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A Novel Condition Monitoring Procedure for Early Detection of Copper Corrosion Problems in Oil-Filled Electrical Transformers

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Abstract: The negative impacts of catastrophic fire and explosion accidents due to copper corrosion problems of oil-filled electrical transformers are still in the spotlight due to a lack of effective methods for early fault detection. To address this gap, a condition monitoring (CM) procedure that can detect such problems in the initial stage is proposed in this paper. The suggested CM procedure is based on identified measurable variables, which are the relevant by-products of the corrosion reaction, and utilizes an Early Fault Diagnosis (EFD) model to detect and solve the copper corrosion problems. The EFD model includes a fault trend chart that can track a fault progression during the useful life of transformers. The purpose of this paper is to verify and validate the effectiveness of the suggested CM procedure by an empirical study in a power plant. The result of applying this procedure was early detection of copper corrosion problems in two transformers with suspected copper corrosion propagation from a total of 84. The corrective action was adding an optimized amount of a passivator, an anticorrosion additive, to suppress the corrosion reaction at the correct time. The main conclusion of this study is the importance of early detection of transformer faults to avoid the negative impacts on societal, company, and individual levels.

Keywords: CBM strategy; condition monitoring; copper corrosion; fault detection; transformer failures

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1. Introduction

In recent decades, copper corrosion problems in the mineral oil-filled electrical transformers containing corrosive sulfur compounds have increased significantly [1,2]. The problem attributes to the formation of sulfur deposits on the internal components, such as copper windings through their insulating paper in the form of semi-conductive copper sulfide (Cu_2S) [2,3]. The main consequence of these deposits is decreasing the dielectric property of the insulation system that can lead to partial discharge and arcing phenomena, which in turn is causing fire and explosion accidents [2,4–6]. The negative impacts of these accidents are very serious, having resulted in injuries and deaths, contamination by chemicals and, furthermore, power outages for customers and loss of power plant profits [4,7,8].

Statistical failure analysis of European substation transformers [9] reported that 5.2% of the total failures between 2000–2010 were due to improper maintenance, and 0.5% due to copper corrosion problems. It also reported that 12.8% of these failures caused fire and explosion accidents. Another international survey [10] over the period of 1996–2010 reported 964 transformer failures of 56 substations from 21 countries, where 13% of these failures led to negative impacts due to fire and explosion accidents. Such accidents can expose people to toxic chemical compounds, severe heat, smoke inhalation, and sound pressure [9,11]. The main consequences of transformer fires are the health and safety impacts on people from several tons of ejected oil containing toxic chemicals [12]. According to a health investigation [7], a medical inspection of blood samples of 482 persons exposed to mineral oil due to a transformer fire accident in Binghamton, NY, USA showed positive results of toxic chemical compounds, such as polychlorinated biphenyls (PCBs), dibenzo-p-dioxin, and dibenzofuran both at the time of the accident and one year later. See the chemical structures [7,13] in Figure 1.

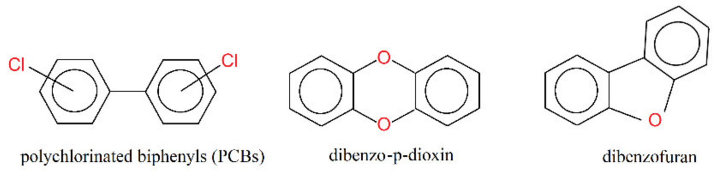


Figure 1. Chemical structures of the toxic chemical compounds into transformer's mineral oil; polychlorinated biphenyls (PCBs), dibenzo-p-dioxin, and dibenzofuran.

All these chemical compounds have a serious effect on people's health, e.g., causing cancer in addition to other symptoms, such as illnesses of the liver, neurologic system and skin, damage to cellular proteins, genetic variants, and congenital disabilities [7,12,14,15].

In order to prevent transformer failures and their negative impacts, Condition-Based Maintenance (CBM) is the common strategy used for high-risk transformers in most power plants [16]. CBM is defined according to [17–19] as preventive maintenance, which includes evaluating the transformer condition, degradation monitoring, failure prediction, and recommendation of corrective actions when a deviation in the performances is detected based on collected information by Condition Monitoring (CM). CM is defined, according to [20], as "an activity, performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the physical actual state of an item". According to [21], applying a relevant CM procedure is considered a vital factor to achieve cost-effective maintenance of an asset.

