SIDAT - Integrated System for Automatic Diagnostic on Power Transformers

Alexsandro Monteiro Carneiro* , Andre Pasquali*, Milton Ernesto Romero Romero*, Evandro Mazina Martins*, Ricardo Santos*, Jacyr Muniz Silva Filho†, Edson Miyamoto† and Luiz Canizio Medeiros da Costa

*CTEI - Technological Center for Eletronics and Informatics
Email: almocams@gmail.com, pasqualiec@gmail.com, miltonr@del.ufms.br, evandro.mazina@ufms.br, ricardo@facom.ufms.br

†Enersul - Rede Energia
Campo Grande - MS - Brazil
Email: jacyr.muniz@enersul.com.br, edson.miyamoto@enersul.com.br

***Abstract*— This paper presents an integrated system for automatic diagnostic on power transformers (SIDAT) of substations. SIDAT performs diagnosis based on several kinds of tests such as thermography images, chromatography, physical-chemical, and electrical. SIDAT also performs prognostic indicating the time life of the equipment. The inference engine for diagnostic is based on rules of the maintenance department of the company and it has been designed as a set Mealy Finite State Machines (FSMs). The system has been tested and evaluated with data coming from a production environment and stores data of 157 power transformers (13.8kVA and 34.5kVA) located in 94 different substations.**

I. Introduction

Maintenance on power transformers of electricity companies is a high cost procedure that involves, among other things, analysing previous situations in order to determine the current state of the equipment. After the diagnostic, the maintenance team should indicate necessary procedures to carry out on the transformer. Those maintenance procedures should be implemented in hard deadlines since the cost of premature failures of those assets can be several times more than the initial cost of the power transformer [5].

Failures, diagnosis, and monitoring of power transformers has been a well studied subject in the area of power systems [3], [12]. Since the change of transformer normal conditions can come up from different sources, such as: thermal, electrical, dielectric, chemical, and electromagnetic, it is necessary to take all that sources into account to give an accurate diagnostic of the current state of a transformer. There are several proposals ranging from new techniques for providing accurate diagnosis [5], [15], monitoring followed by diagnosis [2], [12], and commercial solutions for on-line monitoring and diagnosis [1], [7].

In this paper, we propose a software system named SIDAT focused on the problem of diagnostic of power transformers of substations. The proposed software indicates the maintenance procedures to apply according to the current state (current conditions) of the equipment. SIDAT integrates electric, chromatography, termography, and physical-chemical tests and provides diagnostics observing transformer behaviour on each test. The inference engine for diagnostic is based on rules of the maintenance department of an electricity company in Campo Grande-MS-Brazil and it has been designed as a set of 30 Mealy Finite State Machines (FSMs) to cope with the electric, chromatography, termography, and physical-chemical tests.

In addition to the diagnostic, the user has options to visualize and print reports for each transformer according to the test, current state or even by a historical perspective. SIDAT database keeps all important features of a transformer, including all maintenance procedures performed on the equipment.

The rest of this paper is organized as follows: Section II describes proposals for diagnostic on power transformers found in the literature; Section III presents the architecture of the SIDAT system and its functioning in diagnostic and prognostics; Experiments and results about the SIDAT system is presented in Section VI; Section IV presents the main conclusions about the work.

II. Related Work

Since the subject of diagnostic of power transformers is of utmost importance in the area, there are several research work presenting new techniques for accurate diagnosis. This section presents some research work on this subject.

A web based expert system for fault diagnosis on power transformers is proposed in [9]. The system engine for diagnostic is based on experts knowledge, historical data, and references about the faults on transformers. Basically, the knowledge rules are described in the system and used by indicate a state according to the inputs. Moreover, the authors indicate that one of the main contribution of the system is the extensibility and scalability making it able to be applied for diagnosis on different transformers.

In [15], a two step neural network classifier has been developed and carefully tested for transformer fault diagnosis using dissolved gas-in-oil analysis. Their work evaluated the presence of types of gas in oil and, by using artificial neural networks, identify transformer state.

[2] proposes an agent based diagnostic system. The system is able to acquire information for diagnosis from different sources: dissolved gas analysis (DGA), insulating oil quality, power factor testing, winding resistance, and thermography. Their proposal is a web-based architecture for multi-agent systems that can perform monitoring and diagnosis and it can be extended for different diagnosis methods.

AI techniques such as ANN, fuzzy logic, expert systems are presented in [8] for diagnosis in power transformers. Rough sets, support vector machines, wavelet networks are proposed for the same subject in [4], [10], [16].

