Use of Electric Motor Surge Testing as a Predictive Technology

The advantages and cost savings predictive maintenance (PdM) technologies and programs can yield is well documented. The surge test has always fallen into a “go, or no-go” category as a test used in PdM as it is applied to motors. With the advent of SKF’s Baker AWA-IV software, the pulse-to-pulse EAR (Error-Area Ratio) has opened the door to make surge a predictive maintenance test. In this case study we show the advantages of using pulse-to-pulse EAR. Before proceeding, the EAR algorithm will be explained. The formula that calculates the EAR between two waveforms F1 and F2 is shown below.

\[
EAR_{1,2} = \frac{\sum_{i=1}^{Npts} \text{Abs} (F_{i}^{(1)} - F_{i}^{(2)})}{\sum_{j=1}^{Npts} \text{Abs} (F_{j}^{(1)})}
\]

Basically, the EAR is the area between two waveforms normalized by the area of one of the waveforms. Graphically, the EAR is as shown in Figures 1, 2 and 3.
Figure 1 shows two waveforms with a slight separation. These will be the two waveforms that will be put into the EAR calculation. The EAR is the pink “difference” area of Figure 2 divided by the blue area of Figure 3.
Although the formula looks complicated, the concept of the EAR is simple. The pulse-to-pulse EAR is the application of the EAR formula to two consecutive waveforms acquired during a surge test of a motor.

The SKF Static Motor Analyzer Baker AWA-IV is a portable surge tester that uses the EAR algorithm to automatically find failing insulation. Here is how it works: the Baker AWA-IV automatically applies a number of successive surge pulses to a motor the analyzer is connected to. Each successive pulse is applied at a slightly higher test voltage than the previous pulse. The test voltage starts at zero, and goes up to a user-defined maximum test voltage. The Baker AWA-IV digitizes each surge waveform, displays the waveform on the tester’s front panel, and performs real time PP-EAR calculations using (this) waveform and the previously-acquired waveform. The resulting PP-EAR value is then plotted on the tester’s screen just below the acquired waveform. Since each waveform often varies slightly higher than the previous one, a nonzero PP-EAR value should be expected. Even so, this PP-EAR value should be fairly small – around 2 to 5 percent – and it should also be close to the same value as previously-calculated PP-EAR values.

If all is well, the PP-EAR values should be nearly the same. If not, something other than the increase in applied test voltage has changed the shape of the waveforms. A turn-to-turn insulation failure such as the one showed in Figure 4 below will cause the PP-EAR value to increase suddenly.

![Figure 4: Sudden increase in PP-EAR value](image)

Figure 4 is taken directly off of a Baker AWA-IV analyzer display. The screen includes a number of sections: the upper left is where the test voltage and “ramp” rate are entered, the top center section is where pass/fail criteria are entered, and a plotting area where the surge waveform and PP-EAR values are displayed. In this case, the coil experienced a turn-turn short as indicated by the jump in PP-EAR value above the user defined set point of 20 percent. The red waveform is the failed waveform, and the blue waveform is the “previous to fail” waveform. The PP-EAR value comparing these two waveforms was 92 percent.

**Pulse-to-pulse EAR as a predictive test**
The PP-EAR can be used in a predictive manner to indicate the existence of damage to the turn-turn insulation in a motor before the motor experiences a catastrophic turn-turn insulation failure. This conclusion has been arrived at by reviewing the test results of many motors both “known” to be good as well as motors that have failed in service.

Figure 5 below shows the surge waveforms and the pulse-to-pulse EAR graph for a good motor. The PP-EAR graph is an expectable PP-EAR trend line with the 10% alarm set point. It is clear that there is very little change to the PP-EAR trending values as the voltage is increased for the surge test.

Motor 3072 (Figure 6)
This motor is a 575V -100 hp motor that went to ground after only two weeks of service. It had been “on the shelf” for some time before installation, but was expected to have a reasonable service life of many years. Figure 6 below shows the results of surge testing the motor after it had failed and been removed from service.
There are three surge waveforms displayed indicated by the purple, green and blue waveforms. These are the final waveforms for each of the three phases A, B and C. The PP-EAR graph in the lower right corner shows the PP-EAR data gathered during the test. Clearly Lead 3 / Phase C shows erratic behavior of the PP-EAR numbers. In this example, the Baker AWA-IV operator (Kevin Deverell of RCM Technical Inc., Canada) deliberately increased the allowable limit of the PP-EAR numbers to 40% so that the surge test would run to completion without failing. Normally, the limit of PP-EAR is set to 10% or lower. It is clear that wild and erratic PP-EAR numbers are an indication of turn-turn insulation problems, at least in this case after the motor has failed. (This motor faulted to ground: there was burned insulation and possibly splattered copper and steel on the windings.)

**What about erratic PP-EAR values before failure?**

**Motor 6658 (Figure 7)**

Motor 6658 shown below is a spare 4160V - 400 hp that was on the shelf ready to be installed should the need arise.

