Low voltage motor testers provide a variety of tests, some of which may be very useful. However, on an internet predictive maintenance bulletin, board, it was claimed that (under certain assumptions) degrading motor turn insulation could be detected based on dramatic changes in phase to phase impedance measurements, resulting from dramatic changes in capacitance associated with the degradation.

A working paper (ref (1)) was posted to support this claim. Ref (1) described two cases: case 1, representing a normal/healthy case; and case 2, representing localized degraded turn insulation. Table 1 shows the dramatic results claimed in Ref (1).

<table>
<thead>
<tr>
<th></th>
<th>Case 1 (normal)</th>
<th>Case 2 (degraded)</th>
<th>Factor change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>2.12667E-11 F</td>
<td>4.56647E-14 F</td>
<td>Decrease by factor of 450</td>
</tr>
<tr>
<td>Impedance (400hz low voltage measurement)</td>
<td>203 (ohms)</td>
<td>8710 (ohms)</td>
<td>Increase by factor of 40</td>
</tr>
</tbody>
</table>

Ref (1) includes the following assumptions:
- Resistive effects are neglected.
- Capacitance to ground is neglected

The author of the working paper clarified during the discussion that even though case 2 was referred to as a "shorted turn", there is no actual short or resistive path. The change in reported impedance is due solely to change in capacitive effects. The author cites relative dielectric constants of various materials: 4.1 for resin, 2.5 for enamel, and 2.6 for carbon black. The carbon black is discussed in the context of simulating the change in dielectric constant which might occur following tracking. And again only its dielectric (not conductive) properties are described. The only logical conclusion one can draw is that the claimed change in reported capacitance and impedance are supposed to result from the change in dielectric constants of the materials.

Although the variation among the dielectric constant of the materials mentioned is only a factor of 4.1/2.5 ~ 1.6, we will generously allow that the dielectric constant might change by up to a factor of 4.

I think most readers would suspect that if we change the dielectric constant of a single component of the insulation system by a factor of no more than 4, it is not likely that the total equivalent capacitance seen at the motor terminals would change by a factor of more than 4, and so the change by a factor of 450 is immediately suspect. But we want to know more specifically how much of a change is expected under various scenarios. So we will perform our own analysis of this case and several other scenarios of interest.
Analysis:
For purposes of my analysis, capacitances within the motor will be combined into a single equivalent capacitance in parallel with the motor inductance by use of the "energy method" which is described and justified in Appendix 2. This requires knowledge of not only the motor geometry and dielectric characteristics, but also the voltage distribution. The voltage distributions for the scenarios of interest in this paper were solved using the Matlab and the associated FEMM toolbox. The single Matlab language program included in Appendix 7 created all of the results reported in this paper. The input parameters can be changed between runs to change the system being modeled. Each run of the Matlab program generates a text file with a unique 8-digit run number that documents the input parameters and output results for the program. These text files associated with all of the results in this paper are also included in Appendix 6.

Once we know the voltage distribution, we can find the total capacitive energy stored in the motor by integrating the energy density

Equation 1

\[ dW = 0.5 * \varepsilon_r * \varepsilon_0 * E^2 \text{ dVolume} \]

Where

- \( dW \) is differential energy element
- \( \text{dVolume} \) is differential volume element
- \( \varepsilon_r \) = relative dielectric constant.
- \( \varepsilon_0 \) = dielectric constant of a vacuum
- \( E = \text{Grad}(V) = \text{Electric Field} \)

More specifically, when applied to volumes which are assumed axially uniform, we substitute \( \text{dVolume} = \text{dL} * \text{dA} \) and solve the two-dimensional problem and find the energy per unit length

\[ \frac{dW}{dL} = 0.5 * \varepsilon_r * \varepsilon_0 * E^2 \text{ dA} \]

Now we can see that to find the total energy, we integrate \( 0.5 * \varepsilon_r * \varepsilon_0 * E^2 \) over the area of the two-dimensional solution and then multiply by length to find the total stored energy. Once the total energy is known, we can compute the equivalent capacitance as suggested in attachment 1 using:

\[ C_{eq} = 2 * \frac{W_{total}}{V_s^2} \]

When multiple FE simulations are to be combined corresponding to different parts of the motor (endwinding and slot), the equivalent approach carried out in this paper is to determine an equivalent capacitance for each part, and then add the individual equivalent capacitances to find the final equivalent capacitance for the entire motor.

Input Parameters and assumptions:
The following parameters were taken from ref (1) and used in all of the calculations:

- \( \varepsilon_r = 4.1 \) for resin
- \( \varepsilon_r = 2.5 \) for enamel
- \( R_c = \text{Radius of conductor} = 0.55 \text{ mm} \) (corresponds to 18 AWG)
- \( T_e = \text{thickness of enamel} = 0.6 \text{ mm} \)
- \( T_r = 0.5 \text{ mm} = \text{thickness of resin between enamel at closest point of approach between adjacent conductors} \)
- Test frequency: 400hz
- Stator slots – 36
• 20 turns per coil
• Core Length – 0.08 m
• End Turn Length – 0.13 m
• Total turn length: $2 \times 0.08 + 2 \times 0.13 = 0.42\text{m}$
• Phase to phase measurement
• Neglect all resistive effects

Additional Parameters and Assumptions were added as follows:
• The resin extends for distance $T_l=0.5\text{mm}$ ($T$ stands for thickness, $l$ stands for liner) past the enamel on the outer turns in a coil before transitioning to air (scenario 1) or ground (scenarios 2, 3, 4).
• No capacitive effects between coils (neglect effects of two coils in same slot).
• 20 volt measurement amplitude (does not affect the capacitance or impedance results).
• Coils are wound one-in-hand (one strand per turn).
• Single Circuit Wye Connection
• 12 coils per phase
• Therefore phase to phase measurement involves $2 \times 12 = 24$ coils
• 20 conductors per coil are arranged in a regular rectangular geometry: 4 turns across and 5 turns tall. The electrical position of the turns within the coil is as described in Table 2. The turn number indicates the electrical position within the coil, the location on the table reflects the physical position within the coil.

<table>
<thead>
<tr>
<th>Turn Number</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Electrical Turn numbers within a coil, arranged to show actual physical location within the coil

Thus we see that vertically adjacent turns see 4 times the voltage difference of horizontally adjacent turns. It is recognized that a random wound motor may contain substantial random variability in the positioning of the turns within coils of a random wound motor, but for simplicity, a regular repeating pattern was chosen.

"Generous" Assumptions:
When faced with uncertainty in selecting parameters of the calculation, we have to make assumptions. I will use the term "generous assumptions" throughout this paper to denote scenarios when the selection of assumption is intended to maximize the extent of the capacitive changes relative to the normal capacitive system and relative to the inductive current.

Three generous assumptions are made right off the bat:

• All turn faults ¹ will be added between vertical turn pairs which see the higher voltage stress than the horizontal turn pairs. This results in a larger change in capacitance (16 times as high as we will see later in Appendix 2).
• As previously stated, ref (1) mentions carbon black with a dielectric constant of 2.6 as representative of a fault (degraded) condition, but we will use a relative dielectric constant of 1.0 as representative of the fault/degraded condition. Since the dielectric constant of the resin is 4.1, we naturally expect

¹ Throughout this paper the term "fault" is used to describe the degraded condition which results in change in dielectric constant, but no conduction current. The author realizes this is non-standard usage, but it a convenient term used for brevity.
that the reduction from 4.1 to 1.0 will result in a much greater (more noticeable) reduction of capacitance than the reduction from 4.1 to 2.6.

- Ref (1) discussed a fault with an "area of 1 mm". Certainly we might expect this to mean 1 mm^2, since we expect a turn to turn weakness to be localized. However, we will generously assume that the area whose dielectric constant changes to 1 extends the entire length of the turn (both endwindings and both slot sections)! Additionally, the assumed cross section of the degraded area is shown shaded in red in Figure 1.

Figure 1 – Coil geometry, including faulted area (red)

- Scenario 1 – Ground Effects Neglected
  The ungrounded scenario presents a small challenge in determining the boundary conditions. A traditional finite element approach to this type of problem is applied. Specifically, the boundary is extended very far out to the regions of very low energy density where inaccuracies in the boundary condition do not significantly affect the energy result. Then a boundary condition of zero normal field is applied on the outer boundary. This approach is successfully demonstrated in Appendix 4 for a simpler problem in which the analytical solution is known (the finite element results agree with the analytical results).

Since voltage to ground is irrelevant for the energy determination in the ungrounded model, all of the healthy coils within the motor can be considered identical. The coil chosen for analysis would be the first

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2 Scenario 1 of this analysis includes both a "healthy" and "faulted" analysis, which are intended to correspond to case 1 and case 2 of ref (1), respectively.
coil within 24 series coil assumed connected between −10V and +10V. The voltage within this coil extends from approx −10vac to −9.2 vac.

Figure 2 shows the solution (equipotential plot) over a wide view of the solution domain which extends far beyond the coil. Figure 3 shows a zoom to a middle range view where we can see the expected abrupt change in slope of equipotential lines as they cross the boundary of the assumed block of resin encasing the coil (extends for distance Te beyond the outside turns). Figure 4 shows a further zoom-in on the coil.

Figure 2 - Scenario 1 (Ungrounded) – healthy coil, zoom-out

Figure 3 - Scenario 1 (ungrounded), healthy scenario, zoom middle
Figure 4 - Scenario 1 (ungrounded) – healthy coil

Figure 5 - Scenario 1, fault between turns 11 and 15, zoomed-in

Figure 5 shows the same coil position as Figure 4, except that Figure 5 represents a faulted coil in the area between turn 11 (column 3, row 3) and turn 15 (column 3, row 4). As we expect, the total number of contour lines between turn 11 and 15 is the same since the voltage difference between those two turns is the same in both cases. However, in the healthy coil those contour lines are denser in the enamel than in the resin due to the difference in dielectric constants (4.1 for resin vs 2.5 for the enamel). In the faulted
In spite of the fact that there is very little change in the electric field, there is a reduction in energy density at the area of the fault due to the reduction in dielectric constant as we expect from Equation 1. Thus, for scenario 1, capacitance per meter of coil decreases from $5.4689184320E^{-14}$ in the healthy scenario to $5.3085213690E^{-14}$ in the faulted scenario as is summarized in Table 3. When we add up the contribution from 23 healthy coils and one faulty coil and compare to a healthy motor with 24 healthy coils, we see a fractional difference in $C_{eq}$ on the order of 0.0012 as shown in Table 3. When we combine the contributions from inductive and capacitive current to calculate an impedance, the fractional change in impedance is an extremely low number which is on the same order as the number of significant figures carried and for all practical purposes, negligible. Since impedance is the parameter which is more directly measured, the fractional change in impedance is more relevant to practical diagnostics. The results of this review as compared to reference (1) are summarized in Table 4 and show a sharp contrast in results.