In the currently applied CBM strategy for mineral oil-filled electrical transformers, the oil analysis is based on two measurable variables [3,6,22–26]. The first measurable variable is the corrosive sulfur compounds, such as dibenzyl disulfide (DBDS) [3,6,27,28]. DBDS concentration is measured by using a chromatography technique according to the standard method IEC 62697-1 [29], where a microliter of oil sample injects into a Gas Chromatography-Electron Capture Detector (GC-ECD). The DBDS is detected as a peak form in a chromatogram, and the concentration, in ppm, is calculated by comparing the peak area with a reference. The second measurable variable is the corrosive test Covered Conductor Deposition (CCD) [3,6,23–27], which assesses the oil's ability for formation of copper corrosion according to standard method IEC 62535 [30]. In the CCD test, the sulfur deposit is detected experimentally after heating an oil sample with a Cu-strip wrapped with paper to 150 °C for 72 h. The level of sulfur deposits on the Cu-strip is evaluated as corrosive or non-corrosive oil. Despite using the current CBM strategy, copper corrosion problems are still reported [31]. The main gap in the CBM strategy is the lack of relevant CM procedure to detect early copper corrosion problems [3,4,32]. In this context, according to the mechanism of corrosion reaction [3], see Figure 2, DBDS can deplete at high temperatures to form sulfur deposits on the winding only when Cu ions, as a catalyst, exists in the oil at high temperatures. Hence, monitoring DBDS in the oil is not a definite evidence of the formation of sulfur deposits on the windings. For example, it can detect a high amount of DBDS in the oil, which gives a false indication that the oil is corrosive, but the corrosion reaction may not start due to a deficiency in Cu ions. In contrast, a trace amount of DBDS can be detected, which gives an indication that the oil is non-corrosive, but actually there is a possibility of partial or entire DBDS depletion in the formation of sulfur deposits [3,33]. Besides, the CCD test does not provide accurate information about these deposits on the copper windings either [3,4].

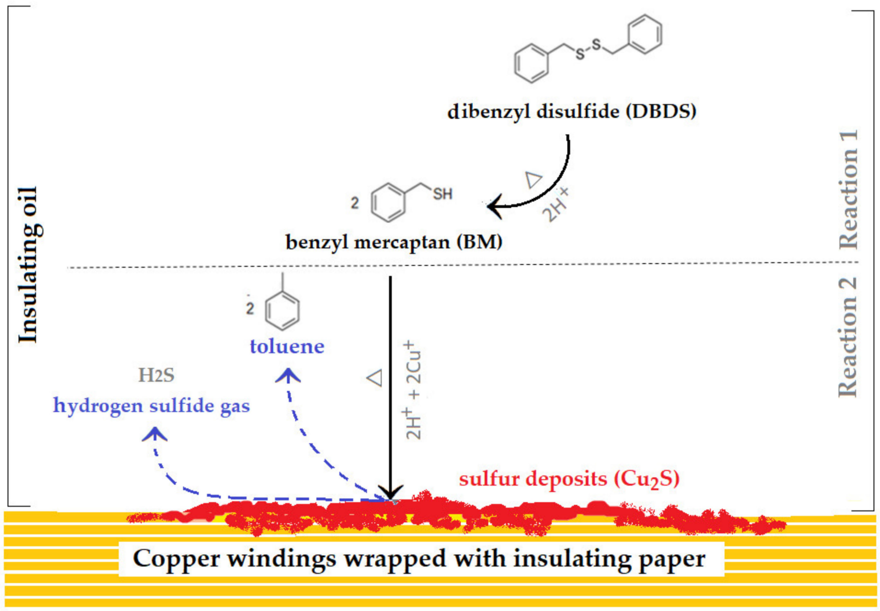


Figure 2. Mechanism of corrosion reaction [3]. The copper sulfide deposits on the insulating papers can form a low-resistance path throughout the layers of the papers and migrate onto the surface of the copper winding [22].

Investigations carried out by the first author in [3,6] demonstrated two novel findings that could be used in the development of a CM procedure for reliable and early detection of copper corrosion problems. The first finding was identifying new measurable variables, hydrogen sulfide (H_2S) gas and toluene, which are the relevant by-products of the corrosion reaction [3]. Based on this finding, a new reaction mechanism was defined, see Figure 2. The second finding was utilizing an Early Fault Diagnosis (EFD) model to detect and solve the copper corrosion problems in the initial stage. The EFD model includes a fault trend chart that can track a fault progression during the useful life of transformers [3,6]. These findings have been proved and verified for broad fault areas, such as gas generation, oxidation, and copper corrosion [6].