Another tendency in diagnostic of power transformers is the use of monitoring as a step before diagnosis. In [6], [12], the monitoring is presented aiming at detection of symptoms or evidence of abnormal condition. Such monitoring techniques should be applied regularly and preferably continuously on-line. Monitoring sytems impose a new challenge which is the number of monitoring equipments (sensors, actuators, etc.) to be used so that the minimum impact comes to the transformer. Other proposals for integrated monitoring and diagnosis are presented in [11], [13], [14].

III. Integrated System for Automatic Diagnostic on Power Transformers

SIDAT system has been designed aiming at providing diagnosis and prognostic of power transformers from: physical-chemical, electrical, chromatographic, and thermography tests, and from historical data. Another requirement for designing SIDAT has been to turn information available to the engineering maintenance group to know the time life for each transformer in order to define the maintenance procedures. In addition, the software should be scalable to include new modules and should be open for integration to other corporate systems. Specifically, the thermography module has been designed to substitute the high cost thermovisors (infrared cameras) for low cost models since all processing is performed by the thermography module in SIDAT.

Figure 1 presents the interaction of SIDAT with other corporate systems and modules. The enterprise system is named SAP/R3 and communicates with SIDAT through a TCP/IP connection. SAP/R3 is the system responsible for storing all equipments historical data.

SIDAT has been developed using the Java programming language and Oracle^{TM} Data Base Management System (DBMS). The modules designed for SIDAT are:

- Physical-Chemical, Chromatography, Electrical, and Thermography tests and diagnostic;
- Reports: to provide different kinds of reports for all people from the maintenance department from the director board to the maintenance engineers;
- Transformers: to keep all information about each transformer and, mostly, the current location and the history of movements by the substations.

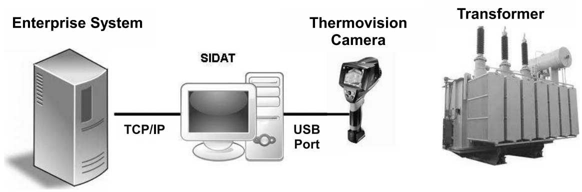

Fig. 1. SIDAT architecture.

All diagnostics modules have been designed based on an expert system using finite state machines (FSMs). In the context of diagnosis, the designed FSMs are Mealy Machines since the output depends on the input and the current state. A Mealy machine is a 6-tuple, $(S,\ S_0,\ \sigma,\ \delta,\ T,\ G)$, consisting of the following: The FSM modelling has captured all knowledge from engineers and maintenance technicians. Basically, one FSM has been designed for each test giving the solution for the current situation/state of the transformer. An FSM is comprised of a set of states S and a set of transitions T.

- a finite set of states (S);
  In Figure 2, the states are: Normal Conditions, Confirm High Content of Oxidation, and Confirmed High Content of Oxidation.
- a start state (also called initial state) S_0 which is an element of (S);
  This is state Normal Conditions in Figure 2.
- a finite set called the input alphabet σ;
  This is the set of input parameters from each test: neutralization index, resistance of isolation, etc.
- a finite set called the output alphabet δ;
  This is the actions (procedures) to take according to the new current state.
- a transition function ($T : S \times \sigma \rightarrow\ S$) mapping pairs of a state and an input symbol to the corresponding next state;
  This is represented by the conditions been evaluated and the edges from one state to another.

- an output function ($G : S \times \sigma \to \delta$) mapping pairs of a state and an input symbol to the corresponding output symbol;
  This is represented by the evaluated conditions and the procedures to take if the condition is true.

Our modelling maps the transformer failures and the procedures that the maintenance group should adopt in case of failures. Three different sets of FSMs have been designed for capturing the transformer state after a physical-chemical test, a chromatography test, and a electrical test.

In the FSMs for physical-chemical tests, the input parameters were water contents, power factor, interfacial voltage, neutralization index, polimerization grade, 2-furfural, askarel oil, and corrosive sulfur. Figure 2 exemplifies an FSM for the physical-chemical tests considering the neutralization index input parameter. In the Figure, each vertex (circle) represents a state and each edge evaluates the input parameter according to a condition. If the condition (underlined) is true, the transition is performed and the output (procedure) is shown. In the FSM exemplified in Figure 2, if the current state is **Normal Conditions** and the value of the neutralization index is greater or equal to 0.2mg/KOH/g then the new current state is **Confirm High Content of Oxidation** and a new test is required by the maintenance group.

