A FUZZY-LOGIC APPROACH TO PREVENTIVE MAINTENANCE OF CRITICAL POWER TRANSFORMERS

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ABSTRACT
In this paper, a predictive method for the diagnosis of power transformer failures is presented. The approach is based on the interpretation of Dissolved Gas Analysis (DGA) data using Fuzzy Logic.

INTRODUCTION
This paper focuses on methods that are based on the consideration that insulating organic compounds (cellulose paper and oil) produce gas when subjected to thermal and electric stress. Most gases originate in insulating oil and their composition is influenced by temperature.

In particular, in this paper, a predictive method for the diagnosis of power transformer failures is presented. The approach is based on the interpretation of DGA data using Fuzzy Logic (FL). The proposed diagnostic method adopts indicators related to the ratios $\frac{C_2H_4}{C_2H_6}$, $\frac{C_2H_2}{C_2H_4}$, $\frac{CH_4}{H_2}$ and to the concentration of specific gases such as hydrogen, carbon monoxide, methane, ethane, ethylene, acetylene [1][6].

DISSOLVED GAS ANALYSIS
Dissolved Gas Analysis (DGA) is one of the most commonly adopted diagnostic method for detecting and evaluating faults in electric devices. Related technical guides, derived by practical experiences and examination of a large machine number, can be found in [7]. These guides concern electric devices filled with insulating oil and solid insulation (paper or cellulose paperboard) and describe how dissolved or free gas concentration can be interpreted in order to diagnose machines conditions.

Faults
Through the data collected during internal inspections of a large number of machines, the IEC Technical Committee 10 (TC-10) has classified the faults that can be detected by gas analysis [11]:

- partial discharges (PD) that connect conductors only partially through insulation system (low temperature plasma discharges);
- low-energy discharge (D1) in oil and/or paper due to the flow of electricity through the disrupted insulation;
- high-energy discharge (D2) in oil and/or paper with high current level; this fault is usually accompanied by large disruptions, burns and device shutdown;
- thermal faults due to overheating of the insulation.

Typical values of gas concentrations
Gassing is a ordinary phenomenon due to aging of any transformer. If gas concentration is under a certain limit, it is considered as a “typical gas pattern”. For each gas, the typical value represents the limit value under which it is reasonably possible to exclude the presence of anomalies. These values are based on operating practices and are usually evaluated considering that only the 10% of transformer population exceeds such without exhibiting anomalies. These typical values for the 90% of the transformer population are defined as 90 percentile typical values. These values are usually adopted for deciding if a more frequent monitoring of gas is necessary in order to prevent a possible fault.

Table I represents the 90 percentile typical values for industrial transformer and for generic power transformers.

<table>
<thead>
<tr>
<th>GAS</th>
<th>Industrial transformer [ppm]</th>
<th>Power transformer [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$</td>
<td>200</td>
<td>60-150</td>
</tr>
<tr>
<td>CO</td>
<td>800</td>
<td>400-850</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>6000</td>
<td>5300-12000</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>200</td>
<td>35-130</td>
</tr>
<tr>
<td>$C_2H_2$</td>
<td>150</td>
<td>50-70</td>
</tr>
<tr>
<td>$C_2H_6$</td>
<td>200</td>
<td>110-250</td>
</tr>
<tr>
<td>$C_2H_4$</td>
<td>&lt; 1</td>
<td>80-270</td>
</tr>
</tbody>
</table>

Table I: Typical gas concentrations for industrial or power transformers

Indicators
On the basis of the above mentioned processes and experimental results collected by several researches, it is possible to give an interpretation of gas concentration measurements. In particular, the IEC Technical Committee 10 (TC 10) has based its statistics on data collected all over the world (about 10,000 transformers, operating in 15 different power grids). By following an approximate approach, as shown in Table II, it is possible to associate the presence of certain gases with the onset of a specific fault. European and American norms, after decades of observations, have identified certain ratios that permit to give a more reliable interpretation of fault nature [13-14].
Faults in gas vacuole | High energy Discharges | Overheating
---|---|---
Hydrogen Methane Ethane | Acetylene Hydrogen Ethylene others | Ethylene Ethane Methane Hydrogen
Carbon oxides (CO e CO₂) for cellulose decomposition

Table II: Main faults categories according to more important gases

These ratios are:

\[
R_1 = \frac{CH_4}{H_2} \quad R_2 = \frac{C_2H_2}{C_2H_4} \quad R_3 = \frac{C_2H_4}{C_2H_6} \quad R_4 = \frac{C_2H_2}{C_2H_4} \quad R_5 = \frac{C_2H_4}{C_2H_6}.
\]

According to the IEC approach, Italian Comitato Elettrotecnico Italiano C.E.I. (Italian Electrical Committee) Standards adopts the Rogers ratios (RR) in order to identify possible faults (R1, R2 and R5). These ratios must be calculated whenever, for any of monitored gases, there is a violation of concentration threshold or a steep rising rate.