In order to do a preliminary verification and validation of the suggested CM procedure for copper corrosion problems, the findings were utilized in an empirical study in a power plant. The application of the suggested procedure was effective toward detecting the copper corrosion problems in the initial stage. The benefit was extending the lifetime of transformers with suspected copper corrosion propagation. Hence, the gap in the currently applied CBM strategy to detect copper corrosion problems in the initial stage is fulfilled. However, the findings have not been verified and validated to ensure the effectiveness toward early prevention of copper corrosion problems for a considerable number of transformers.

The purpose of this paper is to verify and validate the effectiveness of the suggested CM procedure by an empirical study in a power plant. The investigation in this paper is limited to only copper corrosion problems in transformers filled with mineral insulating oil. Other problems, such as iron or silver corrosion and other insulating oils such as silicon and ester, are not considered due to a lack of related accident reports. Another limitation is the applying of the EFD model during the useful life of transformers with insufficient historical data to track the fault.

2. Materials and Methods

2.1. The CM Procedure

The CM procedure was established according to investigations in [3,6] based on an integration between three main elements that built the effectiveness toward preventing early copper corrosion problems in transformers. The first element is monitoring the measurable variables. The second is applying the Early Fault Diagnosis (EFD) model. The last is carrying out corrective actions. The three elements are introduced in detail as follows:

1. Monitoring the measurable variables: The mechanism of the corrosion reaction was established in [3] as two reactions. Reaction (1): dibenzyl disulfide (DBDS) depletes to benzyl mercaptan (BM) at the overheating condition and presence of proton H^+. Reaction (2): The BM decomposes in the presence of Cu ions as a catalyst and proton H^+ at overheating conditions to form sulfur deposits as copper sulfide (Cu_2S) on the copper windings associated with the by-products, H_2S gas and toluene; see Figure 2.

As seen from Figure 2, the mechanism shows that depletion of DBDS to BM and at the same time generation of the by-products, hydrogen sulfide gas and toluene, during transformer's useful life are evidence of formation of sulfur deposits on the windings. The role of Cu ions as a catalyst is vital to complete the corrosion reaction. Accordingly, the suggested measurable variables that need to be monitored are:

- Corrosive sulfur compounds, dibenzyl disulfide (DBDS) by chromatography technique, according to IEC 62697-1 [29].
- Benzyl mercaptan (BM) and any other types of mercaptan by chromatography technique, according to ASTM D5623 [34], or by potentiometric titration, according to ASTM UOP163 [35].
- Toluene compound by chromatography technique, according to ASTM D5580 [36].
- Hydrogen sulfide (H_2S) gas by chromatography technique, according to ASTM D5623 [34] or by potentiometric titration, according to ASTM UOP163 [35].

2. Applying the Early Fault Diagnosis (EFD) Model: After identifying the transformers with suspected copper corrosion propagation where H_2S gas and toluene are generated coinciding with depleting DBDS and BM, a fault trend chart can be created based on measured values of H_2S gas and toluene. This chart can track the corrosion fault progression during the useful life of the transformers. The regular periodic schedule of oil analysis in a normal condition is annually [37]. As soon the H_2S gas and toluene are generated in the oil, the recommended periodic schedule could be within a three month interval [3,6] or according to the maintenance plan. The fault trend chart is based on a novel numerical method in order to track the copper corrosion problems and select the correct time of corrective actions [6]. The numerical method includes the following calculations:

- Caution Limit (CL) of the H_2S gas and toluene, which were defined as 1 and 2 ppm, respectively [3].
- Warning Limit (WL), which was estimated as 50% of the CL value as an indication of starting a fault [6].
- Alarm Limit (AL), which was estimated as 80% of the CL based on an experimental investigation, showed that the acceptable relative error in the oil analysis and uncertainty could be up to 20% [38].
- Relative Alarm Threshold (RAT), which is the difference between AL and WL relative to WL [6]; see Equation (1). For all measurable variables, the RAT value was defined as 0.60, see Table 1.

$$\text{RAT} = (\text{AL} - \text{WL})/\text{WL} \tag{1}$$

- Relative Fault Detection Value (RFDV), which is the difference between the first measured value ($w1$) of H_2S gas or toluene and WL relative to the WL [6]; see Equation (2):

$$\text{RFDV} = (w1 - \text{WL})/\text{WL} \tag{2}$$

If REDV of a measurable variable $\geq$ RAT (0.60), it indicates the possibility that copper corrosion problems have started, according to [6]. Hence, it is recommended that the measuring frequency be increased, such as once per month [39] in order to calculate the daily trend of the value.