### Table 4 - Comparison of results for degraded insulation at one turn pair (ungrounded case)

<table>
<thead>
<tr>
<th>Reference 1 (Case 2 vs Case1):</th>
<th>Fractional change in capacitance</th>
<th>Fractional change in impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease by factor of 450</td>
<td>Increase by a factor of 40</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results of this review (Scenario 1, faulted vs healthy):</th>
<th>Fractional change in capacitance</th>
<th>Fractional change in impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional decrease is 0.0012</td>
<td>Fractional decrease is 7E-9</td>
<td></td>
</tr>
<tr>
<td>(negligible)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An analytical order-of-magnitude "reasonability check" on the above finite element results is included in Appendix 5.

Scenarios Accounting For Ground:

For the remainder of the scenarios of this paper (2, 3, 4) we will use a motor model which borrows the previous ungrounded results for determining capacitive effects in the ungrounded endwinding area, but also includes grounded planes around the coil in the slot section area. In the scenario where ground is included in the model, the voltage to ground affects the energy storage. Since each coil has a different voltage to ground, we can no longer use one coil as representative of the entire motor, we need to model each coil with its own voltage to ground. From the data taken in ref (1), we use 12 coils per phase, or 24 coils within the...
phase to phase measurement of an assumed wye winding. Since we apply a 20vac ungrounded supply, the voltage to ground will float based on capacitive effects and by symmetry we assume the coil voltage goes from –10 volts with respect to ground at the first coil first turn to +10 volts above ground at the last coil last turn. For simplicity, we neglect effects from two coils in the same slot, and instead enclose each coil in a separate rectangular grounded slot. Under these assumptions, the physical position of any slot as compared to any other slot does not affect the solution since the ground-voltage boundary condition around each coil isolates it from the effect of anything outside of the coil. Therefore, for convenience of calculation and display, we arrange the rectangular slots next to each other in a similar ascending voltage order as was applied to the turns (voltage increases as we got first from left to right, and then from bottom to top). The 24 coils are arranged in 6 vertical columns and 4 horizontal rows. The coils will be identified by coil number which indicates electrical position within the 24 phase-to-phase coils. Table 5 summarizes this information. The coils number indicates the electrical position of the coil within the winding, while the coil position within the table illustrates the physical position in which the coils will be displayed. An overview of the "healthy" solution showing the associated voltage pattern is shown in Figure 6.

Table 5 - Electrical Coil Numbers, arranged in the position that they are displayed in FE results

<table>
<thead>
<tr>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 6 - Scenario 2/3/4 - Healthy Winding (zoom out)

Although it is difficult to convey the whole solution in one image, we notice in Figure 6 that the highest density of contour lines (corresponding to the highest fields) occur around the edges of the coils (near ground) and particularly as we approach the line end coils. Since energy density is proportional to the square of electric field, we can already begin to get the sense that ground effects will be much more important in determining stored capacitive energy and therefore equivalent capacitance than turn-to-turn effects.
Scenario 2:
For scenario 2, we position the fault at the same turn location as before (between turns 11 and 15), but we choose a fault location on coil 13 (located at the first column, 3rd row of coils), which has a voltage to ground near 0. Figure 7 shows a zoom-in at the location of the healthy coil 13 (the left of the two coils shown in the figure).

Figure 7 - Scenario 2 - Healthy Coil

Figure 8 - Scenario 2 faulted scenario
Figure 8 shows a zoom-in on the faulted coil 13 for scenario 2. Since this coil near the center of the winding has low stress to ground, the results are similar to the ungrounded scenario (very little change in voltage distribution). A zoom-in to a finer contour size (available on request) shows clearly the same pattern that was seen in scenario 1: non-uniform voltage gradient between turns for the unfaulted scenario (higher voltage gradient in enamel than resin) with a more uniform distribution in the faulted scenario.

The results of scenario 2 are shown in Table 6. The fractional change in impedance for scenario 2 is the same order of magnitude as scenario 1, indicating that the small ground voltage present in coil 13 does not have much effect. The fractional change in capacitance is much lower than in scenario 1 because the total capacitive energy in scenario 2 is much larger due to the ground effects (primarily elsewhere in the motor toward the line end coils).

Table 6 - Scenario 2 Results

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (healthy)</th>
<th>Faulty</th>
<th>Units</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endwinding (ungrounded) capacitance per m per coil</td>
<td>5.4689184320E-14</td>
<td>5.3085213690E-14</td>
<td>F/m</td>
<td>FE output 12021914(normal) &amp; 12021919(fault)</td>
</tr>
<tr>
<td>endwinding meter per coil</td>
<td>0.26</td>
<td>0.26</td>
<td>m</td>
<td>Given</td>
</tr>
<tr>
<td>endwinding capacitance per coil</td>
<td>1.42191879E-14</td>
<td>1.38021556E-14</td>
<td>F</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>endwinding capacitance total</td>
<td>3.41260510E-13</td>
<td>3.40843478E-13</td>
<td>F</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>Slot section capacitance per m</td>
<td>1.8801205340E-09</td>
<td>1.8801192630E-09</td>
<td>F/m</td>
<td>FE output 12021746(normal) &amp; 12021618(fault)</td>
</tr>
<tr>
<td>total slot length in meter (both sides)</td>
<td>0.16</td>
<td>0.16</td>
<td>m</td>
<td>Given</td>
</tr>
<tr>
<td>Total Slot section capacitance</td>
<td>3.00819285E-10</td>
<td>3.00819082E-10</td>
<td>F</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>Total Slot and Endwinding capacitance</td>
<td>3.01160546E-10</td>
<td>3.01159926E-10</td>
<td>F</td>
<td>Sum slot and endwinding</td>
</tr>
<tr>
<td><strong>Fractional difference in capacitance</strong></td>
<td>-2.06E-06</td>
<td></td>
<td></td>
<td>(faulted-normal)/normal</td>
</tr>
</tbody>
</table>

Impedance Analysis

| Capacitive Amps at 20vac, 400hz       | 1.51379801E-05   | 1.51379490E-05      | A           | I = 20V * 2* pi * 400hz * C                         |
| Inductive Amps at 20vac, 400hz        | 0.0050           | 0.0050              | A           | From Appendix 3                                      |
| Total Resultant Amps (Inductive minus capacitive) | 4.98486202E-03 | 4.98486205E-03      | A           | Subtract capacitive from inductive                   |
| Impedance                             | 4.01214716E+03   | 4.01214714E+03      | ohms        | Z = 20volts / I                                      |
| **Fractional difference in impedance**| -6.26E-09        |                     |             | (faulted-normal)/normal                               |

Scenario 3

In scenario 3, we again keep the fault at the same location within the coil (between turns 11 and 15), but we examine "line-end" coil number 1, which (along with coil 24) has the highest potential difference to ground of all the coils in the entire motor. Figure 9 shows a view of coil 1 (left) and it's neighbor coil 2 (right). The healthy scenario is shown on top, the faulted scenario on bottom. Figure 10 shows a closer view of the area of the fault. What we can clearly see is that the faulty scenario has a higher field density in the area between turns 11 and 15. And based on the orientation of the contour lines in the fault area (primarily run vertical rather than horizontal), we can see that the voltage gradient in this area is primarily the result of ground voltage stress, not turn voltage stress. The difference between the healthy and faulty scenario is that more of the steep potential gradient from the area directly adjacent to the right slot wall has moved into the low permittivity area of the fault. It must also be the case that the potential gradient adjacent closer to the right slot wall has decreased in the faulted scenario. This movement of gradient
from an area of high permittivity to lower permittivity is expected to result in a more significant reduction in energy and capacitance than occurred under scenario 2. And indeed, Table 7 shows this to be the case. By moving the turn fault to a coil with a higher voltage to ground, the effect of the higher ground stress is that the fractional increase in capacitance for scenario 3 is more than 5 times that for scenario 2, even though the faulted turns are not adjacent to the slot wall (!). This gives us an appreciation of how much bigger a role the ground stress plays than the turn stress, and motivates the selection of fault location for scenario 4.

