Investigation of an Expert System for the Condition Assessment of Transformer Insulation Based on Dielectric Response Measurements

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***Abstract*—The need for economic, reliable, and effective delivery of electric power has lead to the search for fast, efficient, and effective methods for diagnosing the insulation of high-voltage (HV) equipment in the power industries. The recent dielectric techniques that have been carefully considered by major industries for transformer insulation condition assessment are the recovery voltage method (RVM) and the polarization and depolarization current (PDC) measurement. However, due to the complexity of the transformer insulation structure and various degradation mechanisms under multiple stresses, insulation condition assessment is usually performed by experts with special knowledge and experience. In this paper, an expert system (ES) is developed, which imitates the performance of a human expert, to make the complicated insulation condition assessment procedure accessible to plant maintenance engineers. The structure of the ES is described in detail including knowledge base, inference engine, and human–computer interface. Examples of the application of the ES are also presented to confirm that the system can provide accurate insulation diagnosis.**

***Index Terms*—Conductivity, depolarization current, dielectric diagnosis, expert system, knowledge base, oil moisture, paper moisture, polarization current, recovery voltage, transformer aging.**

I. INTRODUCTION

TRANSFORMER is one of the most important and costly apparatus in a power system. The reliable and efficient fault-free operation of the high-voltage transformer has a decisive role in the availability of electricity supply. The transformer oil/paper insulation gets degraded under a combination of thermal, electrical, chemical, mechanical, and environmental stresses during its operation [1], [2]. In recent years, there has been growing interest in the condition assessment of transformer insulation. This is primarily due to the increasingly aged population of transformers in the utilities around the world. With the growing complexity of power systems, minimization of interruption to customers and reliability of service is of paramount importance. Therefore, assessment of the insulation condition of the transformer is of great industrial interest.

Utility engineers use a number of modern chemical diagnostic techniques to assess the insulation condition of aged transformers. These include dissolved gas analysis (DGA), degree of polymerization (DP) measurement, and furan analysis by the high-performance liquid chromatography (HPLC) technique.

In recent years, new electrical diagnostic methods have been promoted to supplement the classical insulation resistance, dissipation factor, and polarization index measurements. Dielectric diagnostic techniques such as the recovery voltage method (RVM) [1]–[8] and polarization-depolarization current (PDC) measurements [9]–[16] have gained significant importance over the last several years. The interfacial polarization spectrum (IPS) obtained from the RV measurement and the nature of the polarization and depolarization currents obtained from the PDC measurement are believed to be related to the aging status and moisture content of the insulation. However, the evaluation of the actual state of the insulation and the estimation of the transformer performance in further operation are complicated, and it is often necessary to consult experienced experts. This kind of expertise can only be developed over years of experience with the dielectric response measurements, and hence, are not readily available. Unless the heuristics of insulation condition assessment by these dielectric diagnosis techniques are well documented in a rule base and the diagnosis logic is made transparent to the end user, the controversies in judgement procedure due to human factors will continue to persist. In this context, application of a reliable expert system in transformer insulation condition assessment promises to provide a good alternative approach.

The uses of expert system (ES) for power system operations and insulation diagnosis have already been reported by several researchers [17]–[23]. These expert systems are based on the principle of the transmission of human expert knowledge into the system and using it with the same results as consulting the human experts. Many of these ES are used to evaluate diagnostic measurement data from commonly used offline diagnostic methods for the diagnosis of high-voltage insulation. The effectiveness of such an ES in emulating human heuristics, however, depends on the precision and completeness of human knowledge accumulated over the years.

In this paper, an expert system for transformer insulation diagnosis and management based on the aging mechanism of insulation system and service experiences is constructed. The proposed expert system tool aims at assisting the user to obtain unambiguous, reliable, and quick decision in insulation condition assessment of transformers using the RVM and the PDC techniques. By means of this expert system, even an inexperienced user is able to evaluate competently the state of the transformer insulation system and the equipment's behavior in further operations. The structure of the proposed ES and the essen-

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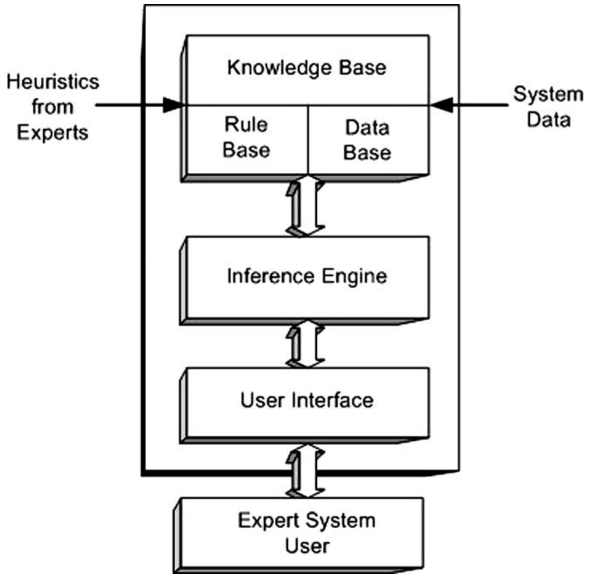


Fig. 1. Structure of the ES.

tial functions of its different components are described in detail. An example of application of the ES is presented to demonstrate that the system can provide reliable and effective insulation diagnosis.