Table 1. Calculating the Relative Alarm Threshold (RAT).

Measurable Variable	CL	WL	AL	RAT
H_2S gas	1.0 ppm	0.50	0.80	0.60
Toluene	2.0 ppm	1.00	1.60	0.60

- Daily Trend (DT%) is the trend of the increase of the measured value per day and is calculated based on first measured value ($w1$) and second one ($w2$); see Equation (3):

$$\text{Daily Trend, DT\%} = ((w2 - w1)/w1) \times 100)/\text{days number} \quad (3)$$

If the DT $\geq$ 0.33%, as stated in [39], that is an indication of "copper corrosion progress." In this case, corrective action could be recommended to suppress the corrosion reaction.

3. Carrying out corrective action: The main corrective action is adding benzene triazole-type metal passivators, an anticorrosion additive, to the insulating oil in-service; Benzo Triazole (called BTA) or Toluiltriazole-dialkylamine (called Irgamet-39). These passivators are usually recommended to suppress the corrosion reaction throughout by neutralizing the activity of the catalyst Cu ions [40–42], see Figure 3. The optimal concentration limit value of BTA and Irgamet-39 are 50 and 150 ppm, respectively [40]. However, exceeding the mentioned optimal concentration limit value can lead to the formation of a high amount of undesirable flammable hydrogen gas (H_2) in the oil, especially with Irgamet-39 compared with lower amounts when using BTA [43], see Figure 3, and acceleration of oxidation process in transformers [40]. Hence, an optimal amount of a passivator should be added at the correct time. On the other hand, adding a passivator after the values of the H_2S gas and toluene have exceeded their caution limits will suppress further anticipated corrosion reaction but will not reduce the sulfur deposits which have already occurred on the copper windings [40].

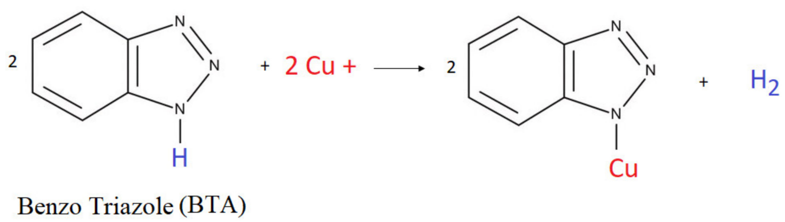


Figure 3. Mechanism reaction of the passivator (BTA) in the process of suppression of the corrosion reaction.

2.2. *Empirical Study Design*

The CM procedure was applied in an empirical study in the Primary Substation Maintenance Department (PSMD), a power plant for the Ministry of Electricity and Water in Kuwait, to prove the effectiveness of this procedure for preventing fire and explosion accidents. The design used in this empirical study included five standard steps according to [44]. The first step was coordinating a workshop with the PSMD team to address and discuss the related questions of the copper corrosion problems. The questions focused on the reasons for the increased rate of transformer fire accidents, the effectiveness of the current CM procedure, the maintenance strategy used to detect the copper corrosion problems, and the challenges to prevent such problems. The main challenge in the PSMD power plant was identified as the gap in the applied CBM strategy due to a lack of relevant CM procedures for detecting copper corrosion problems in the initial stage. The second step was studying the suggestions that could be utilized in the investigation to fulfil the gap. The main suggestion was applying the CM procedure using a new diagnosis model for early fault detection. In the third step, the relevant data of oil analysis were defined. The PSMD team provided access to data of 84 nominated transformers with different power ratings; see Figure 4. The fourth step was linking the data to the proposed suggestion and finding the solution to avoid the fault progression to a risky level. The last was creating a principle for clarifying the findings by using the statistical benchmarks. Another workshop was coordinated after applying the CM procedure to validate the outcome and ensure that stakeholder's needs and requirements were met with the suggested solution.