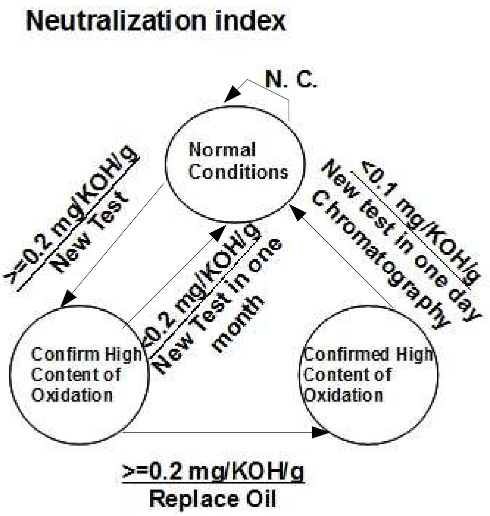

Fig. 2. FSM for the physical-chemical test.

Figure 3 is another FSM for the physical-chemical tests considering the power factor input parameter. In the Figure, if the current state is **Normal Conditions** and the value of the power factor is greater than 0.5% then the new current state is **Confirm High Power Factor** and a new test is required by the maintenance group.

Another set of FSMs has been designed for chromatographic tests. Specifically, the tests evaluated the evolution of key gases (CO, H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2) in oil. By observing the presence of each proportion of gas and comparing it to the

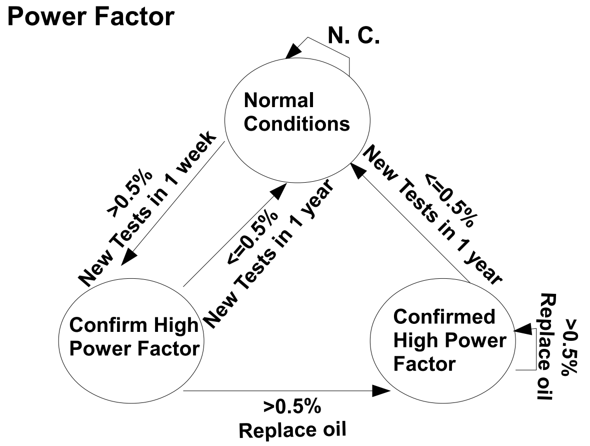

Fig. 3. FSM for the physical-chemical test.

reference value, it is possible to determine arc, overheating, and corona problems.

Figure 4 exemplifies an FSM for the electrical tests. In the Figure, the evaluated input parameters are resistance of isolation, and transformer turns ratio.

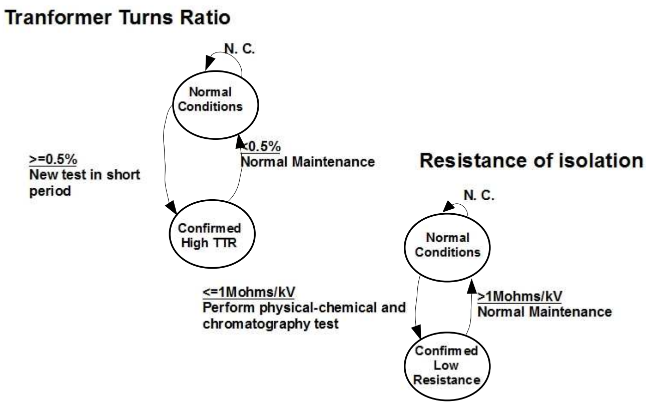

Fig. 4. FSM for the electrical test.

In addition to the tests aforementioned, we have designed a module for chromatographic tests. This new module allows to load an image from a low cost thermovisor, processing that image to identify hot spots and inform that to the user. This module has two options:

- Load two images from transformer of the same class. The first image is from the transformer under analysis and the second one is from a adjacent transformer. The adjacent transformer is on normal conditions. SIDAT compares both transformers and identify hot spots on the transformer under analysis. If there are hot spots and possible failures, the software indicates the maintenance procedures to be done.
- The second option is for equipments that there are not adjacent transformers. In this case, the user should visualize the image, identify

and select the hot spots for SIDAT shows temperature and procedures to be done.

Basically, the fluxogram in Figure 5 shows how FSMs work and interacts with other SIDAT modules.