II. EXPERT SYSTEM BACKGROUND

ES are a special branch of artificial intelligence (AI) where the human knowledge, experience, and expertise are coded into computer programs for solution of problems that follow heuristic logic. The biggest advantage of the ES lies in the fact that they enable even a nonexpert user to determine competently about the state of the insulation system and the insulation behavior in further operation without the necessity of consulting the matter with top experts.

An ES emulates the behavior of an expert essentially by the following major components [18]:

- knowledge base;
- inference engine;
- user interface.

The interrelation between the different components of an ES is demonstrated by Fig. 1.

A. Knowledge Base

Essentially, the knowledge base is the medium through which a human expert's knowledge is made available to the computer. Knowledge of the insulation systems, aging mechanisms, diagnostic tests, and inspection techniques and expertise in interpreting the results obtained from manufacturer, utilities, maintenance manuals, and human experts make up the knowledge base. The most common one is the rule-based system in which the expert knowledge is coded as a set of rules of thumb or "heuristics" in the AI jargon. The production rule contains the knowledge in the IF–THEN form and is stored in the *rule base*. In the present case, the rules used for insulation diagnosis of a transformer have been derived from a wide study of literature and the experience gathered by the authors during their past and current research in this field. The *database*, on the other hand, is comprised of information supplied by the user, past test records, and also information deduced by the system's inference mechanism. All information relevant to the diagnostic procedure, test, and inspection data are stored in the permanent database for diagnosing and trending purposes.

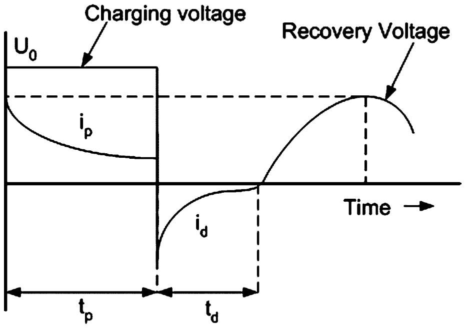


Fig. 2. Dielectric response measurement.

B. Inference Engine

The inference engine is developed to accurately model the behavior of a human expert. The inference engine uses the rules and available facts for reasoning. The inference engine is composed of two major units–the decision unit and the explanation unit. In the decision unit, the ES deduces logical conclusions by manipulating facts from the database and knowledge from the knowledge base by employing a suitable strategy. The inference engine of the ES actually performs the task of intelligent information manipulation to conclude about the state of the insulation system. Finally, the explanation unit generates the report with concluding remarks about the condition of the insulation and recommendations.

C. User Interface (UI)

This is the component, which actually brings about the interaction between the user and the system. Through the user interface (UI), the user can input the necessary data to the ES and also can obtain the results of the diagnosis procedure. The UI can be tailored according to the desire and need of the user.

III. DIELECTRIC RESPONSE MEASUREMENTS

For RVM, a direct voltage is applied across the dielectric for a long period of time and then it is short-circuited for a shorter period, after opening the short circuit, the charge bounded by the polarization will turn into free charges (i.e., a voltage will build up across the dielectric–known as the return voltage). The phenomenon is shown schematically in Fig. 2 [1], [2].

The peak value of the recovery voltage curve and its corresponding time instant are recorded. Then, the entire cycle of measurements is repeated with increasing charging and discharging periods until the maximum of the individual recovery voltage peaks is obtained. Then, the spectra of the maximum recovery voltage are plotted versus the corresponding charging times. The peak value of the RV spectra and the corresponding value of time (central time constant) are often the parameters used to assess the insulation condition from recovery voltage methods [1]–[8].

For PDC, the test object is charged with a direct voltage ($\mathrm{U_0}$) for a long period of time ($\mathrm{t_p}$) and then the voltage source is removed with the test object being short-circuited once again for a long time ($\mathrm{t_d}$). The polarization and depolarization currents ($\mathrm{i_p}$ and $\mathrm{i_d}$) are recorded during these charging and discharging periods, respectively. Typically, the charging and discharging periods are around 10 000 s each. From the values of the measured polarization and depolarization currents ($\mathrm{i_p}$ and $\mathrm{i_d}$), the oil conductivity and the paper conductivity can be estimated and studied to evaluate the oil condition and the paper condition in the insulation [9]–[16]. Equation (1) is used to calculate the conductivity in Siemens per meter (S/m)

$$\sigma = \frac{\varepsilon_O}{U_O \frac{C}{\varepsilon_r}} \left(i_{\mathrm{p}} - i_{\mathrm{d}}\right) \tag{1}$$

where the charging voltage is U_o, and ε_r is the effective relative permittivity of the composite oil-paper insulation system at power frequency. For accurate estimation of this effective permittivity, it is desirable to have correct and complete knowledge about the design and exact composition of the oil paper insulation system of the transformer. In most cases, however, information about the exact design and composition of the transformer insulation system is not readily available from the utilities. For most practical cases, it is sufficient to assume a series arrangement of paper/pressboard and oil duct of the transformer insulation system with around 20% paper and 80% oil [11]. ε_O is the permittivity of vacuum. C is the geometric capacitance measured between the two terminals of the insulation system under test. It can be measured with any capacitance measuring ac bridge at or around the power frequency. Thus, while calculating the conductivity from the polarization and depolarization currents, the geometry of the transformer and the relative amount of oil and paper are taken care of.