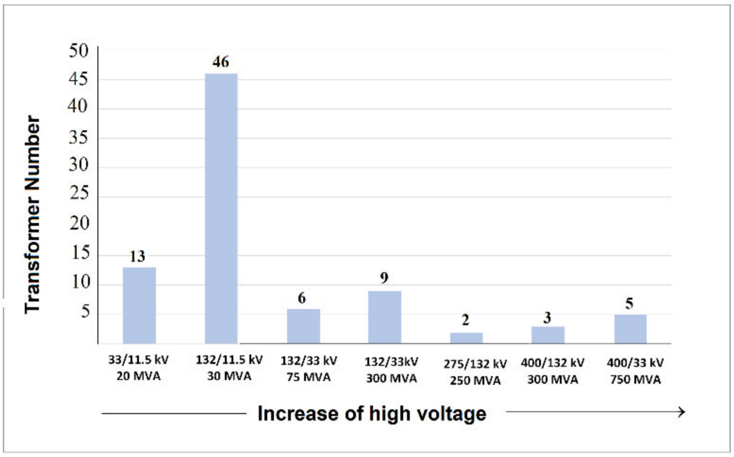


Figure 4. Classification of the 84 transformers according to the voltage (HV/LV, kV) and operated power rating, MVA. The voltage is related to the winding where HV = High Voltage in the secondary winding and LV = Low Voltage in the primary winding. The power rating, MVA = Mega volt-amperes where 1 mega volt-ampere = 1 million volt-amperes [45]. As seen in the figure, the transformers are classified according to the voltage, where the lowest transformer primary voltage is 33/11.5 kV (20 MVA), the medium transformer primary voltage is 132/11.5 kV (30 MVA), and the biggest transformer primary voltage is 400/33 kV (750 MVA).

3. Results

In this section, the outcome of applying the CM procedure of copper corrosion problems is demonstrated. The measured values of the measurable variables of dibenzyl disulfide (DBDS), benzyl mercaptan (BM), hydrogen sulfide (H_2S) gas, and toluene of seven transformers were identified with suspected copper corrosion propagation among the 84 and were recorded in September 2020. These measured values and the calculated RFDV are demonstrated in Table 2.

Table 2. Measured values of dibenzyl disulfide (DBDS), benzyl mercaptan (BM), hydrogen sulfide (H_2S) gas, and toluene. RFDV is calculated according to Equation (2). The measured values are the average of three measurements. The average of Relative Standard Deviations (RSDs) for all was <4%. The uncertainty ($U_{exp.}$) of five measurements of hydrogen gas and toluene was ± 0.07 for mean value 0.50 ppm and ± 0.10 for mean value 1.93 ppm, respectively.

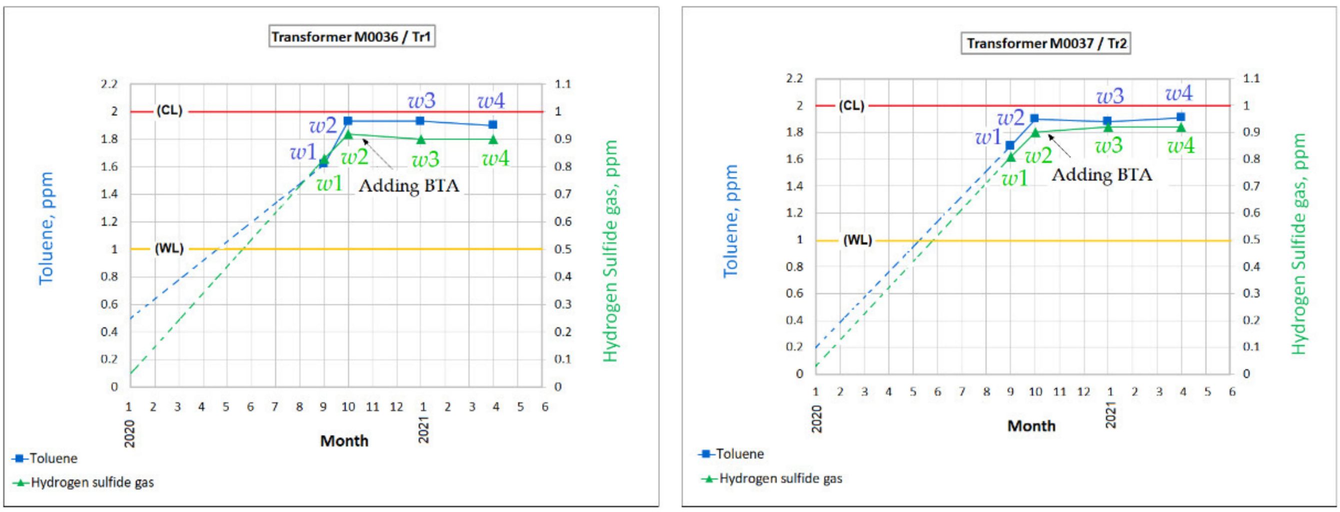
No.	Transformer Serial Number/ID	Voltage HV/LV, kV	Power Rating, MVA	Substation Name	DBDS (ppm)	BM (ppm)	H_2S Gas $w1$ (ppm)	Toluene $w1$ (ppm)	RFDV
1	8235120102/Tr2	132/33	300	Fifth ring road	1.0	<0.1	0.20	0.30	<0.60
2	S251625/Tr1	132/11.5	30	Mahbola-A	3.0	<0.1	0.42	0.25	<0.60
3	111353/Tr1	132/33	300	Omirya-W	<0.1	0.23	0.30	0.93	<0.60
4	07MD970101/Tr1	132/11.5	30	S. Alabdullah	<0.1	0.33	0.10	0.45	<0.60
5	M0036/Tr1	132/11.5	30	Mishref-A	9.0	0.90	0.83	1.62	>0.60
6	M0037/Tr2	132/11.5	30	Mishref-A	6.0	0.80	0.81	1.70	>0.60
7	M0038/Tr3	132/11.5	30	Mishref-A	4.3	<0.1	0.88	1.68	>0.60

