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Propositional logic concept for fault diagnosis in complex systems

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ABSTRACT

A great number of monitoring technologies have been developed especially for complex systems within the critical zones such as electric power substations, nuclear energy systems. But also, there is no single instruction or standardization in fault-focused on-line/off-line monitoring applications due to the acceleration of technological developments. Field experts have difficulty in choosing which test and measurement systems should be used in which stage of the complex systems. In this study, the propositional logic-based concept is presented, which field experts can use to manage this process. In this concept, test and measurement systems can be grouped according to the priority-order. According to the results of the graded groups on this concept, the suspected fault is verified by the cause of the occurrence. The applicability of the proposed concept has been tried to be explained by creating possible failure scenarios on the transformer. The theoretically validated concept can be used for even more fault situations. This concept can also be used in another complex systems with a large number of T&M systems where very different fault conditions can occur. 2009 Elsevier Ltd. All rights reserved.

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1. Introduction

The propositional logic is used in many areas in the industry and it is also a logical representation of the system especially in complex structures [1–4]. It allows the relations between the parts of the system to be seen and monitored as a whole. The propositional logic forms the basis of many different methods that are recommended afterward in the literature. The propositional logic is preferred especially in fault diagnosis and prevention applications in order to make a decision within existing alternatives [5–8]. It consists of propositional formulas using logical connectives at each node for propagation or contraction [9]. It is also suitable for programming as software or in embedded systems. On-line or off-line monitoring of the system can be possible by this way [3,4]. At this stage, although there is no valid method, it is very important to establish the logical propagation and the rule base structures according to field specialists' experiences and historical test records.

Today, many monitoring and testing methods are being developed, especially for complex and critical equipment, and also their diversity is rapidly evolving [10–14]. In this case, there are many options to diagnose the same failure. Certainly, it can be done multiple tests in order to obtain more accurate information regarding the fault. But here, it is obvious that there is a need to prioritize of the test methods. When the applications in the literature are

examined, on-line tests/measurements systems are usually at the beginning of this process (first-order) as in Fig. 1. The tests performed on the system while the system is disabled, are in the middle order. The tests carried out in the laboratory on samples taken from the system, are in the last order.

However, grouping may actually be more difficult than the assumptions shown in Fig. 1. To facilitate this, it is enough to pay attention to the main criteria. Test, measurement, and installation costs are the main criteria. It is very important whether it includes online technology or offline technology. How long time these tests and measurements take and their reliability are also important parameters. The number of staff needed and the results of the risk analysis of the test environment are among the parameters to be evaluated. An accurate ranking is crucial in terms of implementation difficulty and cost.

The approaches and methods used when ranking these test methods should also be logically appropriate. Logical propagation of decision trees/fault trees at the basic level may not always provide a suitable solution, due to the application order difference of each test method, for complex systems. This deficiency can be explained in Fig. 2. These phrases are defined as inputs that are converted into a digital signal and give the possibility of failure. If the test result indicates a fault, it is defined as 1 (True) and if there is no fault, it is defined as 0 (False).

When all possibilities are examined in this structure, it is understood that there is no fault only in one case. And in all other possibilities, it is understood that the system generates fault output.

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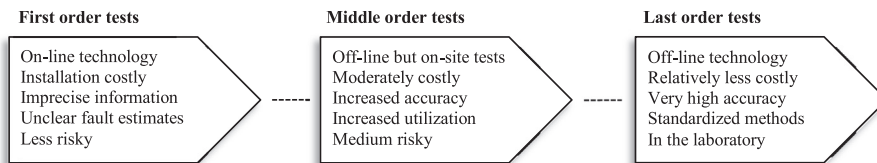


Fig. 1. Condition monitoring technology features.

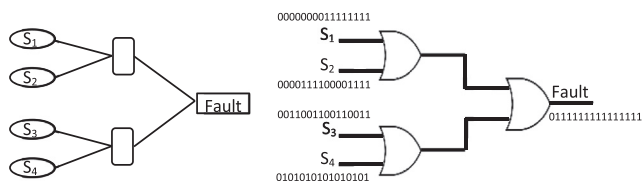


Fig. 2. Cause and effect with fault trees.