**DIAGNOSTIC MODEL BY MEANS OF FUZZY LOGIC**

The proposed diagnostic method can take advantage of historical data series obtained by several studies on transformers. This method uses as indicators hydrogen, carbon monoxide, carbon dioxide, methane, ethane, ethylene, acetylene, and the ratios \(\frac{C_2H_4}{C_2H_6}\), \(\frac{C_2H_2}{C_2H_4}\) and \(\frac{CH_4}{H_2}\) [15-17].

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No faults</td>
</tr>
<tr>
<td>2</td>
<td>Low-energy partial discharge</td>
</tr>
<tr>
<td>3</td>
<td>High-energy partial discharge</td>
</tr>
<tr>
<td>4</td>
<td>Low-temperature thermal fault (T &lt; 150°C)</td>
</tr>
<tr>
<td>5</td>
<td>Low-temperature thermal fault (150°C &lt; T &lt; 300°C)</td>
</tr>
<tr>
<td>6</td>
<td>Medium-temperature thermal fault (300°C &lt; T &lt; 700°C)</td>
</tr>
<tr>
<td>7</td>
<td>High-temperature thermal fault (T &gt; 700°C)</td>
</tr>
<tr>
<td>8</td>
<td>Low-energy electric discharge</td>
</tr>
<tr>
<td>9</td>
<td>High-energy electric discharge</td>
</tr>
<tr>
<td>10</td>
<td>Paper involved in fault</td>
</tr>
</tbody>
</table>

Table III: Type of faults

In order to describe the concentration associated with each of the six gases assumed as fault detectors, the fuzzy set \(U_3 = \{L, M, H\}\) has been defined. The state L, M or H is referred to low, medium, or high concentration of each gas. The membership functions that links states L, M, and H to gas concentration level were developed according to International and European standards. As an example the membership functions of hydrogen concentration is shown in Fig. 2. Similar behaviour are exhibited by the other 5 gases.

Figure 3 shows graphically the further step that was made in the development of the proposed model: for each state (0, 1 or 2) of each Rogers ratio, a characteristic function that associates such state with the selected faults is defined.

In Fig. 3 (\(\frac{C_2H_2}{C_2H_4}\)), the Roger ratio R2 is represented. The state 0 (R0) is characterized by a high membership degree with respect to faults 1, 2, 4, 5, 6 and 7. The membership degree is low with respect to fault conditions 3, 8, 9 and 10.

The state 1 (R1) is characterized by high correlation only with faults 3, 8, and 9, whereas the state 2 (R2) has a strong correlation only with faults 8 and 9. The same considerations apply to Rogers ratios R1 and R5 which are omitted for brevity.

Table IV: Type of fault detectors
The same step is repeated for gas concentration parameters. For each state L, M or H of each gas a characteristic function that correlates such state with the selected faults is defined. Thus, it is possible to take into account key-facts like corona faults, overheating and discharge arcs characterized by a high concentration of hydrogen, ethylene and acetylene or the presence of carbon monoxide which is a signature of paper involvement in the fault.

![Fig. 2: Hydrogen membership function](image)

![Fig. 3: Correlation between R2 and fault conditions](image)

In this way, each gas has a function that describes its correlation with the fault. Usually, ethylene, methane and ethane play a principal role in detecting thermal fault, whereas acetylene gives the last word in detecting high energy discharges. An example of correlation between gas concentration and fault is shown in Fig. 4. Of course similar correlations have been defined for the other five gas-based fault detectors.

The next step consists in defining a fuzzy vector \( F_C \) whose elements are the values assumed by the membership functions in correspondence with input data (the three ratios and the six gas concentration levels).