By using the numerical method, the RFDV of the H_2S gas and toluene for the transformers 1 to 4 was calculated according to Equation (2). The RFDV was <m0.60, which indicated that the corrosion process was not at the risky level. The recommended action, in this case, could be "carrying out a new oil analysis with three months interval" [6] or according to the maintenance plan, to follow up on any increase in the RFDV and collect historical data. In contrast, the RFDV for transformers 5, 6, and 7 was >0.60, which indicated the possibility of starting copper corrosion problems. In this case, a new oil sample was recommended for monitoring H_2S gas and toluene after one month, in October 2020, to calculate Daily Trend (DT%), according to Equation (3). The second measured values ($w2$) of H_2S gas and toluene, and the calculated DT%, are demonstrated in Table 3.

Table 3. The second measured values ($w2$) of hydrogen sulfide (H_2S) gas and toluene after one month. DT% is calculated according to Equation (3). The measured values are the average of three measurements. The average of Relative Standard Deviations (RSDs) for all was <3.5%.

No.	Transformer Serial Number/ID	Toluene $w2$ (ppm)	H_2S Gas $w2$ (ppm)	DT (%)
5	M0036/Tr1	1.93	0.92	>0.33
6	M0037/Tr2	1.90	0.90	>0.33
7	M0038/Tr3	1.69	0.92	<0.33

As seen in Table 3, the DT of the transformer number 7 was <0.33%, which indicated that there was no significant trend in the value. Accordingly, the transformer was still in a safe condition, and the recommended action was "carrying out a new oil analysis with three months interval" or, according to the maintenance plan, to follow up on any increase in the trend level. The DTs of transformers number 5 and 6 were >0.33%, which indicated that there was a trend in the values. Accordingly, copper corrosion problems are in progress in these two transformers. The appropriate corrective action, in this case, was adding passivator BTA to suppress the corrosion reaction. The oil analysis was repeated in January and April 2021, where the result revealed a steady level in the values of the H_2S gas and toluene after adding BTA, which indicated success in preventing the copper corrosion problems. The progress of copper corrosion problems of these two transformers during useful life is demonstrated in the fault trend charts (a) and (b) in Figure 5.



(a) (b)

Figure 5. Fault trend charts of (**a**) Transformer 5 (M0036/Tr1) and (**b**) Transformer 6 (M0037/Tr2). CL = Caution limit, WL = Warning limit, $w1$ = first measured value, $w2$ = second measured value after one month, $w3$ and $w4$ = measured values after adding passivator.

As seen in Figure 5, historical data of H_2S gas and toluene before September 2020 were not available; the dashed line represents estimated values. The first analysis ($w1$) was in September 2020 for (a) transformer number 5, which has serial number/ID = M0036/Tr1, and for (b) transformer number 6, which has serial number/ID = M0037/Tr2. Then after one month, the second measured values ($w2$) were carried out to calculate DT, which was >0.33%. The passivator BTA was added during October 2020. The measured values after adding the BTA ($w3$ and $w4$) were on a steady level, which indicated no more expected faults because the corrosion reaction had already been suppressed.

In order to validate the outcome of the verification of the CM procedure in the PSMD power plant, a workshop was coordinated to discuss the process steps and outcome of the procedure; see the flow diagram in Figure 6. As seen from the flow diagram, after applying the suggested CM procedure on the 84 transformers, copper corrosion problems were detected and solved early in the two transformers. According to the PSMD stakeholders, this outcome and the proposed solution were effective and met their needs and requirements. Accordingly, they decided to employ the procedure for all transformers, around 3900, in all their substations to prevent fire and explosion accidents.