This situation is not acceptable in real systems. Because, even if only one of the four test inputs is True, the False expression is obtained from the output of the system. In fact, the results of the tests carried out here are made for the same fault type and they should be consistent. Even if the logic gate type is changed (from *or* to *and*), it cannot be found a solution in accordance with the actual system nevertheless.

In such a case, it is necessary to perform all the tests related to the fault. Since untested input is assumed to be False by default, there is no sense whether the other entries are True or False. This is a time and cost trouble, surely. It is also clear that there is no precedence of the logic entries of the test results relative to each other. In other words, all entries are equally important. All these deficiencies reveal that the classical logic approaches at the basic level cannot be used in advanced/complex systems.

In complex systems there are many pre-symptom, symptom, sub-fault related to the main faults. Often, fault development follows this sequence but sometimes may not as shown in Fig. 3(a). There are numerous test and measurement alternatives to identify all these failures and root causes. At this stage, experts have to find out which of these T&M methods, in which order to choose, and determine the failure development before the failure occurs. There are some constraints such as time, cost and risk forcing them. They need to follow the gradual path to detect symptoms and sub-faults as shown in Fig. 3(b) and eliminate the conditions that cause the fault. If this cannot be achieved in a timely manner, the fault will eventually occur.

For this reason in this study, a fault diagnosis concept based on propositional logic has been developed as an alternative to the

methods developed in the literature. The motivation of the study was to create a logic-based facilitator in the selection and ranking of test and measurement systems for experts working on complex systems. The innovations in the *propositional logic-based concept* include: a) easy understanding and processing with propositional logic expressions, b) adaptation to the embedded system or computer program if desired c) ability to group test and measurement methods.

2. The propositional logic concept for fault diagnosis

According to propositional logic, a statement or claim produced by using logical connectives is either True or False, but not both [15,16]. Where the True "1" and the False "0" can be specified. Basic logical connectives are shown below;

\neg denotes not, $\neg W$ is the negation of W

$$\rho(\neg W) = \begin{cases} 1, & \rho(W) = 0 \\ 0, & \rho(W) = 1 \end{cases} \quad (1)$$

\vee denotes or, $Z \vee W$ is the disjunction of Z and W

$$\rho(W \vee Z) = \begin{cases} 0, & \rho(W) = 0; \rho(Z) = 0 \\ 1, & \text{otherwise} \end{cases} \quad (2)$$

\wedge denotes and, $Z \wedge W$ is the conjunction of Z and W

$$\rho(W \wedge Z) = \begin{cases} 1, & \rho(W) = 1; \rho(Z) = 1 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

In the propositional logic, the other two connectives whose expressions are conditional (\rightarrow) and biconditional (\leftrightarrow) can be derived by the atomic propositions ρ that use the above connectives. For example; $P \rightarrow Q$ can be expressed as $\neg P \vee Q$, also $P \leftrightarrow Q$ can be expressed as $[(\neg P \vee Q) \wedge (\neg Q \vee P)]$.

In the suggested concept, the tests to be applied to the system for different fault types are grouped by evaluating in many respects such as technology, applicability, costly, etc. Then, these arranged test groups are ranked according to a priority order. The user can choose to perform the desired test/s regardless of a group order. Performing one of the equivalent tests is enough to generate information about the fault. The concept structure for a single fault type is shown in Fig. 4.