The oil conductivity is calculated from the initial values of the polarization and depolarization currents, whereas the paper conductivity is calculated from the final values of the polarization and depolarization currents. The magnitude of the polarization and depolarization currents and the values of the oil and paper conductivities are found to be dependent upon the moisture and aging condition of the insulation.

The knowledge of the relation between these RVM and PDC parameters and the moisture and aging status of the insulation system has so far been confined to a handful of researchers in this field. The evaluation of the actual state of the insulation and the estimation of the transformer's performance in further operation are complicated, and that is why it is necessary to consult experienced experts. For the techniques to be widely accepted as an effective tool for insulation diagnosis, it is mandatory that the evaluation criteria be made transparent to the user. This is where the proposed ES plays a significant role in making the insulation diagnosis; by making these dielectric diagnosis techniques more accessible for the end user rather than confining it to the research laboratories.

IV. CONSTRUCTION OF THE EXPERT SYSTEM

The flowchart of the transformer insulation diagnosis with the developed expert system is shown in Fig. 3.

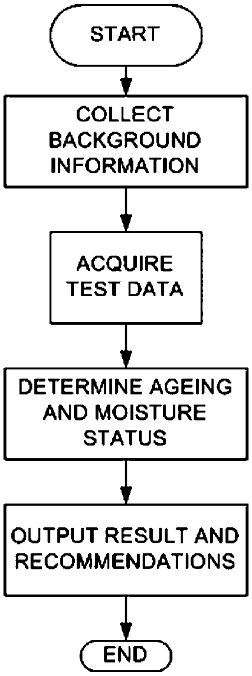


Fig. 3. Flowchart of insulation diagnosis by the expert system.

The first information required by the ES is the background information about the transformer, including nameplate information and operating history. As the results of the offline diagnostic tests are available, the ES can identify the general aging status and estimate the moisture content in the solid insulation. The ES then provides output reports, which can be saved and printed.

The expert knowledge encoded into the ES for diagnosis purposes has been gathered through the authors' own experience in this field over the past years and also from a wide survey of published literatures. It is an accepted fact now [12] that the RVM results alone are a complex convolution of several parameters including aging, moisture, temperature, and insulation geometry. Thus, assessment of the insulation condition by the RVM method, though considered to be straightforward, often needs extra attention. The most recent school of thought includes, in addition to the RVM, the polarization and depolarization current (PDC) measurement for assessment of the oil and the paper condition inside the transformer. The expert system presented in this paper thus combines the RVM and PDC techniques to come out with the final inference about the state of the insulation. The knowledge base of the developed ES thus includes the insulation diagnosis heuristics involving both the RVM and the PDC techniques.

A. RVM Knowledge Base

Bognar *et al.* [3] described an onsite dc testing method and apparatus for determination of the RV spectrum. According to them, the RVM is highly influenced by the water content of the oil impregnated paper insulation and the adsorption of different aging byproducts. They presented results for RV spectrum corresponding to different paper moisture contents as shown in Fig. 4. They observed that the central time constant tends to shift toward lower values as the paper moisture increases.

They also presented RVM results corresponding to different aged transformers. It depicted the fact that more aged trans-

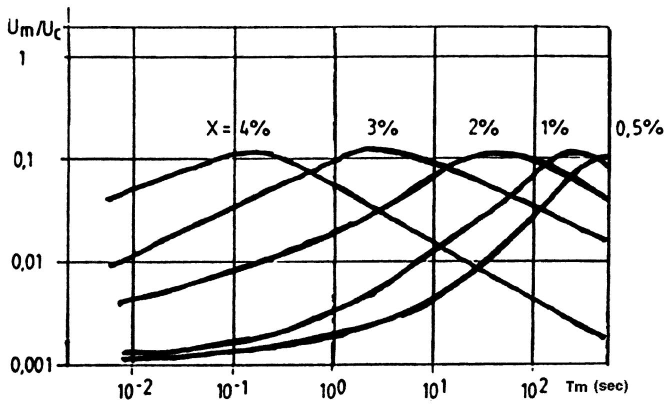


Fig. 4. IPS for oil/paper insulation system at different paper moisture contents.