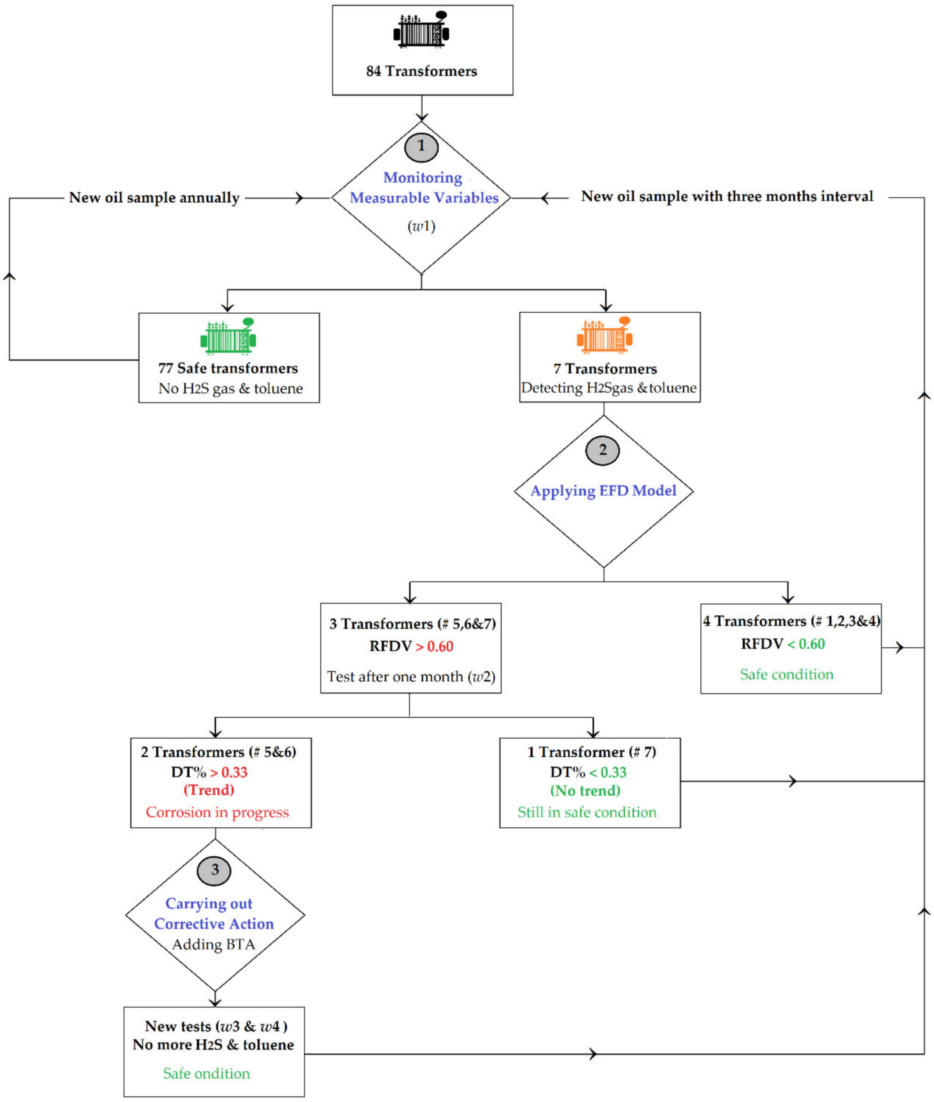


Figure 6. Flow diagram showing the process of the applied CM procedure in the PSMD power plant. Monitoring the measurable variable was the first step, where H_2S gas and toluene were detected in 7 transformers among 84. The second step was applying the EFD method where the RFDV was >0.60 in three transformers. After one month, two of these three transformers were diagnosed with suspected copper corrosion propagation based on DT% which was >0.33. The last step was adding a passivator BTA to these two transformers to suppress the corrosion reaction. $w1$ = first measured value, $w2$ = second measured value after one month, $w3$ and $w4$ = measured values after adding passivator, EFD = Early Fault Diagnosis, REDV = Relative Fault Detection Value, DT% = Daily Trend, BTA = Passivator Benzo Triazole.

4. Discussion

The CM procedure proved to be an accurate approach and useful toward early prevention of copper corrosion problems. The results of this study are summarized and discussed in the following paragraphs.

