ghani received his B.Eng. (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2008, M.Eng. degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and Ph.D. degree in Electrical Engineering from Universiti Teknologi Malaysia in 2019. Currently, he is serving as Senior Lecturer at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, and as Head of the Electrical Asset Condition Monitoring (e-AMCM) Research Group. His research interests are centred on high voltage engineering, power equipment condition monitoring, green electrical insulation, design of experiments, and optimisation. To date, his outstanding research works have been published in Web of Science (20) and Scopus (73) indexed journals. He also has experience in consultation work with industries related to electrical installation design, transformer condition assessment, and partial discharge analysis. He can be contacted at sharinag@utem.edu.my.



Mohd Shahril Ahmad Khiar was born in Selangor, Malaysia, in 1984. He received his BSc. degree in Electrical and Electronics Engineering from Korea University in 2008, M.Eng. degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and Ph.D. degree from the University of Southampton, United Kingdom in 2019. He is currently serving as Senior Lecturer at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, and as Deputy Head of Electrical Asset Condition Monitoring (e-AMCM) Research Group. His research interests include high voltage engineering and insulation materials, sensors, condition monitoring for power equipment, and asset management. Since 2013, he has published over 28 refereed conference and journal articles associated with transformer condition monitoring and asset management. He can be contacted at mohd.shahril@utem.edu.my.

Imran Sutan Chairul was born in Kuala Lumpur, Malaysia, in 1984. He received his B.Eng. (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2008 and M.Eng. degree in Electrical Engineering from Universiti Tenaga Nasional in 2012. He recently completed his Ph.D. degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka and D.Eng. degree in Life and Materials Systems Engineering from Tokushima University, Japan. His research is focused on vegetable-based transformer dielectric liquids. He can be contacted at imransc@utem.edu.my.

Nor Hidayah Rahim received her B.Eng. degree in Electrical Engineering from Universiti Teknologi Malaysia in 2008, M.Eng. degree in Electrical Engineering from Universiti Tenaga Nasional, Malaysia in 2012, and Ph.D. degree from Universiti Teknologi Malaysia in 2019. She is currently serving as Senior Lecturer at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka. Her research interests include high voltage engineering and dielectric materials. She can be contacted at hidayah.rahim@utem.edu.my.

Nur Farhana Mohd Azlan was born in Johor, Malaysia, in 1998. She finished her Matriculation in Science Module II at Johor Matriculation College, Tangkak, in 2017. She received her B.Eng. (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2021. She has recently completed her Master's degree at Universiti Teknikal Malaysia Melaka, where her research is focused on the use of metal passivators in transformer insulating oils. She is currently serving as Executive - Part Quality at Honda Malaysia Sdn. Bhd. She can be contacted at nfarhana.mazlan@honda.net.my.