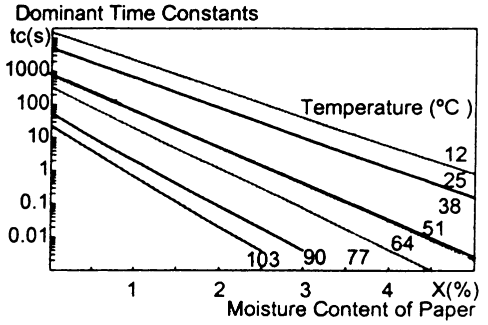


Fig. 5. Relation between dominant time constants and moisture content of paper.

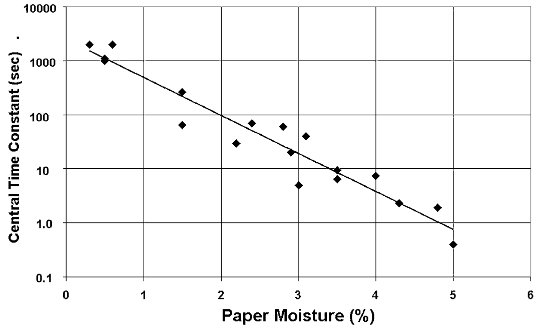


Fig. 6. Database of RVM used for the proposed ES.

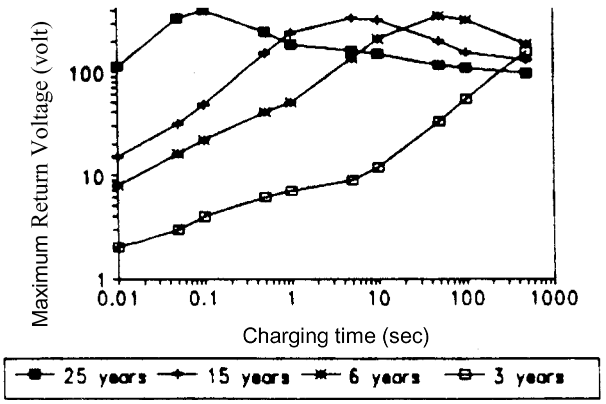


Fig. 7. Effect of aging on the IPS of oil/paper insulation system in transformers.

formers have lower values of central time constant. They also pointed out the temperature dependence of the RV spectra.

Csepes *et al.* [4] presented results on some fundamental laboratory experiments and also measurements on power transformers. They presented a relationship between the central time constant and the paper moisture content with temperature as a parameter, as shown in Fig. 5. As can be seen from Fig. 5, at a given temperature, the central time constant is inversely related with the paper moisture.

Similar nature of variation of central time constant of the RV spectra with the paper moisture was observed for the database used in the current study, as shown in Fig. 6. This database, containing the nature of variation of the central time constant with the paper moisture content, has been derived from the previous test results obtained by the authors during onsite and laboratory testing on actual transformers and also from different published articles and literature. Since the RVM is influenced by the operating temperature, the developed ES is based upon results obtained from tests carried at normal ambient temperatures.

The authors of [4] also reported that the central time constant drops down to lower values for aged insulation compared to new insulation.

In [5] and [6], Saha *et al.* described the investigation of insulation condition of a number of power and distribution transformers. They also presented results of RVM on accelerated aged test samples. They reported that RV spectra parameters vary significantly and consistently with the aging condition of the insulation system.

Yao *et al.* [7] described a moisture control experiment for studying the effect of paper moisture on recovery voltage parameters. They presented results of several paper wrapped test samples at different moisture levels and also full-size transformers of different aging levels and different moisture contents. They, however, concluded that the RVM results are convoluted with both the aging and paper moisture values–so care must be taken while interpreting the insulation condition from the RVM data.

Ghourab [16] described one neural network-based tool for insulation condition assessment from the RVM parameters. The paper demonstrated the effect of aging on the shape of the RV spectra, as shown in Fig. 7. The central time constants are found to be lower for transformers with higher aging.

The central time constant of the RV spectra is thus found to be dependent on the moisture content as well as on the aging condition of the insulation. From the measured value of the central time constant, it will thus be possible to have an estimate of the moisture and general aging condition of the insulation. There is other literature that has been published over the years presenting RVM results on transformers of different ages and different moisture contents. All of these results have been incorporated into the knowledge base of the proposed expert system to enrich its expert knowledge.

Several researchers [9], [12], [15], however, pointed out that the RVM peaks and the corresponding dominant time constants could not be considered as unique criteria for the moisture and aging assessment of pressboard material used in transformers. According to them, the conductivities of the oil and the paper have substantial influence on the shape of the dielectric response of the insulation. It is also known that the geometry of the insulation has some influence on the RV spectra [12]. Thus, the estimation of paper moisture content based only on dominant time