Figure 9 - Scenario 3, Coil View. Healthy top, faulted bottom
Figure 10 - Scenario 3. Zoom-in to faulted turns. (healthy top, faulty bottom)
Table 7 - Scenario 3 Results

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (healthy)</th>
<th>Faulty</th>
<th>Units</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endwinding (ungrounded) capacitance per m per coil</td>
<td>5.4689184320E-14</td>
<td>5.3085213690E-14</td>
<td>F/m</td>
<td>FE output 12021914(normal) &amp; 12021919(fault)</td>
</tr>
<tr>
<td>Endwinding meter per coil</td>
<td>0.26</td>
<td>0.26</td>
<td>m</td>
<td>Given</td>
</tr>
<tr>
<td>Endwinding capacitance per coil</td>
<td>1.42191879E-14</td>
<td>1.38021566E-14</td>
<td>F</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>Endwinding capacitance total (24 coils)</td>
<td>3.41260510E-13</td>
<td>3.40843478E-13</td>
<td>F</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>Slot section capacitance per m (all coils)</td>
<td>1.8801205340E-09</td>
<td>1.8800995670E-09</td>
<td>F/m</td>
<td>FE output 12021746(normal) &amp; 12021829(fault)</td>
</tr>
<tr>
<td>Total slot length in meter (both sides)</td>
<td>0.16</td>
<td>0.16</td>
<td>m</td>
<td>Given</td>
</tr>
<tr>
<td>Total Slot section capacitance</td>
<td>3.00819285E-10</td>
<td>3.00815931E-10</td>
<td>F</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>Total Slot and Endwinding capacitance</td>
<td>3.01160546E-10</td>
<td>3.01156774E-10</td>
<td>F</td>
<td>Sum slot and endwinding</td>
</tr>
<tr>
<td>Fractional difference in capacitance</td>
<td>-1.25E-05</td>
<td></td>
<td></td>
<td>(faulted-normal)/normal</td>
</tr>
</tbody>
</table>

Impedance Analysis

| Capacitive Amps at 20vac, 400hz | 1.51379801E-05 | 1.51377906E-05 | A | I = 20V * 2π * 400hz * C |
| Inductive Amps at 20vac, 400hz | 0.0050 | 0.0050 | A | From Appendix 3 |
| Total Resultant Amps (Inductive minus capacitive) | 4.99486202E-03 | 4.99486221E-03 | A | Subtract capacitive from inductive |
| Impedance | 4.01214716E+03 | 4.01214701E+03 | ohms | Z = 20volts / I |
| Fractional difference in impedance | -3.80E-08 | | | (faulted-normal)/normal |

Scenario 4:

In scenario 4, the fault remains in the line-end coil, but the fault location is moved to the lower left hand corner of the coil, between turns 1 and 5. This puts the fault in an area of very high potential gradient because turn 1 of coil 1 has the highest potential difference to ground within the entire motor and, because the location is directly adjacent to the grounded slot wall and slot corner where the influence of ground is highest. This is clearly expected to give the highest expected change in capacitance for any turn fault location within the motor.

Figure 11 shows an overview of the voltage distribution for scenario 4. Figure 12 zooms in on the area of the faulted turns. We can clearly see that the gradient has increased in the area of the fault. More importantly, we can see that the gradient has significantly decreased to the left of the fault, adjacent to the slot wall. The effect of the fault is to substantially reduce the high voltage gradient adjacent to ground and move some of that high gradient from an area of high dielectric constant (adjacent to the slot wall), into an area of lower dielectric constant (at the fault between turns). This is most evident comparing the top and bottom of Figure 12 by noting in the bottom faulty image the apparent lighter purple area to the left of the fault... it appears lighter because it has fewer black contour lines in this area than in the top healthy image. From Equation 1, we expect this will give a substantial reduction in energy. And the results in confirm that the fractional change in capacitance for scenario 4 is a factor of 200+ higher than it was for scenario 3.
Note that since the turn position of the fault changed for scenario 4, a new Finite Element solution was done for the endwinding (run number 12022059), and incorporated into the results. In contrast, scenarios 2 and 3 used the solution from scenario 1 for the endwinding since the turn position of the fault within the coil was the same for scenarios 1 through 3.

Figure 11 - Scenario 4 (coil view)
Figure 12 - Scenario 4 - Zoom in to faulted turn (normal top, faulted bottom)
### Table 8 - Scenario 4 Results

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (healthy)</th>
<th>Faulty</th>
<th>Units</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endwinding (ungrounded) capacitance per m per coil</td>
<td>5.4689184320E-14</td>
<td>5.3042141780E-14</td>
<td>F/m</td>
<td>FE output 12021914(normal) &amp; 12022059(fault)</td>
</tr>
<tr>
<td>Endwinding meter per coil</td>
<td>0.26</td>
<td>0.26</td>
<td>m</td>
<td>Given</td>
</tr>
<tr>
<td>Endwinding capacitance per coil</td>
<td>1.42191879E-14</td>
<td>1.38021556E-14</td>
<td>F</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>Endwinding capacitance total (24 coils)</td>
<td>3.41260510E-13</td>
<td>3.40843478E-13</td>
<td>F</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>Slot section capacitance per m (all coils)</td>
<td>1.8801205340E-09</td>
<td>1.8718512750E-09</td>
<td>F/m</td>
<td>FE output 12021746(normal) &amp; 12021851(fault)</td>
</tr>
<tr>
<td>Total slot length in meter (both sides)</td>
<td>0.16</td>
<td>0.16</td>
<td>m</td>
<td>Given</td>
</tr>
<tr>
<td>Total Slot section capacitance</td>
<td>3.00819285E-10</td>
<td>2.99496204E-10</td>
<td>F</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>Total Slot and Endwinding capacitance</td>
<td>3.01160546E-10</td>
<td>2.99837047E-10</td>
<td>F</td>
<td>Sum slot and endwinding</td>
</tr>
<tr>
<td>Fractional difference in capacitance</td>
<td></td>
<td></td>
<td></td>
<td>(faulted-normal)/normal</td>
</tr>
</tbody>
</table>

### Impedance Analysis

| Capacitive Amps at 20vac, 400hz | 1.51379801E-05 | 1.50714539E-05 | A | I = 20V * 2*pi * 400hz * C |
| Inductive Amps at 20vac, 400hz | 0.0050 | 0.0050 | A | From Appendix 3 |
| Total Resultant Amps (Inductive minus capacitive) | 4.98486202E-03 | 4.98492855E-03 | A | Subtract capacitive from inductive |
| Impedance | 4.01214716E+03 | 4.01209362E+03 | ohms | Z = 20volts / I |
| Fractional difference in impedance | -1.33E-05 | (faulted-normal)/normal |

### Summary and Conclusion:

Appendix 1 provides a summary of the previously-presented tables for all four scenarios.

Scenario 1 modeled an ungrounded coil, similar to ref 1. This analysis concluded that the change in terminal impedance was negligible (on the order of 1E-8 fractional change in impedance), in sharp contrast to the conclusion or ref 1 which claimed a factor of 40 increase in impedance.

Scenarios 2, 3, 4 added ground effects to the model. The fault was modeled at various locations within a winding which made it abundantly clear that the voltage stress to ground in the area of the turn fault determines how much it will affect the impedance readings (faults in area of large ground stress show up more). Scenario 4 was chosen at the area of absolute highest ground stress within the motor and the change in impedance was more than a factor of 200 higher than any of the other results. However, even with the extremely generous selection of ground stress as well as generous allowance of change in dielectric constant (by a factor of 4) and generous geometry (dielectric constant changed between one pair for the entire length of a turn), the computed fractional change in impedance for scenario 4 was still on the order 1E-5 (one thousandth of one percent). The associated change in current was less than 1E-7 Amps. It is not reasonable to expect that the typical low voltage instruments used would be capable of detecting and resolving this small change or that the user of the test set can reliably discriminate this small change from other variables such as change in voltage, winding differences, etc.
References:
1. "Evaluation of Capacitance in Motor Circuit Analysis Findings", working paper posted on a predictive maintenance forum
2. "The Handbook of Small Electric Motors" by Yeadon & Yeadon
3. "Field and Wave Electromagnetics", 2nd Ed, by Cheng

About the Author:
Peter Schimpf has a Professional Engineer's license from the state of Texas, granted based on examination and experience. He has a BS in Electrical Engineering from the University of Rochester, an MS in Electrical Engineering from Georgia Institute of Technology, and an MEA in Industrial/Systems Engineering from Virginia Polytechnic Institute and State University. He has more than 20 years of experience in power plant electrical equipment, including 4 years working on power transformers and 8 years working on large electric motors. He is currently the electric motor engineer for a large 2-unit nuclear site.

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### Appendix 1. Summary of Results for the Four Scenarios

#### Scenario 1. GROUND NEGLECTED, fault at internal turns (lam 11 to 15)

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (ohm/µft)</th>
<th>Faulted</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>meter per coil</td>
<td>0.42</td>
<td>0.42 m</td>
<td>FE output 12021914(normal) &amp; 12021915(bad)</td>
</tr>
<tr>
<td>capacitance per coil</td>
<td>2.296845744 m</td>
<td>2.295789754 m</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>total phase to phase capacitance (24 coils)</td>
<td>5.126657871 m</td>
<td>5.503133010 m</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>Fractional difference in capacitance</td>
<td>-1.27E-03</td>
<td>(faulted-normal)/normal</td>
<td></td>
</tr>
</tbody>
</table>

#### Impedance Analysis

| Capacitive Impedance at 20ac, 400Hz | 2.77097060E-09 | 2.76713849E-09 | I = 20V ** 2 p * 400Hz = C |
| Inductive Impedance at 20ac, 400Hz | 0.0050          | 0.0050 A       |
| Total Resultant Impedance (Inductive minus Capacitive) | 4.9997722E-03 | 4.9997723E-03 | Subtract capacitive from inductive |
| Impedance | 4.00002217E-03 | 4.00002214E-03 |
| Fractional difference in impedance | -6.7E-06 | (faulted-normal)/normal |

#### Scenario 2. (Includes ground effects) fault on non-line-end coil (coil 13), internal turns (lam 11 to 15)

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (ohm/µft)</th>
<th>Faulted</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endwinding (ungrounded) capacitance per m per coil</td>
<td>5.46891432E-14</td>
<td>3.08621369E-14</td>
<td>FE output 12021914(normal) &amp; 12021915(bad)</td>
</tr>
<tr>
<td>endwinding meter per coil</td>
<td>0.28</td>
<td>0.28 m</td>
<td>FE output 12021914(normal) &amp; 12021915(bad)</td>
</tr>
<tr>
<td>endwinding capacitance per coil</td>
<td>1.42191874E-14</td>
<td>1.38021566E-14</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>endwinding capacitance total (24 coils)</td>
<td>3.41205010E-13</td>
<td>3.40834708E-13</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>slot section capacitance per m (all coils)</td>
<td>8.00120534E-09</td>
<td>8.00091957E-09</td>
<td>FE output 12021745(normal) &amp; 12021261(bad)</td>
</tr>
<tr>
<td>total slot length in meter (both sides)</td>
<td>0.16</td>
<td>0.16 m</td>
<td>FE output 12021745(normal) &amp; 12021261(bad)</td>
</tr>
<tr>
<td>Total Slot section capacitance</td>
<td>3.00819080E-10</td>
<td>3.00819081E-10</td>
<td></td>
</tr>
<tr>
<td>Total Slot and Endwinding capacitance</td>
<td>3.01160546E-10</td>
<td>3.01199966E-10</td>
<td>Sum slot and endwinding</td>
</tr>
<tr>
<td>Fractional difference in capacitance</td>
<td>-2.06E-06</td>
<td>(faulted-normal)/normal</td>
<td></td>
</tr>
</tbody>
</table>