This structure can be replicated the same for other types of faults. Test/measurement entries should be adept to the system in accordance with the propositional logic principle. The X_{ij} entries must be set to "True" to activate the relevant j . test group for the first fault type. When the test limit value which is determined in the system related to the fault is exceeded, "True" is entered and this is the statement P_{jmn} that the system is faulty. When the test limit value is not exceeded, the entry is set as "False" and this is the statement that there is no fault in the system. The propositional formulas are created for the tests group as $(P_{j11} \vee P_{j12} \dots \vee P_{j12})$. The subsequent processes are described below;

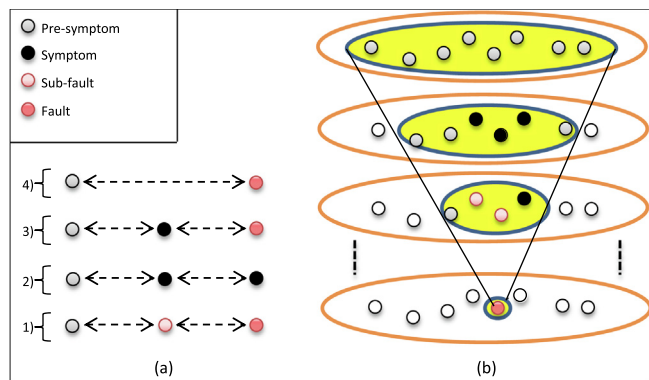


Fig. 3. Fault occurrence process.

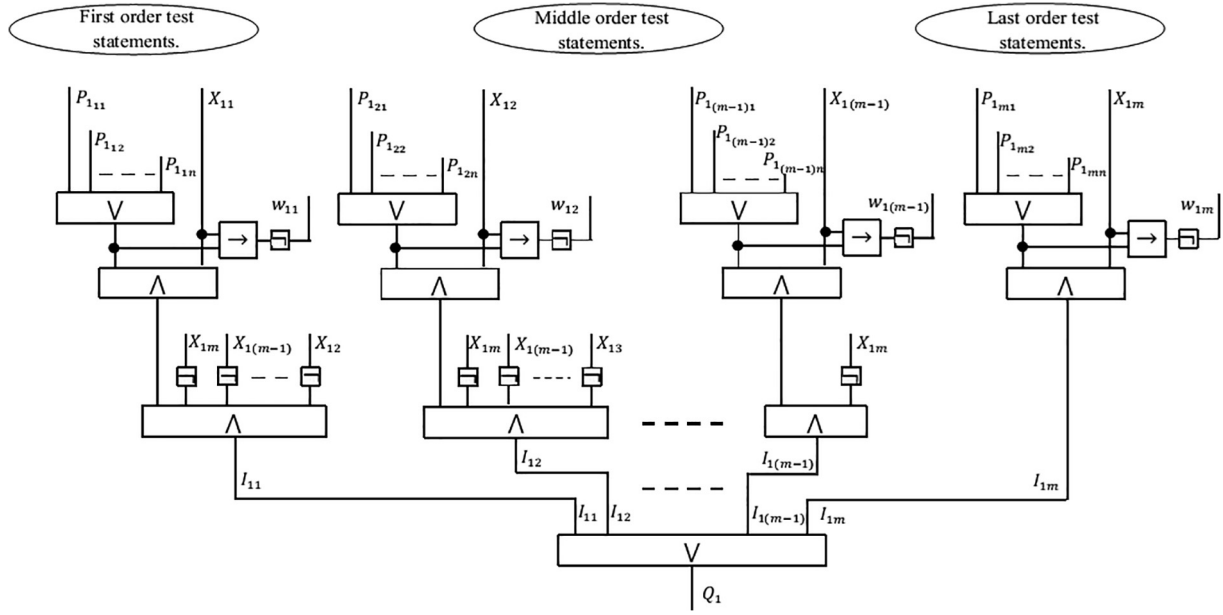


Fig. 4. The propositional logic-based concept (sequential multiple-entry for one fault type).