In the formulation of \( F_C(k) \), \( w_i \) denote the k-th hypothesized fault weight given to the \( F_C \) vector element. Once \( F_C \) has been evaluated on the basis of actual testing data, this vector needs to be compared with a similar reference vector \( F_R(k) \) which represents the typical values experienced by the k-th fault selected among the ten major faults listed in Table III.

\[
F_C = \begin{bmatrix}
w_H L^0 & w_H M^1 & w_H H^2 & w_M L^0 & w_M M^1 & w_M H^2 & w_L L^0 & w_L M^1 & w_L H^2 \\
\end{bmatrix}
\]

The characteristic functions \( F_R(k) \) have been obtained as a result of a large consultation of numerous experienced operators and users and by the reference analysis over 800 test cases. The comparison between \( F_R(k) \) and \( F_C(k) \) is performed in terms of dot product and the result is normalized with regard to the norm of the reference vector. The procedure can be summarized as follows:

1. Calculate on the base of the test data the characteristic Rogers ratios \( C_{H2}/H_4 \), \( C_2/H_4 \) and \( C_2/H_2 \) and input gas concentrations;
2. Define the fault characteristic vector: \( F_C = [\mu 1, \mu 2, \ldots, \mu n] \) adopting the membership functions;
3. Evaluate through the scalar product \( F_P(k) = F_R(k) * F_C(k), k = 1, 2, \ldots, 10 \);
4. Evaluate the proximity of each incipient fault: \( F(k) = \frac{F_P(k)}{T(k)} \);
5. Detect the prevalent and/or the most likely fault type by:
   \( F_d = \max\{F(1), F(2), \ldots, F(10)\} \).

**TEST CASE**

The proposed diagnostic methodology was implemented for the maintenance scheduling of four power transformers.
installed in a petrochemical plant.

The transformers under study are four double secondary winding transformers for converters supplying, rated in the range 6-18 MVA, with insulating oil (ONAN), and 13.2/6.2 kV voltage rates.

Due to operating conditions, the four power transformers under investigation are characterized by early ageing. Failure or breakdown of such transformers may have catastrophic consequences (i.e. explosion of the transformer).

In order to apply the proposed diagnostic model, membership functions were suitable “tuned” taking into account typical values of gas concentration for this type of transformer.

The entire fuzzy model was developed with the Matlab® Fuzzy Logic Toolbox that takes advantage of a simple but powerful graphic interface. This method was applied to historical data series, analyzing transformer conditions since 03/03/1997 up to 12/03/2003. Sample data for gas concentration and Rogers ratios are referred to a single transformer and a testing campaign performed in 04-19-2002. The implementation of such data in the described fuzzy model permitted to evaluate the elements of the $F_c$ vector, shown in Table V.

### Table V

<table>
<thead>
<tr>
<th>#</th>
<th>Ratios</th>
<th>$\mu_1H$</th>
<th>$\mu_2H$</th>
<th>$\mu_3H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_2H_2/C_2H_4=0.04$</td>
<td>0.998</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>$CH_4/H_2=7.47$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>$C_2H_6/C_2H_4=0.04$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>#</td>
<td>Gas (ppm)</td>
<td>$\mu_1H$</td>
<td>$\mu_2H$</td>
<td>$\mu_3H$</td>
</tr>
<tr>
<td>4</td>
<td>$H_2=34$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>$CH_4=254$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>$C_2H_6=28$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>$C_2H_6=726$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>$C_3H_8=1$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>CO=623</td>
<td>0</td>
<td>0.99</td>
<td>0</td>
</tr>
</tbody>
</table>

Table V. $F_c$ vector

Applying the proposed procedure we obtain:

$$F_1 = \max\{0.1, 0.225, 0.237, 0.4, 0.5, 0.4, 0.4, 0.09, 0.06, 0.3\} = 0.5;$$

indicating the presence of a thermal faults with temperatures ranging in the interval 150-300°C. The value of $F_1(10)$ can also suggest that cellulose can be involved in the fault.

An inspection of the internal parts of the transformer (windings, oil, paper insulation) confirmed the diagnosis; in particular, the internal parts of the transformer were blackened and the insulation paper looked liked a “rusk”, meaning that the transformer was operated at high temperatures for a longer time. Thus, the method proved to be effective in estimating the severity of incipient faults.

### CONCLUSIONS

One last remark about proposed diagnostic methodology, based on results interpretation by means of fuzzy logic. This diagnostic approach does not replace the important role of experienced technical operators, but it could be an efficient tool to improve the capacity to correlate many different data. The diagnostic tool, suitable for this particular application, allows to implement procedures for preventive maintenance, taking into account specific needs of industries characterized by a critical process.

### REFERENCES