#### Impedance Analysis

| Capacitive Impedance at 20ac, 400Hz | 1.51376901E-05 | 1.51370490E-05 | I = 20V ** 2 p * 400Hz = C |
| Inductive Impedance at 20ac, 400Hz | 0.0050          | 0.0050 A       |
| Total Resultant Impedance (Inductive minus Capacitive) | 4.98486202E-03 | 4.98486202E-03 | Subtract capacitive from inductive |
| Impedance | 4.91247176E-03 | 4.91247176E-03 |
| Fractional difference in impedance | -6.2E-05 | (faulted-normal)/normal |

#### Scenario 3. (Includes ground effects) fault on line-end coil (coil 1), internal turns (lam 11 to 15)

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (ohm/µft)</th>
<th>Faulted</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endwinding (ungrounded) capacitance per m per coil</td>
<td>5.46891432E-14</td>
<td>3.08621369E-14</td>
<td>FE output 12021914(normal) &amp; 12021915(bad)</td>
</tr>
<tr>
<td>endwinding meter per coil</td>
<td>0.28</td>
<td>0.28 m</td>
<td>FE output 12021914(normal) &amp; 12021915(bad)</td>
</tr>
<tr>
<td>endwinding capacitance per coil</td>
<td>1.42191874E-14</td>
<td>1.38021566E-14</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>endwinding capacitance total (24 coils)</td>
<td>3.41205010E-13</td>
<td>3.40834708E-13</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>slot section capacitance per m (all coils)</td>
<td>8.00120534E-09</td>
<td>8.00091957E-09</td>
<td>FE output 12021745(normal) &amp; 12021261(bad)</td>
</tr>
<tr>
<td>total slot length in meter (both sides)</td>
<td>0.16</td>
<td>0.16 m</td>
<td>FE output 12021745(normal) &amp; 12021261(bad)</td>
</tr>
<tr>
<td>Total Slot section capacitance</td>
<td>3.00819080E-10</td>
<td>3.00819081E-10</td>
<td></td>
</tr>
<tr>
<td>Total Slot and Endwinding capacitance</td>
<td>3.01160546E-10</td>
<td>3.01199966E-10</td>
<td>Sum slot and endwinding</td>
</tr>
<tr>
<td>Fractional difference in capacitance</td>
<td>-1.25E-05</td>
<td>(faulted-normal)/normal</td>
<td></td>
</tr>
</tbody>
</table>

#### Impedance Analysis

| Capacitive Impedance at 20ac, 400Hz | 1.51376901E-05 | 1.51379606E-05 | I = 20V ** 2 p * 400Hz = C |
| Inductive Impedance at 20ac, 400Hz | 0.0050          | 0.0050 A       |
| Total Resultant Impedance (Inductive minus Capacitive) | 4.98486202E-03 | 4.98486202E-03 | Subtract capacitive from inductive |
| Impedance | 4.91347176E-03 | 4.91347176E-03 |
| Fractional difference in impedance | -3.8E-06 | (faulted-normal)/normal |

#### Scenario 4. (Includes ground effects) fault on line-end coil (coil 1), turns adjacent to slot wall (lam 1 to 5)

<table>
<thead>
<tr>
<th>Capacitive Analysis</th>
<th>Normal (ohm/µft)</th>
<th>Faulted</th>
<th>Calculated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endwinding (ungrounded) capacitance per m per coil</td>
<td>5.46891432E-14</td>
<td>3.08621369E-14</td>
<td>FE output 12021914(normal) &amp; 12022059(bad)</td>
</tr>
<tr>
<td>endwinding meter per coil</td>
<td>0.28</td>
<td>0.28 m</td>
<td>FE output 12021914(normal) &amp; 12022059(bad)</td>
</tr>
<tr>
<td>endwinding capacitance per coil</td>
<td>1.42191874E-14</td>
<td>1.38021566E-14</td>
<td>Multiply the two rows above</td>
</tr>
<tr>
<td>endwinding capacitance total (24 coils)</td>
<td>3.41205010E-13</td>
<td>3.40834708E-13</td>
<td>Faulted based on 23 normal + 1 faulty coil</td>
</tr>
<tr>
<td>slot section capacitance per m (all coils)</td>
<td>8.00120534E-09</td>
<td>8.00091957E-09</td>
<td>FE output 12021745(normal) &amp; 12021261(bad)</td>
</tr>
<tr>
<td>total slot length in meter (both sides)</td>
<td>0.16</td>
<td>0.16 m</td>
<td>FE output 12021745(normal) &amp; 12021261(bad)</td>
</tr>
<tr>
<td>Total Slot section capacitance</td>
<td>3.00819080E-10</td>
<td>3.00819081E-10</td>
<td></td>
</tr>
<tr>
<td>Total Slot and Endwinding capacitance</td>
<td>3.01160546E-10</td>
<td>3.01199966E-10</td>
<td>Sum slot and endwinding</td>
</tr>
<tr>
<td>Fractional difference in capacitance</td>
<td>-4.39E-05</td>
<td>(faulted-normal)/normal</td>
<td></td>
</tr>
</tbody>
</table>

#### Impedance Analysis

| Capacitive Impedance at 20ac, 400Hz | 1.51376901E-05 | 1.50714596E-05 | I = 20V ** 2 p * 400Hz = C |
| Inductive Impedance at 20ac, 400Hz | 0.0050          | 0.0050 A       |
| Total Resultant Impedance (Inductive minus Capacitive) | 4.98486202E-03 | 4.98486205E-03 | Subtract capacitive from inductive |
| Impedance | 4.91247176E-03 | 4.91200062E-03 |
| Fractional difference in impedance | -1.33E-05 | (faulted-normal)/normal |
Appendix 2. The Energy Method for Combining Capacitances

Model:
Apply a single phase ungrounded test voltage $V_s$ to the terminals of a stationary motor. Neglect resistance.

The voltage distribution is completely determined by magnetic effects. Therefore, adding capacitances to turn and to ground does not change the voltage distribution within the winding (although it may change the voltage to ground).

Motivation For The Energy Approach: Between each pair of conductors (and between conductors and ground), we can estimate a physical capacitance $C_p$. When analysing the capacitances within a motor and attempting to find an equivalent capacitance which reflects the terminal behavior, there may be a temptation to combine the effects of all physical capacitances based on series and parallel combinations using simple circuit analysis and without regard to the voltage imposed on the system by interconnection to the winding. This would be correct if there were no interconnections between the capacitance network and the winding other than at the two test terminals. However, in reality this is not the correct approach since it does not account for the various voltage constraints imposed on the capacitive network by the multiple intermediate interconnections to the winding. Consider two pairs of physically adjacent coils which both have the same spacing (same physical capacitance $C_p$), but different turn-to-turn voltage. The first pair has a voltage difference of 0.1 volt and the second pair has a voltage difference of 0.4 volts. The turn capacitance of the 2nd pair will draw 4 times as much current, and this current reduction will be seen in 4 times as many coils. The net effect is that the second coil creates 16 times as large an effect on terminal current as the first coil. We note that the energy stored in the 2nd capacitor is also 16 times as large as the first, which leads us to believe that capacitive energy storage might be an important factor to consider.

Analysis of Capacitor:
Symbols:
$C$ = capacitance
$w = \text{radian frequency} = 2\pi f$
$Xc = \text{Capacitive reactance} = 1/(wC)$
$W = \text{Max capacitive stored energy}$
$Q = \text{reactive power (not charge)}$
$V, I = \text{capacitor terminal quantities, expressed in rms}$
$V_p = V \text{ expressed as peak value}$

$W = 0.5 \ast C \ast V_p^2$
$W = C \ast V^2$
$V^2 = W / C$
$Q = V \ast I$
$Q = V \ast V / Xc$
$Q = V \ast V \ast w*C$
$Q = V^2 \ast w*C$
Substitute $V^2 = W_{\text{max}} / C$
$Q = W \ast w$

The last result tells us that for a given frequency, the reactive power injected into the system by a capacitor can be uniquely determined from the max stored energy. If two capacitors $C_1$ and $C_2$ satisfy $0.5*C_1*V1p^2 = 0.5*C2*V2p^2$, then those two capacitors will deliver the same vars, even though the individual capacitances may be different.
Var Balance:
Reactive elements exchange energy with the electrical system at a rate of twice line frequency (the stored energy will be Wmax twice and 0 four times during a single electrical cycle). The polarity of vars exchanged with the electrical system are opposite for capacitors and inductors. Conservation of energy demands that the vars flowing into an electrical system from all sources (voltage supply, capacitors, inductors) sum to 0. In a motor under test, the vars exchanged with inductive elements far exceeds the vars exchanged with capacitive elements. Thus, the var balance can be written as follows:

\[ Q_s = Q_l - Q_c \]

where:
- \( Q_s \) is vars supplied by the external test voltage source \( V_s \)
- \( Q_l \) are the inductive vars consumed by the motor magnetic circuit
- \( Q_c \) are the total capacitive vars supplied by the motor capacitances

Equivalent Circuit
We intend to replace the multiple actual capacitances with an equivalent capacitance \( C_{eq} \) connected in parallel with the inductance. The voltage at the machine terminals will not change, so \( Q_l \) will not change. In order to correctly predict the source current, we must keep \( Q_s \) the same as in the actual case. The only way we can do this is to keep \( Q_c \) the same (so that the var balance is not changed). The value of the \( C_{eq} \) which will accomplish this is a capacitance which when applied across the source voltage provides the same maximum energy storage (and therefore the same vars) as the sum of the maximum energy stored in all the actual physical capacitances when exposed to their respective voltages.