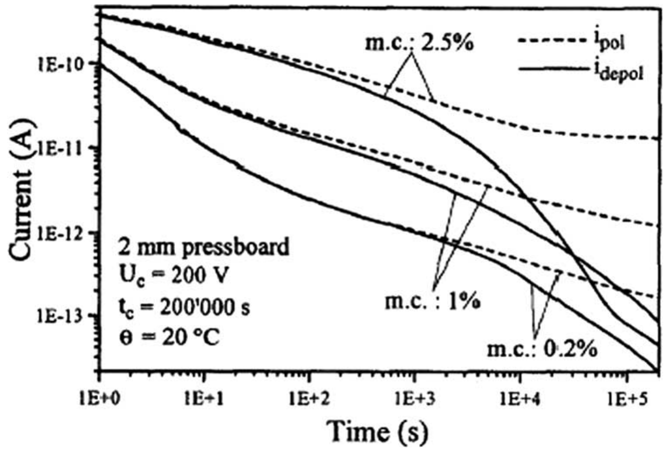


Fig. 8. Polarization and depolarization currents for pressboard with different moisture contents.

constant of the RV spectra is not totally appropriate [12]. This can be addressed by a proper modeling tool incorporated into the ES. The modeling work being carried out by the authors of this paper will be reported in a future paper to address this issue. However, PDC measurement can be used to separately estimate oil and paper conductivity [9]–[15]. The effect of geometry of the insulation can also be effectively taken care of during such estimations. Thus to alleviate the criticism of solely RV dominant time constant-based interpretation of insulation condition, the PDC interpretation scheme has been supplemented with the existing RVM-based interpretation scheme in the proposed ES. The rules and knowledge base for insulation condition assessment by the PDC interpretation technique is discussed in the following section.

B. PDC Knowledge Base

Houhanessian *et al.* [9] investigated the effect of oil and paper moisture and aging on the polarization and depolarization currents during the PDC measurement. Fig. 8 [9] is a plot of the polarization and depolarization current for the solid insulation with different moisture contents. Fig. 8 shows that the polarization and depolarization currents at larger times are sensitive to moisture content of the solid insulation. The higher the moisture content is, the higher will be the difference between the corresponding polarization and depolarization currents and their magnitudes will go up as well. Therefore, the conductivity of the paper calculated using (1) would be a good indicator of the moisture content in the solid insulation.

Gafvert *et al.* [10] also presented the correlation between the moisture content in the paper insulation and the nature of the polarization current–as shown in Fig. 9 [10]. They also reported the results of moisture and conductivity estimates from RVM and PDC tests on a series of aged transformers.

They also reported in [11], the dependence of the polarization and depolarization currents on the paper conductivity. Fig. 10 [11] displays the influence of paper conductivity on polarization current. The current values in Fig. 10 have been normalized by dividing with the charging voltage U_a and the geometric capacitance C_0.

It is observed from Figs. 9 and 10 that the polarization current behaves in the same way in response to moisture and conductivity of the solid insulation. Higher moisture/conductivity tends to increase the polarization current magnitude at longer times. A similar trend has been observed for the depolarization current as well. Conductivity calculated from the polarization and depolarization currents can thus be used as a good indicator for the moisture content of the paper insulation.

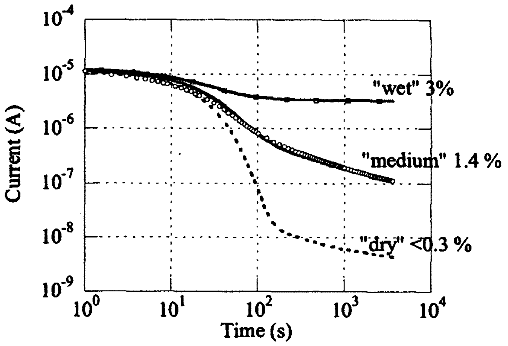


Fig. 9. Influence of paper moisture on polarization current.

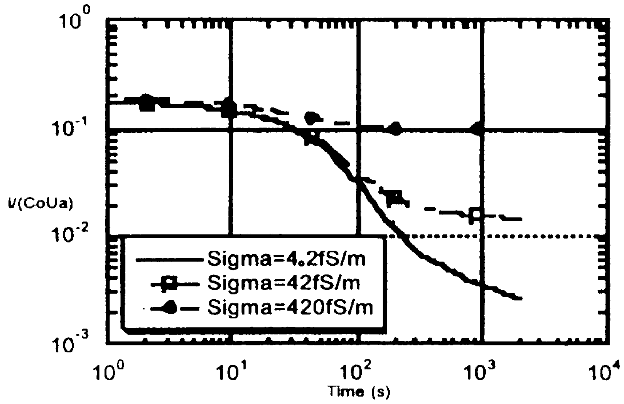


Fig. 10. Influence of paper conductivity on polarization current.