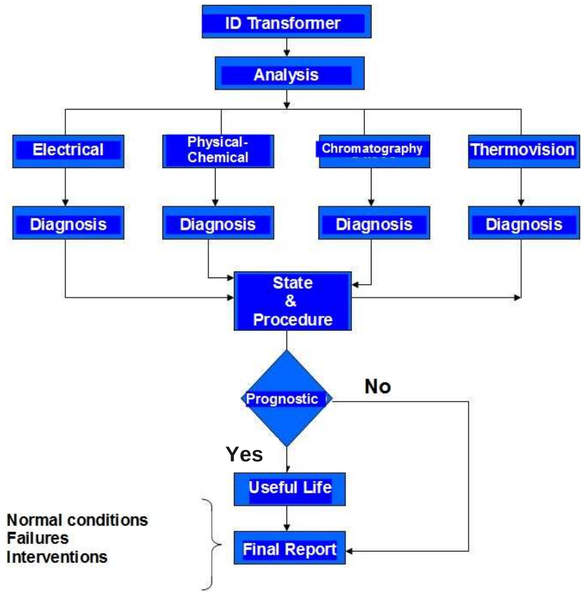

Fig. 5. SIDAT fluxogram.

The fluxogram comprises six steps:

1) In the ID Transformer module, a SIDAT user finds a transformer in the system by the serial number or location. SIDAT shows to the user all information regarding the equipment.
2) After a specific transformer is selected in the Analysis module, the system looks for all tests on that equipment and its current state.
3) The user enters with new data of a specific test in the system. This is performed in one of the tests modules (electrical, physical-chemical, chromatography, thermovision).
4) After saving data of the new test, the system runs the FSMs according to the test and presents a new current state (diagnosis) and the procedure to be performed on the equipment. These activities are provided by **Diagnosis** and **State & Procedure** modules.
5) The **Final Report** module of SIDAT allows the user to include a final report of the test just performed. That report can add information for the procedure or indicate how the test has been performed.
6) Additionally, the user can run the Prognostic procedure and observe the useful life of the equipment according to the current state. These functionalities are provided by **Prognostic** and **Useful Live** modules.

IV. Results

This section presents a set of tests on the SIDAT software. The tests were based on historical data from the maintenance department of Enersul - Rede Energia. For all tests, we adopt 3 transformers tested in different periods (from 1996 up to 2001) and evaluated considering Physical-Chemical, Chromatographic, and Electrical tests. We have chosen three power transformer for the tests and diagnosys by SIDAT. The results are presented from Tables I-X.

In the following tables, we consider some abreviatons:

- TR means a substation Transformer.
- WF means Water Factor.
- PF means Power Factor.
- IV means Interfacial Voltage.
- NI means Neutralization Index.
- NC means Normal Conditions.
- OF means Oxidation Factor.

Tables I and II present Physical-Chemical tests for three different transformers. Table III shows the states for diagnostics of physical-chemical tests. Tables IV and V present the results (procedures) to take into account for the tests in Tables I and II.

TABLE I
Physical Chemical Tests.

TR	Date (D/M/Y)	Humidity	Strength
1	11/25/11/1997	38	88
	28/06/1998	18.7	69
	18/02/1999	49.5	37
	11/03/1999	20	60
	12/03/1999	20	60
2	28/03/1996	0	76
	03/03/1997	0	57
	19/03/1998	14.7	59
	20/03/1998	0	74
	15/06/1999	143	51
3	15/05/1996	0	76
	08/10/1996	0	74
	25/11/1997	25	62
	31/03/1999	18	67
	13/08/2001	7.2	73

TABLE II
Physical-Chemical Tests (cont.)

TR	PF	IV	NI
1	0.25905	30	0.03
	0	32.7	0.029
	0.05705	28	0.02
	0	31.4	0.02
	0	31.4	0.02
2	0.25805	20.2	0.087
	0.25005	21	0.073
	0.2015	22	0.085
	0.2371	24.7	0.054
	0.2535	23	0.08
3	0.32005	18.7	0.083
	0.32705	23.5	0.07
	0.28205	23.3	0.085
	0	24	0.07
	0	32.5	0.02

The results (states and procedures) given by the SIDAT system are according to the state machines previously designed. We can notice, for example, the results shown in columns NI and PF follows the states and procedures of the state machines in Figures 2 and 3. According to the state machine of the