$$\begin{aligned}
 I_{11} &= (P_{111} \vee P_{112} \cdots \vee P_{11n}) \wedge X_{11} \wedge (\neg X_{1m}) \wedge (\neg X_{1(m-1)}) \cdots \wedge (\neg X_{13}) \wedge (\neg X_{12}) \\
 I_{12} &= (P_{121} \vee P_{122} \cdots \vee P_{12n}) \wedge X_{12} \wedge (\neg X_{1m}) \wedge (\neg X_{1(m-1)}) \cdots \wedge (\neg X_{13}) \\
 &\vdots \\
 I_{1(m-1)} &= (P_{1(m-1)1} \vee P_{1(m-1)2} \cdots \vee P_{1(m-1)n}) \wedge X_{1(m-1)} \wedge (\neg X_{1m}) \\
 I_{1m} &= (P_{1m1} \vee P_{1m2} \cdots \vee P_{1mn}) \wedge X_{1m}
 \end{aligned} \tag{4}$$

$$Q_1 = I_{11} \vee I_{12} \vee I_{13} \cdots \vee I_{1(m-1)} \vee I_{1m} \tag{5}$$

Wherein the statements are written according to the structure shown in Fig. 4. But, if two or more tests are performed on different groups in the structure, the later test result is more reliable. For example, if the result for a suspected fault is true in the previous test group and false in the next test group, the next test result will be valid. If a similar situation happens, it means that the suspected fault does not occur. In other words, a different fault is developing, other than the suspected fault. Therefore, a new fault estimate should be made with reference to the previous test results and the procedure should be continued until the final result is obtained. This concept is applicable to detect for all types of faults, without a number limit. Whether or not the suspected fault occurs according to the selected test results is indicated by w_{ij} outputs. If w_{ij} is False, it indicates that it is on the right way, and if w is True, a different fault type option should be considered instead of the suspected fault.

$$\begin{aligned}
 w_{11} &= \neg[X_{11} \rightarrow (P_{111} \vee P_{112} \cdots \vee P_{11n})] \\
 w_{12} &= \neg[X_{12} \rightarrow (P_{121} \vee P_{122} \cdots \vee P_{12n})] \\
 &\vdots \\
 w_{1m} &= \neg[X_{1m} \rightarrow (P_{1m1} \vee P_{1m2} \cdots \vee P_{1mn})]
 \end{aligned} \tag{6}$$

For all the other fault probabilities on the system the statements may be given as below;

$$\begin{aligned}
 Q_1 &= I_{11} \vee I_{12} \vee I_{13} \cdots \vee I_{1(m-1)} \vee I_{1m} \\
 Q_2 &= I_{21} \vee I_{22} \vee I_{23} \cdots \vee I_{2(i-1)} \vee I_{2i} \\
 &\vdots \\
 Q_k &= I_{k1} \vee I_{k2} \vee I_{k3} \cdots \vee I_{k(j-1)} \vee I_{kj}
 \end{aligned} \tag{7}$$

3. Adaptation of concept on the power system equipment

This concept has been developed for fault diagnosis and monitoring of complex systems. For this reason, the equipment to be selected as an example must also be a complicated system. The power transformer is a complex element, as well as an investment with expensive critical value required for operating a power system [17,18]. They have many on-line/off-line technologies in order to monitor or detect emerging/developing faults [19–21]. So, there are dozens of tests and measurements that can be done even for a single fault type. But of course, there is no obligation to do them at the same time. It is a matter of expertise which test should be selected in which order. By the proposed concept, we present a different alternative to the diversity in the literature, based on propositional logic.

3.1. Possible fault scenarios

There are several types of faults that can occur in the transformer. This section deals with possible fault scenarios to explain that the method is available for the fault detection and diagnosis processes on the power transformers. In fact, a fault is a result and it can occur due to many different reasons. Therefore, it is important to diagnose the cause of the fault. These tests/measurements are grouped in accordance with the order of priority and shown in Fig. 5. Here, these tests and measurements have the benefit either directly or indirectly to determine the related fault. Also, these groups can be supplemented with different tests for faults, or a separate group can be created. The logical inferences “ P_{jnm} ” obtained according to the evaluation of the selected test results are transferred as input to the designed conceptual structure. The results produced by each grouped tests provide information to the specialist about which of the test to be chosen in the next grouped tests. Thus, the cause of the related fault can be diagnosed more accurately and effectively by making only the necessary tests in due course.