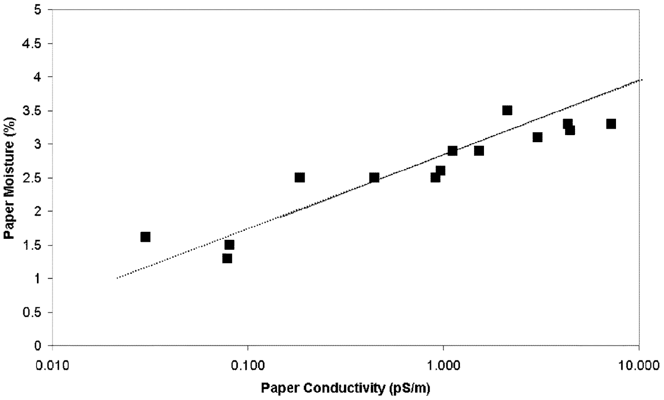


Fig. 11. Paper moisture versus paper conductivity.

Based on this observation, a database has been developed with paper conductivity versus paper moisture content. All of these data have been collected from the field and laboratory testing experience of the authors over the years, from the cited literature and also from other published articles and literature. Fig. 11 displays the relation between paper conductivity and paper moisture content, which has been used for the database of the expert system.

Dependence of the polarization and depolarization currents on the oil moisture/conductivity have been reported by several

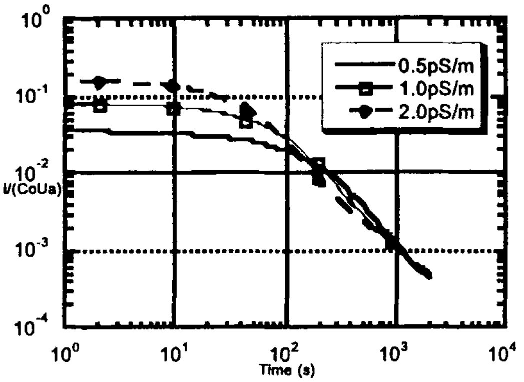


Fig. 12. Influence of oil conductivity on polarization current.

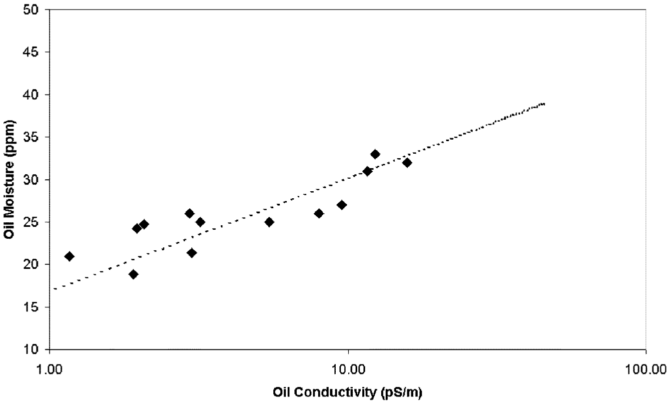


Fig. 13. Oil moisture versus oil conductivity.

researchers like Frimpong *et al.* [11], Hassig *et al.* [15] etc. It was demonstrated that the initial part of the polarization and depolarization currents are sensitive to the oil moisture/conductivity. A higher oil moisture/conductivity tends to increase the magnitude of the polarization and depolarization currents during the initial period. Fig. 12 [11] demonstrates the variation of polarization current with oil conductivity. The current values in Fig. 12 have been normalized by dividing with the charging voltage U_a and the geometric capacitance C_0.

The database for oil conductivity versus oil moisture content was developed, once again, from field and laboratory test results performed buy the authors over the years and also from several other published articles and literature. Fig. 13 is the plot for the relationship between oil conductivity and oil moisture content, which has been used for the database of the developed expert system.

The polarization and depolarization currents are once again very sensitive to the operating temperature. All of the test results that have been used for the database of the ES were conducted at normal ambient temperature.

The expert system thus can estimate the values of the oil and paper moisture contents using Figs. 11 and 13 after computing the oil and paper conductivities from the polarization and depolarization currents.

Effect of general insulation aging on the polarization and depolarization currents was reported by several researchers including [9]–[16]. The polarization and depolarization currents for aged transformers are normally higher in magnitude than those corresponding to a relatively new transformer. Fig. 14 [15] shows the polarization current plots for one new and another aged transformer.

It is thus possible for the developed expert system to infer about the general aging status of the insulation from the magnitude of the polarization and depolarization currents.