\[ W_{total} = \text{sum} \left( 0.5 \times C_k \times V_{kp}^2 \right) \]  \[ \text{[Equation A]} \]
\[ C_{eq} = \frac{2 \times W_{total}}{V_{sp}^2} = \text{sum} \left( C_k \times V_{kp}^2 \right) / V_{sp}^2 \]
\[ C_{eq} = \frac{\text{sum}(C_k \times V_{kp}^2)}{V_{sp}^2} \]  \[ \text{[Equation B]} \]
\[ C_{eq} = \frac{\text{sum}(C_k \times V_{k}^2)}{V_{s}^2} \]  \[ \text{[Equation C]} \]

where:
- \( W_{total} \) is sum of all capacitive energy stored the motor at the time when it is maximum
- \( C_k \) are individual turn and ground capacitances
- \( V_k \) is rms voltage across the individual turn and ground capacitances
- \( V_s \) is rms source voltage
- \( V_{kp} \) and \( V_{sp} \) are \( V_k \) and \( V_s \) expressed on a peak basis.
- \( C_{eq} \) is the single equivalent capacitance to be connected in parallel with the entire motor inductance

Note that max stored energies \( 0.5 \times C \times V_{p}^2 \) are defined in terms of peak (rather than rms) voltages. However, since \( C_{eq} \) is a ratio with voltage squared in both numerator and denominator, it is unaffected by the choice of peak or rms and we can correctly compute it using either rms or peak values (compare equation B to equation C). In order to calculate the correct maximum stored energy per equation A, we must use a peak value. But if we are only interested in \( C_{eq} \) and not energy, we can calculate using either rms or peak and the computed \( C_{eq} \) and resulting current contributions will still be correct.
Appendix 3. Determination of Inductive Current During the Test.

When the motor is energized for test, the current drawn will be affected by both inductive and capacitive effects. We want to find the inductive current drawn by the motor described in ref (1), so that we can estimate the inductive impedance, and then the change in total impedance resulting from the capacitive changes calculated in this paper.

The "generous" assumptions are the ones which result in a smaller inductive current (higher inductance), since these will make the capacitive effects appear larger in comparison.

Ref (1) did not provide information about the motor such as horsepower, speed, voltage.

The wire is stated to be 18AWG, which would have a cross section of approx 0.001473 square inch.

Per Table 8.3 of "The Handbook of Small Electric Motors" by Yeadon & Yeadon, conductors are typically designed for steady state current density in the range of 2,000 to 8,000 A/inch^2. We generously pick the lower end of the band as 2,000A/inch^2. Multiplying current density by area, we get a current of 2.95 Amps in each conductor.

From the dimensions, we can judge it is a small motor, and so it is reasonable to assume that it is wound one-in-hand, single circuit wye, so that the turn current is equal to the line current. So 2.95A would presumably be the highest full load amperage of this motor.

Before we will apply corrections for voltage and frequency, we pause to consider whether we should start with full load amps (FLA) or something else. The condition of the rotor during the test is locked rotor (~5*FLA) so an argument could be made for starting with this. But to make a generous allowance for uncertainty, we will make a correction in the other direction and start with no-load amps (~ 0.25*FLA). 0.25 * 2.95A = 0.7365A.

Now, we correct the current by the ratio of voltages and frequencies. We generously assume the highest reasonable voltage of 460vac.

This gives 0.7365A * (20vac/460vac) *(60hz/400hz) = 0.005A

We conclude that 0.005A is generously the minimum expected current for this motor at 20vac 400hz.

This is a very tiny current. As a reasonability check, we convert to inductance using
L = V/(2*Pi*f*I) = 20vac / (2*pi*400hz*0.005A) = 1.66 H = 1660 mH

Our reasonability check confirms this is a generously high inductance, corresponding to a generously low current.
Appendix 4. Demonstration of energy summation in an unbounded geometry for simple case with known analytical solution.

The geometry to be studied is a parallel pair of cylindrical conductors in free space. The conductor radiuses are chosen as \( R_c = 0.55 \) m. The conductor center-to-center distance is chosen as \( D_{cc} = 2.8 \) mm.

"Field and Wave Electromagnetics", 2nd Ed, by Cheng gives the capacitance as:

\[
C = \frac{\pi \epsilon_0}{\arccosh \left( \frac{D_{cc}}{2R_c} \right)} \text{ F/m}
\]

Substituting \( \epsilon_0 = 8.854188-12 \) F/m and the parameters \( R_c \) and \( D_{cc} \) above, we have:

\[
C = 3.141592654 \times 8.854187817E-12 / \arccosh(2.8/1.1) \text{ F / m}
\]

\[
C = 2.781622848E-11 / 1.586425815 \text{ F / m}
\]

\[
C = 1.753389803E-11 \text{ F / m}
\]

The geometry was re-created using the same program (Appendix 7) that was used for scenario's 1 through 4. The dimensions used were \( R_c=0.55 \) mm, \( T_e=0.6 \) mm, \( T_r = 0.5 \) mm. We see that this gives \( D_{cc} = 2*0.55 + 2*0.6 + 0.5 = 2.8 \) mm as required. All relative permittivity values were set to 1.

A test voltage of 5 volts was selected (the selection of test voltage affects the reported energy result, but does not affect the calculated capacitance).

The program output results were 1.754645592E-011 F/m (Run 12022015) with a maximum mesh size 0.08 mm.

When the mesh size was reduced to 0.06 mm, (run 12022027), the results were even closer (1.753328847E-011 F/m), as expected.

The voltage solution is shown in Figure 13 and Figure 14. The two program run files (listing inputs and outputs at given below)

--- Output file generated by program:mcap2.m 
Run Label (MMDDHHMM):12022015

Inputs are as follows:
- faulted (1 for yes, 0 for no): 0
- groundplane (1 for grounded slot model, 0 for ungrounded): 0
- Nclx and Ncly (number of coils in x and y directions): 1 and 1
- Ntx and Nty (number of turns in x and y directions): 1 and 2
- Rc (Radius of Conductor): 0.55 mm
- Te (thickness of enamel per side): 0.60 mm
- Tr (thickness of resin betw enamel of adjacent conductors): 0.50 mm
- Tl (thickness of resin betw enamel and side of slot): 0.50 mm
- EpsilonR_Eb (relative dielectric const): 1.00
- EpsilonR_Resin (relative dielectric const): 1.00
- EpsilonR_Degraded (Relative dielectric const): 1.00 mm
- Vs (test voltage): 5.00 V
- MaxMeshResin and MaxMeshEnamel(max FE mesh size here): 0.08 and 0.08 mm
- ftx,ftx,fry, (parameters identifying faulted coil/turn loc): 1, 1, 3, and 3
- SeriesColleUG (Series Coils betw terminals for UG calc): 1 mm
- myprecision (tolerance for residuals, argument to ei_probdef): 0.0000'
- Total energy is 2.19330699e-010 Joules per m
- Equivalent Capacitance at 5 volts is 1.754645592e-011 F per m

--- Output file generated by program:mcap2.m 
Run Label (MMDDHHMM):12022027

---

3 The variable myprecision was set at 1E-10 for both runs. (not formatted properly in the program output).
Inputs are as follows:

faulted (1 for yes, 0 for no): 0
groundplane (1 for grounded slot model, 0 for ungrounded): 0
Nc1x and Nc1y (number of coils in x and y directions): 1 and 1
Ntx and Nty (number of turns in x and y directions): 1 and 2
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin betw enamel of adjacent conductors): 0.50 mm
Tl (thickness of resin betw enamel and side of slot): 0.50 mm
EpsilonR_Ename (relative dielectric const): 1.00
EpsilonR_Resin (relative dielectric const): 1.00 mm
EpsilonR_Degraded (Relative dielectr const): 1.00 mm
Vs (test voltage): 5.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.06 and 0.06 mm
fcx, fcy, ftx, fty (parameters identifying faulted coil/turn loc): 1, 1, 3, and 3
SeriesCoilsUG (Series Coils betw terminals for UG calc): 1 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0.0000
Total energy is 2.191661058e-010 Joules per m
Equivalent Capacitance at 5 volts is 1.753328847e-011 F per m

Figure 13 - Two conductor solution (zoom-out)
Figure 14 – Two-conductor solution (zoom-in)
Appendix 5. Analytical Estimation of Capacitance Results for Scenario 1

The intent is to do an analytical order of magnitude reasonability check for the results obtained from the finite element simulation for scenario 1.

We will look only at the energy of horizontally-adjacent and vertically-adjacent pairs (neglect diagonally adjacent pairs for simplicity). We start with the roughest approximation in the whole analysis: we borrow the result for the physical capacitance of adjacent turn pairs from Appendix 4 (remember, the dimensions were the same). We apply a correction for the change in relative dielectric constant. Then following the energy approach, we calculate the energy in each turn pair (horizontal, vertical, and faulted vertical), add them all up (each 4x5 coil has 16 vertical turn pairs and 15 horizontal turn pairs, so among the 24 coils we have 384 vertical turn pairs and 360 horizontal turn pairs), and solve $C_{eq} = 2 \times \frac{W_{total}}{V_s^2}$. The detailed calculation is shown in Table 9.

