WINDING CIRCUIT ANALYSIS TECHNIQUES
FOR PREDICTIVE MAINTENANCE

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Abstract: This paper describes a method of using circuit analysis techniques as a non-destructive trouble-shooting tool in predictive maintenance of electrical devices.

I. INTRODUCTION

Winding Circuit Analysis - using readings of resistance, impedance, inductance, phase angle, I/F and insulation resistance - provides an outstanding and non-destructive troubleshooting tool. In addition, it has been shown that comparisons of these readings between like coils, transformers, AC and DC motors allow the user to set upper and lower control limits [1, 2]. By applying the same concept to existing electrical machines, periodic testing can be performed and trended.

The purpose of this paper is to demonstrate the application of Winding (Motor) Circuit Analysis (MCA) techniques to Predictive Maintenance (PdM) for AC/DC motors, transformers and motor rotors. Several new concepts shall be presented including: MCA AC rotating machine trending; the EMCAT™ Rotor Grading System™ (RGS) for rotor analysis and trending; Transformer trending; and, DC motor trending and analysis. In each case, a definition of schedule-able findings and immediate action findings shall be described.

A. Trending Fault Descriptions

The limits to PdM testing using MCA are limited only to the range of the instrument, and are not dependant upon equipment size and voltage ratings. While it is true that a direct short in medium voltage equipment (above 600 Volts) develops and fails rapidly, the symptoms that lead up to the direct short are often seen well in advance of the failure. In reality, the detection of these faults depends upon frequency of testing and how the data is trended. It is the same as if the statement, “Once a bearing begins to come apart, it will do so rapidly, too rapidly to detect using vibration analysis,” were to be discussed. This would be a true statement if vibration analysis was unable to detect the degradation of the bearings over time. However, we all know that vibration analysis is highly accurate in long-term trending of bearing failure. It is the same with MCA, infrared, and most other PdM tools.

There is a simple secret to trending MCA test results: Comparison. The actual value of the data collected can be used for comparing equipment to each other and to set upper and lower control limits for manufacturing and acceptance testing. For trending and analysis purposes, MCA is a comparative tool using percent unbalance and difference between tests methods.

In the percent unbalance method, the difference between like coils (ie: between the phases in a three phase motor) is trended over time. This method is best for resistance, impedance and inductance. While resistance values are impacted by temperature, for instance, the relative difference between phases is not. By using the percent unbalance method, the user or software does not have to rely upon performing temperature correction calculations. Impedance and inductance are not significantly impacted by temperature. However, the unbalance method is the most convenient way of detecting faults over time. The limits are more visual than numerical: Graphical trending of the percent unbalance should not change visibly over time. An abrupt change in a graph indicates that a fault is occurring and must be addressed immediately. A slight change over time indicates that a fault is being trended and must be considered on a schedule (ie: next shutdown). Changes to the resistive unbalance normally indicate that connections are becoming loose. When inductance and impedance unbalance are due to rotor position (in a three phase motor this indicates a 'good winding') the relative unbalance will show similar values (ie: L = 11%, Z = 12% vs. L = 5%, Z = 50%). If the relative unbalance values between L and Z separate, this indicates a breakdown in electrical insulation over time and should be addressed.

The difference between tests method is used for phase angle, I/F and insulation resistance. In the case of phase angle (Fi) and I/F, changes over time in excess of two digits of difference between phases indicates a severe winding fault. This type of detection is an indicator of a breakdown of insulation between turns or coils in the windings. For instance,
if the Fi trends between 0 and 1 difference between readings and the I/F trends between 1 and 2 difference between readings, a sudden change to Fi = 3 and I/F = 4 would indicate a significant fault has occurred between conductors or coils. In the case of insulation resistance, any change within the range of the MCA device indicates a degradation of insulation between windings and ground.

B. AC Rotating Machine Testing

AC rotating machinery can be trended over time using simple graphical methods. As shown in Figure 1, an abrupt change to readings will indicate that a severe fault is occurring and must be addressed.

![Figure 1 AC Trend Test](image1)

In this case, the impedance, inductance, phase angle and I/F readings have each changed drastically. If this motor is still in operation, it should be replaced immediately. Readings that require scheduled repairs will gradually change from green to yellow then to red. This would represent a change in readings as shown in Table I.