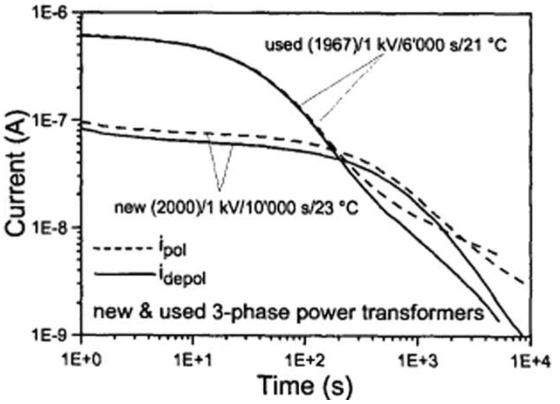
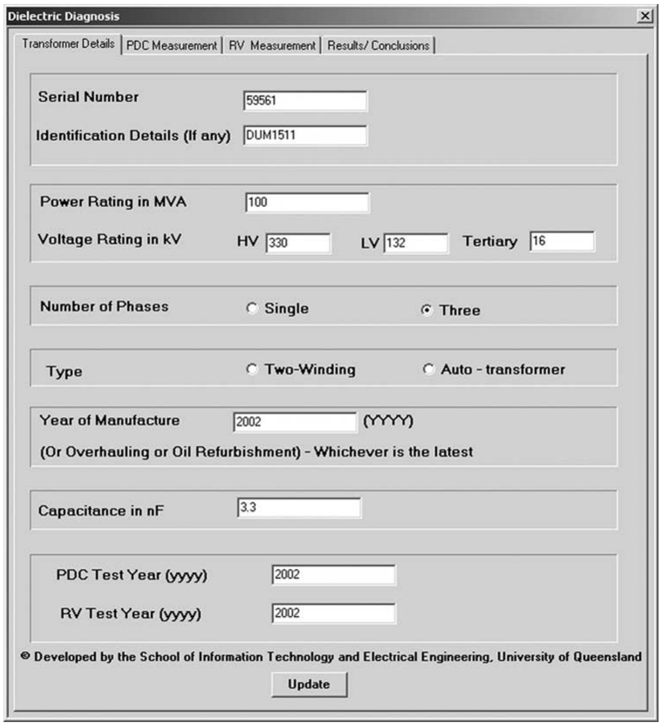


Fig. 14. Influence of aging on polarization and depolarization currents.



Serial Number: 59561
Identification Details (If any): DUM1511
Power Rating in MVA: 100
Voltage Rating in kV: HV 330 LV 132 Tertiary 16
Number of Phases: ○ Single ● Three
Type: ○ Two-Winding ○ Auto - transformer
Year of Manufacture: 2002 (YYYY)
(Or Overhauling or Oil Refurbishment) - Whichever is the latest
Capacitance in nF: 3.3
PDC Test Year (yyyy): 2002
RV Test Year (yyyy): 2002
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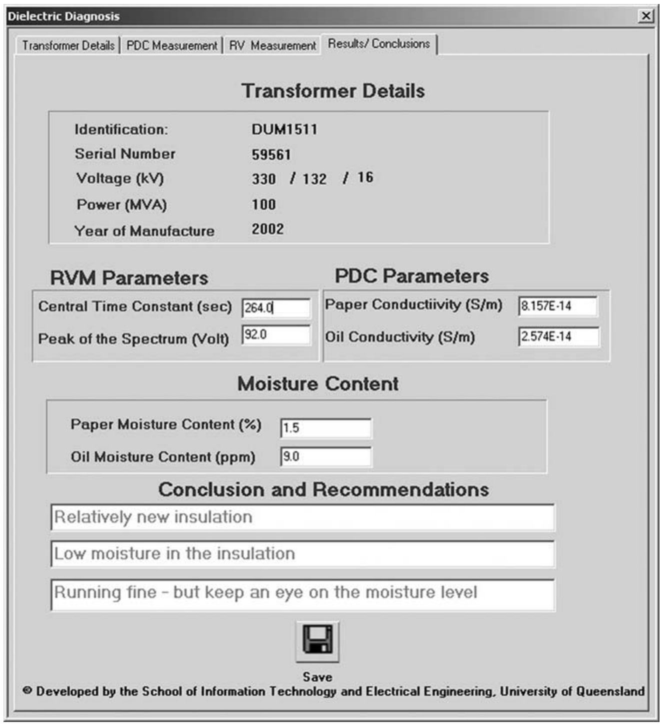
Fig. 15. Input window for background information.

V. Performance of the Developed Expert System

The performance of the ES developed in the present work is demonstrated here by insulation diagnosis performed on an aged transformer recently tested by RVM and PDC techniques.

Once invoked, the ES will ask for the transformer background information from the user. These include the serial number and other identification details of the transformer, its year of manufacture or maintenance/overhauling, its power and voltage ratings, capacitance, date of RVM and PDC tests, etc. The user interface for the input is shown in Fig. 15.



Transformer Details

Identification: DUM1511
Serial Number 59561
Voltage (kV) 330 / 132 / 16
Power (MVA) 100
Year of Manufacture 2002

RVM Parameters
Central Time Constant (sec) 264.0
Peak of the Spectrum (Volt) 92.0

PDC Parameters
Paper Conductiivity (S/m) 8.157E-14
Oil Conductivity (S/m) 2.574E-14

Moisture Content
Paper Moisture Content (%) 1.5
Oil Moisture Content (ppm) 9.0

Conclusion and Recommendations
Relatively new insulation
Low moisture in the insulation
Running fine - but keep an eye on the moisture level