Table 9 - Analytical estimation of scenario 1 results

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
<th>From where</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test (source) voltage</td>
<td>$V_s$</td>
<td>20</td>
<td>Volts</td>
<td>Given</td>
</tr>
<tr>
<td>Coil Voltage</td>
<td>$V_{coil}$</td>
<td>0.833333333</td>
<td>Volts</td>
<td>$V_s / 24$</td>
</tr>
<tr>
<td>Turn Voltage</td>
<td>$V_{turn}$</td>
<td>0.041666667</td>
<td>Volts</td>
<td>$V_{coil} / 20$</td>
</tr>
<tr>
<td>Capacitance per meter in vacuum or fault</td>
<td>$C_{perMeterVac}$</td>
<td>1.753390E-11</td>
<td>F/M</td>
<td>From Appendix 4</td>
</tr>
<tr>
<td>Length of turn</td>
<td>$\text{MeterPerTurn}$</td>
<td>0.42</td>
<td>M</td>
<td>Given</td>
</tr>
<tr>
<td>Capacitance per turn in a vacuum or fault</td>
<td>$C_{perTurnVacuum}$</td>
<td>7.364237E-12</td>
<td>F</td>
<td>Multiply previous two rows</td>
</tr>
<tr>
<td>Average of resin (4.1) and enamel (2.5) based on length of each along the line between conductors</td>
<td>$\text{EpsilonR_AverageNormal}$</td>
<td>2.970588235</td>
<td>unitless</td>
<td>$(2 \times Te \times EpsEnamel + Tr \times EpsResin) / (2 \times Te + Tr)$ where $Te = 0.6$, $Tr = 0.5$, $EpsEnamel = 2.5$, $EpsResin = 4.1$</td>
</tr>
<tr>
<td>Capacitance Per Normal Turn</td>
<td>$C_{perTurn_Normal}$</td>
<td>2.187612E-11</td>
<td>F</td>
<td>Multiply previous two rows</td>
</tr>
<tr>
<td>Voltage as multiple of turn voltage</td>
<td>Voltage (V)</td>
<td>0.166666667</td>
<td>3.03835E-13</td>
<td>384</td>
</tr>
<tr>
<td>Energy per turn pair (W) = 0.5<em>Cp</em>V^2</td>
<td>Number Of Adjacent Turn Pairs In Healthy Motor</td>
<td>0.538697E-14</td>
<td>360</td>
<td>6.83629E-12</td>
</tr>
<tr>
<td>Total Energy In Healthy Motor (product of previous two columns)</td>
<td>Number of adjacent pairs in faulty motor</td>
<td>0.166666667</td>
<td>0</td>
<td>0.166666667</td>
</tr>
<tr>
<td>Total Energy In Faulty Motor (product of relevant two columns)</td>
<td>Vertical Caps (normal)</td>
<td>4</td>
<td>1.23509E-10</td>
<td>1.23307E-10</td>
</tr>
<tr>
<td>Horizontal Caps (normal)</td>
<td>1</td>
<td>6.31595E-13</td>
<td>6.31595E-13</td>
<td>6.31595E-13</td>
</tr>
<tr>
<td>Faulted Vertical Cap</td>
<td>4</td>
<td>1.02281E-13</td>
<td>0</td>
<td>0.001631898</td>
</tr>
<tr>
<td>Total Energy (sum three rows above)</td>
<td></td>
<td>1.23509E-10</td>
<td>1.23307E-10</td>
<td>1.23307E-10</td>
</tr>
<tr>
<td>Fractional Difference</td>
<td></td>
<td>0.001631898</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The result for capacitance is surprisingly close (on the order of 6E-13F here vs 5E-13F for the finite element simulation). More importantly, we calculated a fractional change in capacitance of –0.0016, which is reasonably close to the –0.0012 calculated by the finite element simulation.

Our order of magnitude reasonability check passes. We have every reason to trust the finite element simulation.
Appendix 6. Listing of program run files (12021618, 12021746, 12021829, 12021851, 12021914, 12021919, 12022059)

==================================
*** Scenario 2 ***
Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12021618

Inputs are as follows:
faulted (1 for yes, 0 for no): 1
groundplane (1 for grounded slot model, 0 for ungrounded): 1
Nclx and Ncly (number of coils in x and y directions): 6 and 4
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin between enamel of adjacent conductors): 0.50 mm
Tl (thickness of resin between enamel and side of slot): 0.50 mm
EpsilonR_Enamel (relative dielectric const): 2.50
EpsilonR_Resin (relative dielectric const): 4.10
EpsilonR_Degraded (Relative dielectric const): 1.00 mm
Vs (test voltage): 20.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fCx, fCy, ftx, fty (parameters identifying faulted coil/turn loc): 1, 3, 3, and 3
SeriesCoilsUG (Series Coils between terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0 mm
Total energy is 3.760238526e-007 Joules per m
Equivalent Capacitance at 20 volts is 1.880119263e-009 F per m

==================================
*** Healthy condition - slot section ***
Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12021746

Inputs are as follows:
faulted (1 for yes, 0 for no): 0
groundplane (1 for grounded slot model, 0 for ungrounded): 1
Nclx and Ncly (number of coils in x and y directions): 6 and 4
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin between enamel of adjacent conductors): 0.50 mm
Tl (thickness of resin between enamel and side of slot): 0.50 mm
EpsilonR_Enamel (relative dielectric const): 2.50
EpsilonR_Resin (relative dielectric const): 4.10
EpsilonR_Degraded (Relative dielectric const): 1.00 mm
Vs (test voltage): 20.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fCx, fCy, ftx, fty (parameters identifying faulted coil/turn loc): 1, 3, 3, and 3
SeriesCoilsUG (Series Coils between terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0 mm
Total energy is 3.760238526e-007 Joules per m
Equivalent Capacitance at 20 volts is 1.880120534e-009 F per m

==================================
*** Scenario 3 - Fault ***
Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12021829

Inputs are as follows:
faulted (1 for yes, 0 for no): 1
groundplane (1 for grounded slot model, 0 for ungrounded): 1
Nclx and Ncly (number of coils in x and y directions): 6 and 4
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin between enamel of adjacent conductors): 0.50 mm
Tl (thickness of resin between enamel and side of slot): 0.50 mm
EpsilonR_Enamel (relative dielectric const): 2.50
**EpsilonR_Resin** (relative dielectric const): 4.10
**EpsilonR_Degraded** (Relative dielectric const): 1.00 mm
Vs (test voltage): 20.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fcx,fcy,ftx,fty (parameters identifying faulted coil/turn loc): 1, 1, 3, and 3
SeriesCoilsUG (Series Coils betw terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0 mm
Total energy is 3.760199134e-007 Joules per m
Equivalent Capacitance at 20 volts is 1.88009567e-009 F per m

---

**Scenario 4 - Fault**

Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12021851

Inputs are as follows:
faulted (1 for yes, 0 for no): 1
groundplane (1 for grounded slot model, 0 for ungrounded): 1
Nclx and Ncly (number of coils in x and y directions): 6 and 4
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Tr (thickness of resin betw enamel of adjacent conductors): 0.50 mm
Tl (thickness of resin betw enamel and side of slot): 0.50 mm
EpsilonR_Enamel (relative dielectric const): 2.50
EpsilonR_Resin (relative dielectric const): 4.10
EpsilonR_Degraded (Relative dielectric const): 1.00 mm
Vs (test voltage): 20.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fcx,fcy,ftx,fty (parameters identifying faulted coil/turn loc): 1, 1, 3, and 3
SeriesCoilsUG (Series Coils betw terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0 mm
Total energy is 3.74370255e-007 Joules per m
Equivalent Capacitance at 20 volts is 1.871851275e-009 F per m

---

**Healthy condition in ungrounded/enwinding geometry**

Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12021914

Inputs are as follows:
faulted (1 for yes, 0 for no): 0
groundplane (1 for grounded slot model, 0 for ungrounded): 0
Nclx and Ncly (number of coils in x and y directions): 1 and 1
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin betw enamel of adjacent conductors): 0.50 mm
Tl (thickness of resin betw enamel and side of slot): 0.50 mm
EpsilonR_Enamel (relative dielectric const): 2.50
EpsilonR_Resin (relative dielectric const): 4.10
EpsilonR_Degraded (Relative dielectric const): 1.00 mm
Vs (test voltage): 20.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fcx,fcy,ftx,fty (parameters identifying faulted coil/turn loc): 1, 1, 3, and 3
SeriesCoilsUG (Series Coils betw terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0 mm
Total energy is 1.093783686e-011 Joules per m
Equivalent Capacitance at 20 volts is 5.468918432e-014 F per m

---

**Fault in ungrounded/endwinding geometry**

Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12021919

Inputs are as follows:
faulted (1 for yes, 0 for no): 1
groundplane (1 for grounded slot model, 0 for ungrounded): 0
Nclx and Ncly (number of coils in x and y directions): 1 and 1
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin betw enamel of adjacent conductors): 0.50 mm

---
Tl (thickness of resin between enamel and side of slot): 0.50 mm
EpsilonR_Enamel (relative dielectric const): 2.50
EpsilonR_Resin (relative dielectric const): 4.10
EpsilonR_Degraded (relative dielectric const): 1.00 mm
Vs (test voltage): 20.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fcx, fcy, ftx, fty (parameters identifying faulted coil/turn loc): 1, 1, 3, and 3
SeriesCoilsUG (Series Coils between terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0 mm
Total energy is 1.061704274e-011 Joules per m
Equivalent Capacitance at 20 volts is 5.308521369e-014 F per m

*** Endwinding for Scenario 4 ***
Output file generated by program: mcap2.m
Run Label (MMDDHHMM): 12022059

Inputs are as follows:
faulted (1 for yes, 0 for no): 1
groundplane (1 for grounded slot model, 0 for ungrounded): 0
Nclx and Ncly (number of coils in x and y directions): 1 and 1
Ntx and Nty (number of turns in x and y directions): 4 and 5
Rc (Radius of Conductor): 0.55 mm
Te (thickness of enamel per side): 0.60 mm
Tr (thickness of resin between enamel of adjacent conductors): 0.50 mm
Vs (test voltage): 5.00 V
MaxMeshResin and MaxMeshEnamel (max FE mesh size here): 0.08 and 0.08 mm
fcx, fcy, ftx, fty (parameters identifying faulted coil/turn loc): 1, 1, 1, and 1
SeriesCoilsUG (Series Coils between terminals for UG calc): 24 mm
myprecision (tolerance for residuals, argument to ei_probdef): 0.0000
Total energy is 6.630267723e-013 Joules per m
Equivalent Capacitance at 5 volts is 5.304214178e-014 F per m

4 The mm shown after SeriesCoilUG is result of improper formatting of the output. The number is correct if you ignore the mm.
5 The myprecision parameter was not formatted properly in the output report. 1E-10 was used for all cases in this report.
Appendix 7. Matlab Program File

% File mcap2.m by electricpete
% Compute voltage distribution and equivalent capacitance
% Many different geometries are possible using this one program by
% adjusting the input variables listed below
% See my whitepaper (Analysis of Effects of Capacitance....)
% for examples

% PREVIOUS CHANGES IN MCAP1:
% 11/30/08: Increased precision of reported C and W on 11/30/08. Kept name mcap1

% CHANGES MADE WHEN CREATED MCAP2 (12/02/08)
% Report EpsilonR_Degraded on the output (has been 1 all previous runs)
% increase precision reported on energy output
% changed from precision parameter 1E-8 to variable my precision and sent myprecision to report
% Note that all runs starting 12/02/08 used the following inputs:
% myprecision = 1E-10
% 12/02 20:15 - Fixed an error with reporting format for myprecision in the output report
% (again 1202 runs all have myprecision=1E-10, even if it doesn't show up in the report)
% clear old values of any variables in memory
clear % Need to execute this step before input any parameters!