TABLE III

States for the physical-chemical tests

TR	WF	PF	IV	NI
1	Confirm high WF	NC	NC	NC
	NC	NC	NC	NC
	Confirm High WF	NC	NC	NC
	NC	NC	NC	NC
	NC	NC	NC	NC
2	NC	NC	Confirm high OF	NC
	NC	NC	Confirm high OF	NC
	NC	NC	Confirm high OF	NC
	NC	NC	NC	NC
	Confirm very high WF	NC	NC	NC
3	NC	NC	Confirm high OF	NC
	NC	NC	NC	NC
	NC	NC	NC	NC
	NC	NC	NC	NC
	NC	NC	NC	NC

TABLE IV

Results for the Physical-Chemical Diagnostics

TR	WF	PF
1	New tests in 1 week	Normal maintenance
	New tests in 1 month	Normal maintenance
	New tests in 1 week	Normal maintenance
	New tests in 1 month	Normal maintenance
	Normal maintenance	Normal maintenance
2	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	New tests in 1 week	Normal maintenance
3	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance

NI, the transformer should move from state "Normal Conditions" to state "Confirm High Content of Oxidation" only when NI>=0.2. The physical-chemical tests performed obtained NI values from 0.02-0.087 so that the state for the NI parameter in Table V should remains in "Normal Maintenance".

Tables VI and VII present Chromatographic tests for three transformers in different periods. Table VIII shows the states for diagnosys of chromatographic tests. Tables IX and X present the results (diagnosys) for the tests in Tables VI and VII.

Comparing the SIDAT diagnostic results and the default results given by the specialists of physical-chemical and chromatographic tests, the engineers and technicians of the electrical company have concluded that SIDAT is able to be used as a tool for automatic diagnostics for physical-chemical, electrical, chromatographic, and thermography tests.

Tables XI and XII present the states and procedures for the electrical tests.

V. Acknowledgments

This work was supported by the R&D Program of ANEEL and Enersul - Rede Energia. The authors would like to thank the engineers and technicians of the maintenance department of Enersul - Rede Energia, for their valuable support to the development of this project.

TABLE V

Neutralization Index and Interface Voltage for the Physical-Chemical Diagnostics

TR	IV	NI
1	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
2	New tests in 1 week	Normal maintenance
	Change oil	Normal maintenance
	Change oil	Normal maintenance
	New tests in 1 month	Normal maintenance
	Normal maintenance	Normal maintenance
3	New tests in 1 week	Normal maintenance
	New tests in 1 month	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance
	Normal maintenance	Normal maintenance

TABLE VI

Chromatographic Tests

TR	Date	H_2	CH_4
1	22/12/1997	152	36
	29/12/1997	76	48
	21/12/1998	0	0
	09/08/1999	41	7
	11/02/2000	376	43
2	06/07/1998	0	0
	08/09/1998	0	10
	08/09/1999	25	12
	03/04/2000	0	0
	19/07/2000	0	0
3	22/12/1997	0	0
	27/02/1998	0	0
	22/04/1998	0	0
	07/05/1998	0	0
	18/11/1998	0	0

VI. Conclusions

Power transformers are critical, capital-intensive assets for electricity companies. In that scenario, techniques that improve maintenance procedures, by providing accurate diagnosis of the equipments, can also minimize current of future expenses to those transformers by the company.

This work has presented a software system, named SIDAT, that provides diagnostic of power transformers by integrating thermography, physical-chemical, electrical, and chromatography tests. The proposed system informs the current state of the equipment and also indicates the maintenance procedure to perform according to the state. The inference engine has been designed by a set of FSMs that capture the knowledge of the transformer expert. Currently, SIDAT databases keep information of more than 157 power transformers (13.8kVA or 34.5kVA) located in 94 different substations. Each transformer has, on average, 7 tests performed in a year. SIDAT database stores registers of 30 years of historical data.

The system has been used as a basic tool for the maintenance team since technicians to take decisions as for the procedures and equipments up to the director board to take decisions about investments on the fleet of transformers of the company.

TABLE VII

Chromatographic Tests

TR	CO	C_2H_4	C_2H_6	C_2H_2
1	778	128	10	137
	788	130	13	129
	85	11	3	0
	1486	68	8	0
	821	146	14	109
2	331	42	35	0
	280	30	5	0
	440	57	9	0
	363	23	0	0
	284	34	6	0
3	388	171	0	0
	668	220	0	0
	458	167	16	0
	458	167	16	0
	600	205	33	0

TABLE VIII

Events for States Confirmed Defect and Solved Defect

Confirmed Defect	Solved Defect
True	True
True	False
False	Don't care

TABLE IX

Chromatographic state. Confirmed Defect (true) and Solved Defect (true)