![Table I. Reading Change Table for AC Rotating Equipment](image2)

<table>
<thead>
<tr>
<th>Reading</th>
<th>Change from Baseline</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, Z, L</td>
<td>&lt; 3%</td>
<td>Green</td>
</tr>
<tr>
<td>R, Z, L</td>
<td>&gt; 3% &lt; 5%</td>
<td>Yellow</td>
</tr>
<tr>
<td>R, Z, L</td>
<td>&gt; 5%</td>
<td>Red</td>
</tr>
<tr>
<td>Phase Angle, I/F</td>
<td>&lt; 1 pt</td>
<td>Green</td>
</tr>
<tr>
<td>Phase Angle, I/F</td>
<td>&gt; 1 pt &lt; 3 pt</td>
<td>Yellow</td>
</tr>
<tr>
<td>Phase Angle, I/F</td>
<td>&gt; 3 pt</td>
<td>Red</td>
</tr>
</tbody>
</table>

These scores are trendable and may be compared over time by setting a baseline and performing periodic comparisons to the baseline. Changes by more than 5 points RGS indicate rotor faults are occurring. The faults detected by RGS include: Eccentric rotor; Broken rotor bars; Large casting voids; and, Rotor fractures.

C. Rotor Grading System (RGS)

The RGS represents a special, trend-able method for performing an initial evaluation of the condition of a rotor. The system is based upon the relative average difference of each rotor test sinusoidal waveform from each other. Points are scored for deviation from the average, with higher scores indicating higher deviation. Because some motors do not produce a sinusoidal waveform, a rotor signature that shows a higher score than found in Table II should be compared to rotor test signature tables.

![Table II. Rotor Grading System Scores](image3)

<table>
<thead>
<tr>
<th>Score</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5</td>
<td>Good</td>
</tr>
<tr>
<td>&gt; 5, &lt; 15</td>
<td>Poor, Compare to Tables</td>
</tr>
<tr>
<td>&gt; 15</td>
<td>Severe, Compare to Tables</td>
</tr>
</tbody>
</table>

D. Transformer Trending

Transformer trending is similar to AC rotating machine testing. The primary difference is that the test tolerances are less forgiving. In the case of an electric motor, the turns ratio between the stator windings and rotor windings creates a minimal unbalance that must be compensated for. In the case of a transformer, tested per IEEE Standards 388 and 389 with an MCA test device, the relative turns ratio...
from phase to phase should have an imperceptible difference. Therefore, the tolerances are as shown in Table III.

### Table III. Transformer Tolerances

<table>
<thead>
<tr>
<th>Reading</th>
<th>Change from Baseline</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, Z, L</td>
<td>&lt; 1%</td>
<td>Green</td>
</tr>
<tr>
<td>R, Z, L</td>
<td>&gt;1%, &lt; 3%</td>
<td>Yellow</td>
</tr>
<tr>
<td>R, Z, L</td>
<td>&gt; 3%</td>
<td>Red</td>
</tr>
<tr>
<td>Phase Angle, I/F</td>
<td>&lt; 1 pt</td>
<td>Green</td>
</tr>
<tr>
<td>Phase Angle, I/F</td>
<td>&gt;1 pt &lt; 2 pt</td>
<td>Yellow</td>
</tr>
<tr>
<td>Phase Angle, I/F</td>
<td>&gt; 2 pt</td>
<td>Red</td>
</tr>
</tbody>
</table>

E. DC Motor Trending

Direct Current electric motors can only be evaluated by trending test results over time, when data is collected from the drive. In the case of trending a DC motor, the shunt fields (shunt and compound motors) are performed as one reading and the armature (all DC motors) as one reading. The key to trending a DC armature, in particular, is that the complete circuit is evaluated through the armature circuit. In order to evaluate the condition of the armature, for troubleshooting, a bar-to-bar test must be performed using impedance. In order to trend, all readings are compared periodically.

The changes from reading to reading are evaluated in the same method as an AC electric motor from reading to reading. Changes between the field and armature from the baseline reading should not exceed the values shown in Table I.

### III. CONCLUSION

MCA systems can be used to perform non-destructive in-place trending of electrical machines for predictive maintenance programs. MCA is capable of trending AC and DC rotating equipment, AC motor rotors and transformers. Limits can be set for changes between tests in order to determine, if changes occur, the severity of the change and how soon action must be performed.

### REFERENCE


Howard W. Penrose, Ph.D is the General Manager of ALL-TEST Pro, a Division of BJM Corp, a manufacturer of Motor Circuit Analysis equipment. He has over 15 years in the electric motor and reliability industry starting as an electric motor repair journeyman in the US Navy to leading Motor System Maintenance and Management programs within the industry for service companies, the US Department of Energy, utilities, states, and many others. Dr. Penrose spent over a year with the University of Illinois at Chicago teaching Industrial Engineering and performing energy, reliability, waste stream and production industrial surveys in a variety of industrial facilities as part of the UIC Energy Resources Center. Dr. Penrose is the Treasurer of the Connecticut Section of IEEE, a past Chair of the Chicago Section of IEEE, past Chair of the Chicago Section IEEE Power Electronics and Dielectrics and Electrical Insulation Societies, has numerous published research papers and books, and is a trained vibration analyst, infrared analyst, and motor circuit analyst.