The dibenzyl disulfide (DBDS) values in the transformers 3 and 4 were <0.1 ppm and H_2S gas and toluene were detected, see Table 2, which indicates the possibility of depleting the DBDS entirely during the useful life of transformers. This result shows that monitoring only DBDS without tracking H_2S gas and toluene is insufficient to accurately evaluate the condition of copper corrosion problems. In the same table, the medium-sized transformers, numbers 5, 6, and 7, were installed from the same manufacturer and have the same specifications. This result motivates monitoring all transformers that have the same manufacturer and specifications if copper corrosion problems are detected in one of them.

Sulfur deposits that have already occurred on the insulating paper of the copper windings cannot be reduced because the corrosion reaction is irreversible [46]. The serious risk of these deposits is the deterioration of the insulating papers, which is considered the heart of the transformers [47]. The only solution, in this case, is the costly investment process called "rewinding" where the damaged parts of the insulating papers are replaced [48,49]. De-sulfurization treatment process of mineral oils is another solution used to prevent copper corrosion problems, in addition to adding passivators [50]. For example, handling the oil with rare earth that has a mixture of aluminium oxide, aluminium silicate, and soluble metal salts to extract the corrosive sulfur compounds from the oil [51]. Another example is the filtration of the oil online during the operation through a column containing a mixture of sulfur scavenging material and polar sorbents [52]. These processes are adequate to remove corrosive sulfur compounds from the oil. However, the source of corrosive sulfur is not only from the oil, it can also be decomposed continuously from transformers components such as glues, gaskets, rubbers, etc., which can have sulfur in percentage [24].

The Early Fault Diagnosis (EFD) model based on a novel numerical method was successfully verified in the empirical study at the PSMD power plant. Other studies also used numerical methods to increase the effectiveness of maintenance strategy of transformers, i.e., a Markov Prediction Model (MPM) to evaluate, in general, the current state of transformers as good or poor based on values of CM parameters and historical data [53–55]. Another study [56] utilized a statistical distribution model (SDM) to evaluate the transformer's deterioration by using a health index (HI%) based also on values of CM parameters and historical data. Both the MPM and the SDM models provide vital information of the current status of transformers and can predict their condition in the future. However, the approaches use very complex numerical methods that are not easily applicable in practice, and none of them demonstrated a method to detect faults in the initial stage. On the contrary, the EFD model is easy for maintenance teams to apply and is relevant for early fault detection.

Recommended future work can include increasing the effectiveness of the CM procedure by using smart technologies and self-conditioning, such as an online sensor device to detect and collect big data sets of hydrogen sulfide (H_2S) gas and toluene during the useful life of transformers. The development of such a device that triggers an alarm when the Relative Fault Detection Value (REDV) exceeds 0.60 can help a maintenance team to monitor the data more effectively.

5. Conclusions

The main conclusion of this study is the importance of early detection of transformer faults to avoid the negative impacts on societal, company, and individual levels. Identifying the copper corrosion problems in the initial stage of the PSMD power plant led to deferring the replacement investment costs of two medium transformers, in addition to avoiding the negative impacts. The results indicate that relevant measurable variables and early detection of copper corrosion problems can provide valuable information for the CM procedure. In addition, the fault trend chart demonstrated the capability to track the copper corrosion problems during the useful life of transformers.

The application of the fault diagnosis (EFD) model has highlighted several benefits that, for example, can contribute to reducing a transformer's fire rate in the PSMD power plant in the future. Carrying out sustainable maintenance can extend the lifetime of the transformers, e.g., the early corrective action for the two transformers with suspected fault propagation. More research and empirical studies are required to enhance the effectiveness of the application of the EFD model, not only for transformers but also for other assets that contain oil, such as turbines, compressors, engines, etc.

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Abbreviations

AL	Alarm Limit
BTA	Benzo Triazole
CBM	Condition-Based Maintenance
CCD	Covered Conductor Deposition
CL	Caution Limit
CM	Condition Monitoring
DBDS	Dibenzyl disulfide
DT	Daily Trend %
EFD	Early Fault Diagnosis
HI	Health Index %
H_2S	Hydrogen sulfide gas
Irgamet 39	Toluiltriazole-dialkylamine
MPM	Markov Prediction Model
PCB	Polychlorinated biphenyl
PPM	Part per million
PSMD	Primary Substation Maintenance Department
RAT	Relative Alarm Threshold
RFDV	Relative Fault Detection Value
RSD	Relative Standard Deviation %
SDM	Statistical Distribution Model
$U_{exp.}$	Expanded uncertainty
WL	Warning Limit

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