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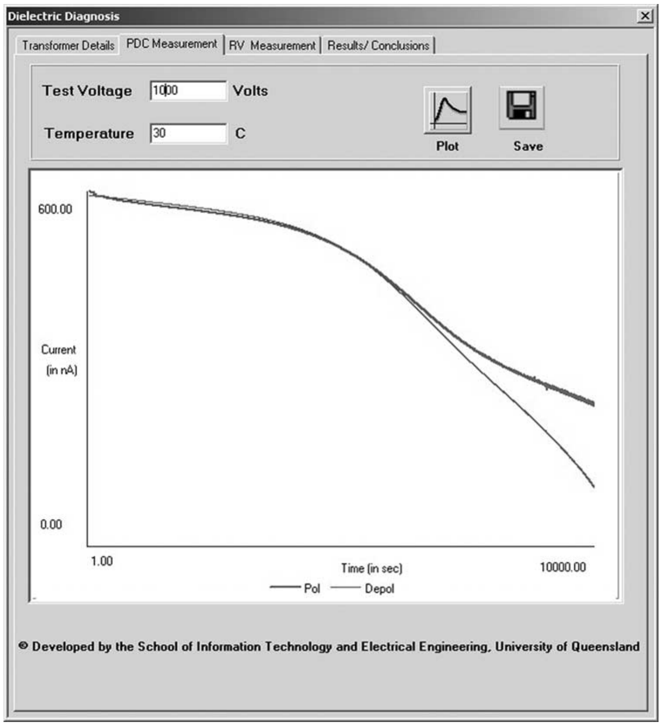
Fig. 16. Output and results display window.



Test Voltage 1000 Volts
Temperature 30 C

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Fig. 17. Display window for polarization and depolarization currents.

Once the transformer background information is fed to the database of the ES, its inference engine is commanded to perform the diagnosis procedure based on the RVM and PDC parameters including central time constant, oil and paper conductivity and aging and maintenance history of the transformer. The inference engine follows the basic flowchart as shown in Fig. 3 to arrive at its conclusion regarding the moisture content and aging status of the transformer. The paper moisture content values obtained independently from the RVM and PDC tests are combined together to output the paper moisture content value, whereas the oil moisture is displayed as the result obtained from the PDC test only. The general aging status of the insulation is once again a combined inference drawn from the RVM, PDC, and aging/maintenance history of the transformer.

The ES then displays the results of the estimate of moisture and aging status in the output display window as shown in Fig. 16. The ES also provides a general conclusion about the state of the insulation and recommends further necessary action.

In addition to this, the ES also has the provision for display of the RV spectra and the polarization-depolarization currents for viewing and easy reference. Fig. 17 shows a sample plot for the polarization and depolarization currents in the corresponding ES display window.

The performance of the developed ES is currently being evaluated for its accuracy and reliability by employing it for insulation diagnosis of transformers of different size, different moisture contents, and different aging conditions. So far, the ES has been exclusively tested on power transformers. The authors believe that after adequate measurement data are made available to the ES database, the same ES can be useful for other transformers as well. The following Table I show some preliminary results obtained from the expert system regarding moisture estimates of oil and paper from some transformers and also from some oil-paper test samples [7]. A reasonably good agreement is observed between the oil and paper moisture content values measured by Karl Fischer Titration method and estimated by the expert system.

TABLE I
(a) DESCRIPTION OF THE TEST OBJECTS (b) MEASURED AND ESTIMATED VALUES OF OIL AND PAPER MOISTURES

Test Object	Description
A	Aged and moist oil-paper laboratory sample
B	Aged and moist oil-paper laboratory sample
C	Aged and moist oil-paper laboratory sample
D	100 MVA old transformer
E	100 MVA transformer after oil refurbishment
F	30 MVA old transformer
G	45 MVA very old transformer

(a)

Test Object	Oil Moisture (ppm)		Paper Moisture (%)	
	Measured	Estimated	Measured	Estimated
A	17	20	2.5	2.5
B	33	32	3.5	4.0
C	25	22	3.0	3.0
D	32	33	4.0	4.0
E	10	9	1.5	1.5
F	26	23	3.0	3.0
G	36	39	4.0	4.0

(b)

The authors are currently working upon enriching the database with more test results. Future research in this field will be aimed at making the ES responsive to the effects of temperature on the dielectric response of the insulation system. Efforts will also be devoted for making the ES adaptive by enabling it to learn from new experiences. With research in the field of evolutionary computations, the prospects for the developed expert system look bright.

VI. CONCLUSION

Dielectric diagnosis techniques RVM and the PDC have been established as a nondestructive dielectric diagnosis technique for transformer insulation condition assessment for the last few years. However, its popularity has not been as well spread as anticipated due to the requirement of the expertise for its evaluation and analysis. The present paper aims at developing an expert system tool for transformer insulation condition assessment based on the RVM and PDC techniques. The proposed ES includes the knowledge gathered by field-test experience over the past years and also from a wide survey of published literature. The ES is demonstrated to perform insulation diagnosis in an effective and reliable manner. The ES is expected to be useful to even inexperienced maintenance engineers for quick and reliable insulation condition assessment of transformers based on the dielectric response measurements. Currently, the ES is under the process of incorporating more and more test results to strengthen the database and also efforts are being made to make the ES adaptive in nature.

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