TR	Key gas	NBR
1	NC	Confirm high energy arc
	NC	Confirm high energy arc
	Confirm Cel overheat	Solve defect
	Confirm Cel overheat	NC
	Solve defect	Confirm high energy arc
2	NC	undetermined fault
	Confirm Cel overheat	NC
	Confirm Cel overheat	undetermined fault
	Solved defect	NC
	NC	undetermined fault
3	NC	Undetermined fault
	NC	NC
	NC	Undetermined fault
	NC	NC
	NC	Undtermined fault

TABLE X

Chromatographic state. Confirmed Defect (true) and Solved Defect (true)

TR	Rogers	Duval
1	High energy arc	High gas ref.
	Confirmed high energy arc	High partial discharge
	Solve defect	NC
	NC	High gas ref.
	High energy arc	High partial discharge
2	Undetermined fault	NC
	NC	NC
	Undetermined fault	NC
	NC	NC
	Undetermined fault	high gas ref.
3	Undetermined fault	High gas ref.
	NC	Thermo fault >700°C
	Undetermined fault	Normal conditions
	NC	High gas ref.
	Undetermined fault	Thermo fault >700°C

TABLE XI

States for the electrical tests

States	
Confirm high PF	4000
Confirm destructive defect	4100
Confirm High TTR	4200
Confirm low resistance	4300

TABLE XII

Procedures for the electrical tests

Procedures	
Monitoring with period reduce	400
Reduce period of physical-chemical and chromatographic tests	410
Perform procedure to detect problem	420

References

[1] Siemens AG. Tmds^{TM} transformer monitoring & diagnostic system. [online] http://www.energy.siemens.com, 2011.

[2] H. H. Borsi and E. Gockenbach. New possibility for monitoring and diagnosis of power transformers via an agent based system. In *25th International Power System Conference*, 2010.

[3] A. Bossi. Cigre-wg 12-05: An international survey on failures in large power transformers in service. *Electra*, 88:21–48, May 1983.

[4] Weigen Chen, Chong Pan, Yuxin Yun, and Yilu Liu. Wavelet networks in power transformers diagnosis using dissolved gas analysis. *IEEE Transactions on Power Delivery*, 24, 2009.

[5] Gerards Gavrilovs and Olegs Borscevskis. Power transformers diagnostic. In *10th International Symposium Topical Problems in the Field of Electrical and Power Engineering*, Parnu, Estonia, 2011.

[6] Gerards Gavrilovs and Olegs Borscevskis. Replacement of power transformers basis on diagnostic results and load forecasting. In *World Academy of Science, Engineering and Technology*, pages 239–244, 2011.

[7] Alstom Grid. Ms 3000 transformers' monitoring system. [online] http://www.alstom.com/grid/, 2011.

[8] J. L. Guardado, J. L. Naredo, P. Moreno, and C. R. Fuerte. A comparative study of neural network efficiency in power transformers diagnosis using dissolved gas analysis. *IEEE Transactions on Power Delivery*, 16, 2001.

[9] M. Babita Jain and M. B. Srinivas. A novel web based expert system architecture for on-line and off-line fault diagnosis and control (fdc) of transformers. In *IEEE Region 10 Conference TENCON*, Hyderabad, India, 2008.

[10] Dae-Jong Lee, Jong-Pil Lee, Pyeong-Shik Ji, Jae-Woon Park, and Jae-Yoon Lim. Fault diagnosis of power transformer using svm and fcm. In *IEEE International Symposium on Electrical Insulation*, 2008.

[11] T. Leibfried. Online monitors keep transformers in service. *Computer Applications in Power*, 11(3), 1998.

[12] I. A. Metwally. Failures, monitoring and new trends of power transformers. *IEEE Potentials*, 30(3), 2011.

[13] B. Richardson. Diagnostics and monitoring of power transformers. *IEE Colloquium*, 1997.

[14] S. Tenbohlen and F. Figel. On-line condition monitoring of power transformers. *IEEE Power Engineering Society Winter Meeting*, 3, 2000.

[15] Y. Zhang, X. Ding, Y. Liu, and P. J. Griffin. An artificial neural network approach to transformer fault diagnosis. *IEEE Transaction on Power Delivery*, 11(4), 2008.

[16] W. Zhao and Y. Zhu. Power transformer fault diagnosis based on rough set theory and support vector machine. In *Fourth International Conference on Fuzzy Systems and Knowledge Discovery*, 2007.