% Input parameters
faulted = 1;  % 1 for fault present, 0 for no fault
groundplane=0; % 1 for conductor in grounded slot, 0 for ungrounded
Ntx = 4; % Number of turns/coil in x direction
Nty = 5; % Number of turns/coil in y direction
Rc = 1.1/2; % Radius of Conductor
Te = 0.6;  % thickness of enamel
Tr = 0.5;   % thickness of resin between enamel of adjacent conductors
Tl = Tr; % thickness of liner (between slot and enamel of conductors near slot)
Vs = 5;    % Test voltage applied at terminals
MaxMeshResin = Rc/7; % max mesh size allowed in resin region (smaller may be used)
MaxMeshEnamel = Rc/7; % max mesh size allowed in Enamel region (smaller may be used)
EpsilonR_Enamel = 2.5
EpsilonR_Resin = 4.1
EpsilonR_Degraded = 1 %
programname = 'mcap2.m'
myprecision=1E-10

% Input Parameters related to the ungrounded case only:
SeriesCoilsUG=24 % series coils connected between the points of application of Vs

% Input Parameters related to the grounded case only (set to 1 for ungrounded)
Nclx = 1; % Number of coils in x direction
Ncly = 1; % Number of coils in y direction
% note iclx, icly, itx, ity are counters for variables Ntx, Nty,Nclx,Ncly

% Input parameters related to the faulted case only:
fcx = 1; % column number (X direction) of the Coil with the Faulted turns
fcy = 1; % row number (Y direction) of the Coil with the Faulted turns
ftx = 1; % column number (X direction) of the lower Turn of the Faulted pair
fty = 1; % row number (Y direction) of the lower Turn of the Faulted pair
% Other Items calculated from input parameters
TurnsPerCoil = Ntx*Nty;
Dcc = 2*Rc + 2*Te + Tr;  % Center to Center distance of conductors
CoilWidth = (Ntx-1) * Dcc + 2* Rc+2*Te+  2 * Tl;
CoilHeight = (Nty-1) * Dcc +2* Rc+2*Te+  2 * Tl;

% Ntt = total turns in series across Vs: used for calc'ng turn voltage
if groundplane  % for grounded case, calc based on number of coils:
    Ntt = TurnsPerCoil*Nclx*Ncly;
else  % for ungrounded case, calc based on SeriesCoilsUG parameter
    Ntt = TurnsPerCoil*SeriesCoilsUG
end

% Assorted Flags that will be passed as arguments to FEMM commands
AutoMeshTrue = 1;  % allows mesh generator to determine max mesh size
AutoMeshFalse = 0; % we will provide a max mesh size parameter
HideSegmentTrue = 1; % hides segment in post-processor view
HideSegmentFalse = 0; % keeps segment visible in post-processor view

% Initialization
% ei_   denotes commands in the FEMM Electrostatic Input processor (pre-processor)
% eo_   denotes commands in the FEMM Electrostatic Output processor (post-processor)
echo on
path(path,'C:\Program Files\femm42\mfiles')  % sets the path
openfemm   % launches FEMM
newdocument(1) % create new FEMM E-static file

ei_probdef('millimeters', 'planar', myprecision, 1000, 30) % sets mm as default unit
% planar (2-d) problem
% myprecision is tolerance argument
% 1000 mm is depth of problem (into the page)
% 30 is min angle parameter for triangle mesh generator

% Set up material, and boundary properties
ei_addmaterial('air', 1, 1, 0)  % EpsilonR = 1
ei_addmaterial('copper', 1, 1, 0)  % EpsilonR = 1
ei_addmaterial('resin', EpsilonR_Resin,EpsilonR_Resin,0)
ei_addmaterial('enamel', EpsilonR_Enamel,EpsilonR_Enamel,0)
ei_addmaterial('degraded',EpsilonR_Degraded,EpsilonR_Degraded, 0)  % EpsilonR = 1

ei_addboundprop('OuterBoundary', 0,0,0,0,1) % Mixed boundary, C0=C1=0 % for ungrounded case
% ei_addconductorprop('FloatingConductor', 0, 0, 0) % the floating way to represent slot
% ei_addconductorprop('FloatingConductor', 0, 0, 1) % simpler approach - represent ground as 0 volts by symmetry

% ========= THE BIG LOOP ==========
% CREATES ALL COILS (LEFT TO RIGHT, BOTTOM TO TOP)
% WITHIN EACH COIL, CREATE ALL TURNS (LEFT TO RIGHT, BOTTOM TO TOP)

for icly = 1:Ncly  % Loop through all coils
    for iclx = 1:Nclx
        %========== SET UP THE COIL =======
        LLHCx = (iclx-1)*CoilWidth ;
        LLHCy = (icly-1)*CoilHeight ;
ei_drawrectangle(LLHCx, LLHCy, iclx*CoilWidth, icly*CoilHeight)

ei_clearselected

ei_selectsegment(LLHCx+CoilWidth/2, LLHCy);
ei_selectsegment(LLHCx, LLHCy+CoilHeight/2);
ei_selectsegment(LLHCx+CoilWidth, LLHCy+CoilHeight/2);
ei_selectsegment(LLHCx+CoilWidth/2, LLHCy+CoilHeight);

if not(groundplane) % ungrounded case - rect hidden in postprocessor
  ei_setsegmentprop('<None>', 0, 1, HideSegmentTrue, 0, '<None>'
else % grounded case - rectangle is ground (called floating conductor)
  ei_setsegmentprop('<None>', 0, 1, HideSegmentFalse, 0, 'FloatingConductor'
end

ei_clearselected

% add block label to the interior (just inside the corner, but not in any conductor)
ei_addblocklabel(LLHCx+0.5*Tl, LLHCy+0.5*Tl)
ei_clearselected

ei_selectlabel(LLHCx+0.5*Tl, LLHCy+0.5*Tl);
ei_setblockprop('resin', AutoMeshFalse, MaxMeshResin, (icly-1)*Nclx + iclx ) % 3rd argument sets max mesh size as MaxMeshResin % 4th argument sets group number as a unique coil number (tricky)
ei_clearselected

% LOOP THROUGH ALL TURNS WITHIN COIL
for ity = 1:Nty % loop through all conductors within this coil
  for itx = 1:Ntx
    % SET UP THE TURN
    tcx = LLHCx + Tl + Te + Rc + (itx-1)*Dcc ; % turn center x coord
tcy = LLHCy + Tl + Te + Rc + (ity-1)*Dcc ; % turn center y coord

    % Assign turn voltage:
    % itx and ity are related to physical position
    % it will follow left to right, bottom to top order
    % assign turn number based on electrical position
    TurnNo = itx + (ity-1)*Ntx + TurnsPer Coil*(iclx-1 + (icly-1)*Nclx)
    TurnVoltage = Vs/(Ntt-1)*((TurnNo-1)*Vs/2 ;
    % Maps TurnNo 1..NNT into voltage -Vs/2...Vs/2
    TurnConductorName = strcat('T',int2str(TurnNo)) ;
    ei_addconductorprop(TurnConductorName, TurnVoltage,0,1)

    % set up conductor
    ei_drawarc(tcx-Rc,tcy, tcx+Rc,tcy,180,10) % sets 40 as segments
    ei_clearselected
    ei_selectarcsegment(tcx,tcy+Rc) ; % point close to arc 1
    ei_selectarcsegment(tcx,tcy-Rc) ; % point close to arc 2
    % Assign conductors to their respective potential
    ei_setarcsegmentprop(5, '<None>', 0, 0,TurnConductorName) % 5 degrees max mesh around the segment % no boundary condition
    ei_clearselected

    % set up block label in conductor
    ei_addblocklabel(tcx,tcy)
ei_clearselected
    ei_selectlabel(tcx,tcy) ;
ei_setblockprop('copper', AutoMeshTrue, 0, 0)
ei_clearselected
% set up enamel
  ei_drawarc(tcx-Rc-Te,tcy, tcx+Rc+Te,tcy,180,10)   % sets 20 as max segments
  ei_drawarc(tcx+Rc+Te,tcy, tcx-Rc-Te,tcy,180,10)   % sets 20 as max segments

% set up block label in enamel
% Add block label at the 10:30 position
  Rlabel = Rc + Te/2 ; % radius at which label will be placed
  sl = Rlabel/sqrt(2) ;  % side of the isosceles right triangle with radius
  ei_addblocklabel(tcx-sl,tcy+sl)
  ei_clearselected
  ei_selectlabel(tcx-sl,tcy+sl) ;
  ei_setblockprop('enamel', AutoMeshFalse, MaxMeshEnamel, (icly-1)*Nclx + iclx )
  ei_clearselected

end  % for itx..
  end % for ity ..
  end % for iclx..
  end % for icly

% ===EXTRA STEPS REQUIRED FOR FAULTED GEOMETRY=====================
if faulted
  LLHCx = (fcx-1)*CoilWidth ;  % LLHC x coordinate for the coil with faulted turn
  LLHCy = (fcy-1)*CoilHeight ;  % LLHC x coordinate for the coil with faulted turn
  extra = Tr/8  % go just a little bit beyond the conductor to help the mesh generator

  % Coordinates of center of lower turn within the faulted pair are tcx, tcy:
  tcx = LLHCx + Tl + Te + Rc + (ftx-1)*Dcc ;  % turn center x coord
  tcy = LLHCy + Tl + Te + Rc + (fty-1)*Dcc ;  % turn center y coord