In this study, seven different failure scenarios have been created for 4 main faults. The main faults are defined as thermal faults (Q1), OLTC faults (Q2), winding faults (Q3), and Insulation faults (Q4). Sub-fault conditions that cause these main faults to occur

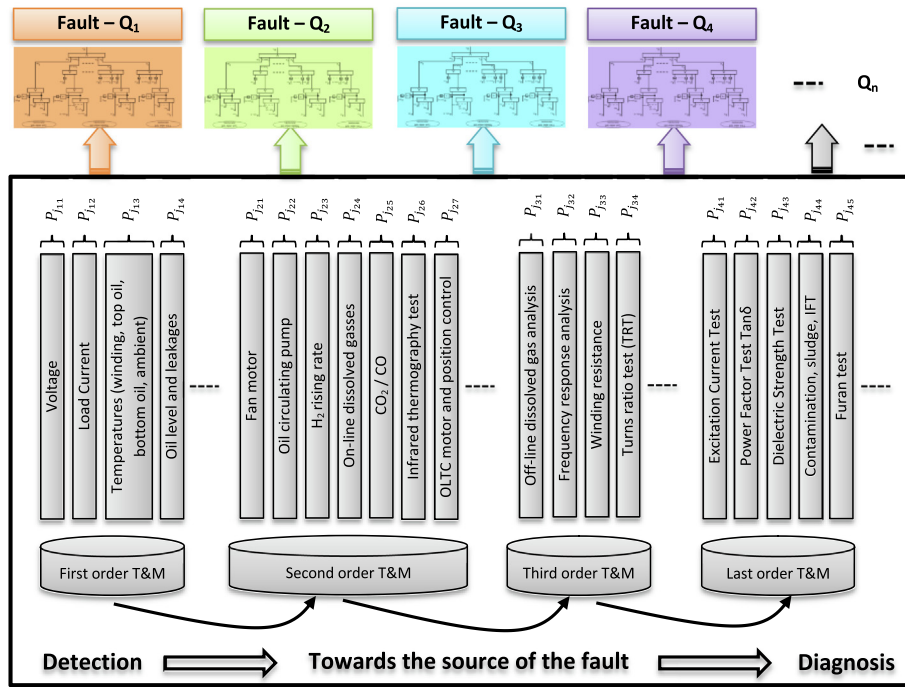


Fig. 5. T&M Group-order for different possible fault types on power transformer.

are also given in Table 1 as options in accordance with Fig. 5. One or more options from the grouped T&M system can be selected for each fault or sub-fault condition. These are the key options for suspected fault/s. Where, the T&M options can be pre-configured by a specialist for fault condition. In the next process, the technical staff facilitates the process by tracking these configured options.

3.2. Output statements and interpretations

Table 2, which is created according to the configured options, will help to determine the relevant main fault and the sub-fault conditions that may cause it. Actually, the first group consists of the on-line monitored parameters and provides preliminary information about the occurrence of the fault, although the location and the reason are unknown. The second order tests include easy-to-use T&M systems, both online and offline. And they provide more accurate estimates of the suspected malfunction. The third and last order T&M systems include offline /on-site tests or laboratory tests. The tests at this stage are used to determine the exact cause location of the failure. In the following, the causes of different main

faults are tried to be determined by the proposed propositional logic concept.

3.2.1. For the first main fault Q1 (Overheating)

The first order T&M indicate only the operating temperature is above the limit value. Problems that may cause overheating of the transformer are the failure of the oil circulation pump and fans. When a problem occurs in one of these elements, the output Q1 will appear as True. Therefore, when one of these is detected, the other T&M will not be necessary.

3.2.2. For the first main fault Q1 (Overloading)

The first order T&M indicates that the operating temperature and current value are above the limits. In this case, we have to eliminate structural fault options that may cause temperature rise. These are the oil cycle pump and the fans. Then it should be checked whether this is due to an internal fault. This can be achieved by monitoring the H₂ gas increase rate. If all of these options are False and if the CO₂/CO ratio is greater than 3, it can be assumed that there is a temperature increase due to overloading.