  % Draw Horiz lines in 1st conductor:
  ei_drawline(tcx+Rc,tcy,tcx+Rc+Te+extra,tcy)
  ei_drawline(tcx-Rc,tcy,tcx-Rc-Te-extra,tcy)
  % Draw Horiz lines in 2nd conductor:
  ei_drawline(tcx+Rc,tcy+Dcc,tcx+Rc+Te+extra,tcy+Dcc)
  ei_drawline(tcx-Rc,tcy+Dcc,tcx-Rc-Te-extra,tcy+Dcc)
  % Draw vert lines connective previous H lines:
  ei_drawline(tcx+Rc+Te+extra,tcy,tcx+Rc+Te+extra,tcy+Dcc)
  ei_drawline(tcx-Rc-Te-extra,tcy,tcx-Rc-Te-extra,tcy+Dcc)

  % add block labels
  db = (Rc+Te/2)/sqrt(2)
  ei_addblocklabel(tcx-db,tcy+db)  % 10:30 on lower conductor (overwrites an existing enamel label by design)
  ei_addblocklabel(tcx-db,tcy+Dcc-db)  % 7:30 on upper conductor
  ei_clearselected
  ei_selectlabel(tcx-db,tcy+db) ;  % center in resin between two
  ei_clearselected
  ei_setblockprop('degraded', AutoMeshFalse, MaxMeshResin, fcx + (fcy-1)*Nclx)
ei_clearselected

% Need to restore label on the bottom conductor since it has been overwritten at
10:30 position
    ei_addblocklabel(tcx-db, tcy-db)  % put it at 7:30 position
    ei_clearselected
    ei_selectlabel(tcx-db, tcy-db)
    ei_setblockprop('enamel', AutoMeshFalse, MaxMeshEnamel, fcx + (fcy-1)*Nclx)
    ei_clearselected
end % if faulted

% ===EXTRA STEPS REQUIRED FOR UNGROUNDED GEOMETRY=====================
if not(groundplane)
    % draw a circle. Generally Nclx and Ncly will be 1, but keep it general in case
    want to try two adjacent coils in slot
    ccenterx = Nclx*CoilWidth/2
    ccentery = Ncly*CoilHeight/2
    maxdim=max(Nclx*CoilWidth,Ncly*CoilHeight)

    % inner arc - just a boundary for mesh setting
    ei_drawarc(ccenterx-5*maxdim,ccentery, ccenterx+5*maxdim ,ccentery,180,50)   % sets
    20 as max segments
    ei_drawarc(ccenterx+5*maxdim,ccentery, ccenterx-5*maxdim ,ccentery,180,50)   % sets
    20 as max segments
    ei_clearselected
    ei_selectarcsegment(ccenterx,ccentery+5*maxdim)
    ei_selectarcsegment(ccenterx,ccentery-5*maxdim)
    % Assign conductors to their respective potential
    ei_setarcsegmentprop(5, '<None>', 1, 0,'<None>')
    % sets it up as hidden from the plotter
    ei_clearselected

    % outer arc - just a boundary for mesh setting
    ei_drawarc(ccenterx-10*maxdim,ccentery, ccenterx+10*maxdim,ccentery,180,50) % sets
    20 as max segments
    ei_drawarc(ccenterx+10*maxdim,ccentery, ccenterx-10*maxdim,ccentery,180,50) % sets
    20 as max segments
    ei_clearselected
    ei_selectarcsegment(ccenterx,ccentery+10*maxdim)
    ei_selectarcsegment(ccenterx,ccentery-10*maxdim)
    % Assign conductors to their respective potential
    ei_setarcsegmentprop(5, 'OuterBoundary', 0, 0,'<None>')
    ei_clearselected

    % set max mesh for inner circle to 5*MaxMeshResin
    ei_addblocklabel(ccenterx+3*maxdim,ccentery)
    ei_clearselected
    ei_selectlabel(ccenterx+3*maxdim,ccentery)
    ei_setblockprop('air', 0, 3*MaxMeshResin, 0)
    ei_clearselected

    % set max mesh for inner circle to 20*MaxMeshResin
    ei_addblocklabel(ccenterx+7.5*maxdim,ccentery)
    ei_clearselected
    ei_selectlabel(ccenterx+7.5*maxdim,ccentery)
    ei_setblockprop('air', 0, 20*MaxMeshResin, 0)
    ei_clearselected
end
% =======PROBLEM DEFINITION COMPLETE. REMAINING STEPS PROVIDE OUTPUT===================

% construct identification string for this run based on MMDD HHMM

c=clock
runlabel = strcat(num2str(c(2),'%02.0f'),num2str(c(3),'%02.0f'),num2str(c(4),'%02.0f'),num2str(c(5),'%02.0f'))
ei_saveas(strcat(runlabel,'.fee'))

% tell FEM to analyse the geometry
ei_analyse

% bring up solution window
% Comment out selected displays
Vplotmax = -Vs/2 + (TurnsPerCoil*Nclx*Ncly-1)*Vs/(Ntt-1)
ei_loadsolution
eo_hidenames
eo_hidepoints
eo_showcontourplot(20,-Vs/2,Vplotmax)
pause % can get the big picture now

% now get energy and capacitance info - (note may not have enough capacitance decimal points here ... look at output file)
% Energy is a factor of 2 off if we consider Vs as rms, but the calculated capacitances are correct.
eo_hidedensityplot % won't be able to see it once select block anyway -> get rid of legend
eo_showcontourplot(50,-Vs/2,Vplotmax) % use a more dense contour plot since don't have to worry about obscuring color

eo_groupselectblock
Etotal = eo_blockintegral(0)
c = 2*Etotal(1)/(Vs)^2
mystring=strcat('Energy=', num2str(Etotal(1)), 'J/m, Ceq=', num2str(c),' Farads/m')
messagebox(mystring)
eo_refreshview
pause

% zoom to the fault
eo_zoom((fcx-1)*CoilWidth,(fcy-1)*CoilHeight,fcx*CoilWidth,fcy*CoilHeight)
eo_clearblock

eo_showdensityplot(1,0,-Vs/2,Vplotmax,0)
eo_showcontourplot(50,-Vs/2,Vplotmax)
pause

% ====== GENERATE OUTPUT REPORT ======================

fid = fopen(strcat(runlabel,'.txt'),'w');
fprintf(fid,strcat('Output file generated by program:',programname))
fprintf(fid,'
')
fprintf(fid,strcat('Run Label (MMDDHHMM):',runlabel))
fprintf(fid,'
')
fprintf(fid,strcat('Inputs are as follows: 
'))
fprintf(fid,'faulted (1 for yes, 0 for no): %1.0f 
',faulted)
fprintf(fid,'groundplane (1 for grounded slot model, 0 for ungrounded): %1.0f
',groundplane)
fprintf(fid,'Nclx and Ncly (number of coils in x and y directions): %2.0f and %2.0f
',Nclx,Ncly)
fprintf(fid,'Ntx and Nty (number of turns in x and y directions): %2.0f and %2.0f
',Ntx,Nty)
fprintf(fid,'Rc (Radius of Conductor): %4.2f mm 
', Rc)
fprintf(fid,'Te (thickness of enamel per side): %4.2f mm \r\n', Te)
fprintf(fid,'Tr (thickness of resin betw enamel of adjacent conductors): %4.2f mm\r\n', Tr)
fprintf(fid,'Tl (thickness of resin betw enamel and side of slot): %4.2f mm \r\n', Tl)
fprintf(fid,'EpsilonR_Enamel (relative dielectric const): %4.2f \r\n', EpsilonR_Enamel)
fprintf(fid,'EpsilonR_Resin (relative dielectric const): %4.2f \r\n', EpsilonR_Resin)
fprintf(fid,'EpsilonR_Degraded (Relative dielectr const): %4.2f \r\n', EpsilonR_Degraded)
fprintf(fid,'Vs (test voltage): %4.2f V \r\n', Vs)
fprintf(fid,'MaxMeshResin and MaxMeshEnamel(max FE mesh size here): %4.2f and %4.2f mm \r\n',MaxMeshResin,MaxMeshEnamel)
fprintf(fid,'fcx,fcy,ftx,fty (parameters identifying faulted coil/turn loc): %2.0f, %2.0f, %2.0f, and %2.0f \r\n', fcx,fcy,ftx,fty)
fprintf(fid,'SeriesCoilsUG (Series Coils betw terminals for UG calc): %4.0f mm \r\n', SeriesCoilsUG)
% fprintf(fid,'myprecision (tolerance for residuals, argument to ei_probdef): %4.0f mm \r\n', myprecision) % WRONG
fprintf(fid,'myprecision (tolerance for residuals, argument to ei_probdef): %6.4f \r\n', myprecision)

eeo_clearblock
eo_groupselectblock % select everything for final energy (outer circle not incl in previous coil)
W = eo_blockintegral(0) % Energy
fprintf(fid,'Total energy is %15.10g Joules per m \r\n', W(1)) % increased decimal places 11/30/08
C = 2*W(1)/Vs^2
fprintf(fid,'Equivalent Capacitance at %2.0f volts is %15.10g F per m \r\n', Vs, C) % increased decimal places 11/30/08
fclose('all')
z=runlabel % sends runlabel to the screen for easy cut/paste
Appendix 8. Changes to this report
12/03/08 - Posted as Rev2
12/04/08 – Revisision 3

- Added this list of changes
- In Appendix 4, corrected arccos to arccosh and added additional intermediate calculation details. Carried more significant figures.
- Updated Appendix 5 with changed capacitance result from Appendix 4 (more significant figures)
- Corrected page 2 (Analysis) reference to Appendix 6 for program run text files
- In Appendix 7 added comments explaining the meanings of fcx, fcy, ftx, fty
- Corrected Table 3, Table 6, Table 7 and Table 8 to refer to Appendix 3 vs 2 for inductive current.
- Rev 3a, 3b – corrections in rev numbers and further typo correction in App 5.

Revision 4
- Revised the list of appendices to include appendix 8
- Added some additional explanation of the calculation performed in Appendix 5
- Correct the spelling of the word "estimation" in the title of Appendix 5
- Corrected typographical error: "5*LRA" to "5*FLA" in Appendix 3