Table 1 Possible fault scenarios and T&M selections.

Possible Fault Scenarios	First order T&M	Second order T&M	Third order T&M	Last order T&M
Thermal fault – Q1				
Overheating	$P_{111}, P_{112}, P_{113}, P_{114}$	P_{121}, P_{122}	–	–
Overloading	$P_{111}, P_{112}, P_{113}, P_{114}$	$P_{121}, P_{122}, P_{123}, P_{125}$	–	–
Sludge, contamination	$P_{111}, P_{112}, P_{113}, P_{114}$	$P_{121}, P_{122}, P_{126}$	–	P_{144}
OLTC fault – Q2				
Motor	$P_{211}, P_{212}, P_{21}, P_{214}$	P_{223}, P_{227}	–	–
Contacts	$P_{211}, P_{212}, P_{21}, P_{214}$	P_{223}, P_{227}	P_{221}	–
Winding – Q3				
Axial or radial displacement	$P_{311}, P_{31}, P_{313}, P_{314}$	–	P_{332}	–
Insulation – Q4				
Aging, breakdown	$P_{411}, P_{412}, P_{413}, P_{414}$	P_{423}, P_{425}	P_{433}	P_{442}

will be overloaded and can be detected as a fault in the OLTC motor.

3.2.6. For the first main fault Q3 (winding displacements)

Especially during short circuit faults, the windings are forced mechanically. Sometimes, the windings can be displaced in the radial or axial direction. This change causes imbalance in impedances or voltages. If no measures are taken, it will be vulnerable to repeated short circuit faults. However, minor displacements in the windings after these failures may not be detected in the first indicators. Therefore, it is recommended to perform frequency response (FRA) analysis test on the transformer after short circuit faults. This test will provide very clear information about winding displacement.

3.2.7. For the first main fault Q4 (insulation breakdown)

The cellulosic material used for the insulation of the windings ages over time and consequently the insulation weakness may occur. At some weak points, short circuits may occur between the windings. This may cause imbalances in the current values. Since this situation will cause point heating, gas increase rates can be preferred in the second order in determining the related failure. However, winding resistances or $\tan\delta$ value may need to be measured for a clearer determination.

4. Conclusion

Due to the diversity of test and measurement instruments used in critical complex system or equipment, experts are faced with certain difficulties even if they are very good in their fields. Fault detection and diagnosis process can sometimes become very costly because of wrong choices. Such problems can be eliminated by the concept proposed in this study.

The adaptation of the proposed concept has been carried out for different fault types on the power transformer. In this study, four main faults and some of the sub faults that may be effective in their emergence are discussed. In fact, in a complex system such as a transformer, the number of main faults and sub faults is much higher than it is here. However, the elements chosen are sufficient to explain the function of the proposed concept.

One or more tests can be selected from the T&M system groups in order to determine the cause and nature of the possible failures. These selections can be determined once by an expert depending on the type of faults. This roadmap can be followed in the next process. However, if the indications of the suspected fault are not confirmed in the following test steps, the possibility of related fault should be reviewed. So, another possible fault scenario and process is repeated according to the roadmap determined by the expert.

The propositional logic-based concept resembles a kind of action plan specified which test can be used at which stage. This concept facilitates the management and decision-making process of the experts regarding the type of fault. Surely, these structures which are grouped in different numbers and orders may change in parallel with the demands of the experts or technological developments. This concept could also be applied to different fault types

to evaluate the entire same system. Finally, we recommend this concept for all complex systems containing different monitoring systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] O. Coudert, J.C. Madre, Metaprime: an interactive fault-tree analyzer, *IEEE Trans. Reliab.* 43 (1) (1994) 121–127.
- [2] X. Geng, D. Ouyang, X. Zhao, S. Hao, Probabilistic logical approach for testing diagnosability of stochastic discrete event systems, *Eng. Appl. Artif. Intell.* 53 (2016) 53–61.
- [3] S. Tripakis, A combined on-line/off-line framework for black-box fault diagnosis, in: *International Workshop on Runtime Verification*, Springer, Berlin, Heidelberg, 2009, pp. 152–167.
- [4] M.L. Tyler, M. Morari, Propositional logic in control and monitoring problems, *Automatica* 35 (4) (1999) 565–582.
- [5] M.Y.E. Henna, S.A. Nagy, Prevention of cascaded events of distance relay zone three using logic controls, *Conference Papers in Science (Vol. 2013)*, Hindawi, 2013.
- [6] E. Nashawati, N. Fischer, B. Le, D. Taylor, Impacts of shunt reactors on transmission line protection, *38th Annual Western Protective Relay Conference*, 2011.
- [7] N.M. Haleem, A.D. Rajapakse, Application of new directional logic to improve DC side fault discrimination for high resistance faults in HVDC grids, *J. Mod. Power Syst. Clean Energy* 5 (4) (2017) 560–573.
- [8] M. Abramovici, M.A. Breuer, Fault diagnosis based on effect-cause analysis: an introduction, in: *Proceedings of the 17th Design Automation Conference*, ACM, 1980, pp. 69–76.
- [9] E. Mendelson, *Introduction to mathematical logic*, Chapman and Hall/CRC, 2009.
- [10] R. Murugan, R. Ramasamy, Failure analysis of power transformer for effective maintenance planning in electric utilities, *Eng. Fail. Anal.* 55 (2015) 182–192.
- [11] J. Townsend, M.A. Badar, J. Szekercs, Updating temperature monitoring on reciprocating compressor connecting rods to improve reliability, *Eng. Sci. Technol.* 19 (1) (2016) 566–573.
- [12] H. Henaou, G.A. Capolino, M. Fernandez-Cabanias, F. Filippetti, C. Bruzzese, E. Strangas, S. Hedayati-Kia, Trends in fault diagnosis for electrical machines, *IEEE Ind. Electron. Mag.* 8 (2) (2014) 31–42.
- [13] A. Hadyia, A. Güngör, Fatigue v-notch sensor for monitoring the health of critical structures, *Eng. Sci. Technol.* 22 (2) (2019) 391–398.
- [14] Y. Bicen, F. Aras, A robust algorithm based on a failure-sensitive matrix for fault diagnosis of power systems: an application on power transformers, *Turkish J. Elec. Eng. Comput. Sci.* 23 (1) (2015) 298–315.
- [15] M. Sheeran, G. Stålmarck, A tutorial on Stålmarck's proof procedure for propositional logic, *Formal Methods System Design* 16 (1) (2000) 23–58.
- [16] H. Krad, Formal methods and automation for system verification, in: *2011 Fourth International Conference on Modeling, Simulation and Applied Optimization*, IEEE, 2011, pp. 1–12.
- [17] M.I. Hasan, Improving the cooling performance of electrical distribution transformer using transformer oil-Based MEPCM suspension, *Eng. Sci. Technol.* 20 (2) (2017) 502–510.
- [18] Y. Biçen, F. Aras, H. Kirkici, Lifetime estimation and monitoring of power transformer considering annual load factors, *IEEE Trans. Dielectr. Electr. Insul.* 21 (3) (2014) 1360–1367.
- [19] X. Zhang, E. Gockenbach, Asset-management of transformers based on condition monitoring and standard diagnosis, *IEEE Electr. Insul. Mag.* 24 (4) (2008) 26–40.
- [20] N.A. Bakar, A. Abu-Siada, Fuzzy logic approach for transformer remnant life prediction and asset management decision, *IEEE Trans. Dielectr. Electr. Insul.* 23 (5) (2016) 3199–3208.
- [21] S. Tenbohlen, S. Coenen, M. Djamali, A. Müller, M. Samimi, M. Siegel, Diagnostic measurements for power transformers, *Energies* 9 (5) (2016) 347.