![Figure 7: Motor 6658 (4160V/400hp) in storage, ready for installation](image)

Once again, there are three waveforms displayed that are the final waveforms for phases A, B, and C on the motor. The PP-EAR graph shows Lead 1 / Phase A has a rather erratic set of PP-EAR values at the beginning of the test. However, the maximum value did not exceed the 10% value set by the operator of the static motor analyzer.

Apparently, the waveform did not jump enough to be seen by the operator or the other failure detection algorithms in the Baker AWA-IV. Since the waveforms for all three phases are on top of each other, it is clear that the waveforms never really showed a significant jump. However, the very sensitive nature of the EAR algorithm did "see" a change in the waveform of Lead 1 / Phase A. It is very reasonable to conclude that Lead 1 / Phase A has poor turn-turn or possibly even poor ground wall insulation. The indications were so slight that the problem was missed by the human eye but was easily recognizable by the PP-EAR algorithm.

Before this motor was put back on the self as a standby, it was run in high loaded conditions. So, although motor 6658 did not fail this test, it is indication of deterioration of turn-to-turn insulation. If this motor were
to be put into service the life expectancy would be significantly shorter than a new motor. The same applies to the test results on the second motor below.

![Figure 8: Motor 4089 (575V/100hp) in storage, ready for installation](image)

**Motor 4089**

Motor 4089 (Fig. 8) is 575 100 hp on the shelf, ready for service. The results of the surge test below again show an erratically fluctuating PP-EAR for all three leads.

Although this motor did not fail the preset 10 percent alarm levels, a reasonable conclusion can be drawn that there is a problem with this motor. To get a better overview how often this occurrence happens these results were from a batch of 90 motors tested. Out of the 90 spare motors, two of them had these erratic PP-EAR trend lines.

**Motors with a bolted or welded short**

Damaged turn insulation in windings often allow adjacent copper coils to come into contact with one another. So much heat is created as a consequence that the copper coils weld to each other. It is well known that motors with bolted faults don’t last long in service. They will fail in minutes to hours. Such motors can show high vibration, high operating temperatures, and unbalanced operating currents.

The surge test is able to find a number of these situations by comparing the waveforms of each phase to each other. If one waveform is very much different than the others, there must be a different inductance in the affected phase that causes the different ringing pattern. Care must be taken to avoid confusion with waveform differences caused by rotor coupling. Typical rotor coupling can be seen in the differences between the waveforms in Figures 5 and 8. Often there is no rotor coupling as shown in Figure 7.

**Motor 7369 (Figures 9, 10, and 11)**

This motor was tested after it failed to establish the root cause of the failure. Measurements made by the Baker AWA-IV showed that the motor failed everything: phase resistances were unbalanced, the ground wall insulation failed the hipot test, and the surge failed.

As shown in the figures below, Lead 1 / Phase A has a bolted fault that – the waveform never shifted because winding has a completely welded connection between two coils. Notice the PP-EAR values are all “normal” and also notice the maximum PP-EAR limit was set to 60 percent - normally it is 10 percent.
Final example of the sensitivity of PP-EAR
Figure 12 below shows the PP-EAR finding a problem with the turn-turn insulation in a small stator. The two waveforms indicated by the blue line and the red line are the previous to fail and the failed waveforms. As can
be seen, the red waveform has jumped slightly and dropped in amplitude slightly. These two waveforms have an EAR of 13 percent, which exceeded the user set maximum of 6 percent. Note there are also fairly erratic PP-EAR values up until the insulation catastrophically failed.

**Figure 12: Turbine generator with turn-to-turn insulation failure**

This particular stator uses “hairpin” coils that are inserted one at a time into the slots of the stator. The ends of the hairpin coils are then soldered to each other with a silver brazing process as shown in Figure 13.

**Figure 13: Hairpin coil end turns**

Unfortunately, the brazed ends are very sharp and are un-insulated, which allows a significant amount of discharge to occur. The suggestion that the erratic PP-EAR values are an indication of discharge is reasonable,
and also suggests the erratic PP-EAR values of those motors above are caused by small discharges in the winding.

**Conclusion**

Historically, the surge test was implemented by comparing the waveforms of the three phases of a motor to each other. Differences in shape of the waveforms were used to identify turn insulation damage. In 1995, portable computer controlled surge testing equipment became available which allowed for real time analysis of the surge waveforms. Such analysis made it possible for the computer to identify arcing turn-turn faults in failing insulation and automatically stop the test at the first indication of failure. Additionally, the computer controlled testers could now quantifiably determine the difference between the waveforms of each phase allowing a much more consistent application of the surge test: the instrument operator did not have to be expertly trained to recognize the changes in the waveform shape that indicated an arcing fault occurred. The error-area ratio was developed in the effort to automate the analysis of waveforms and give a number to the differences in waveforms.

Since 1999, the EAR algorithm has been used on successive pulses within a phase’s surge test. Early applications of PP-EAR showed that the computer controlled tester was actually better at “seeing” turn insulation failure. In the past few years, more and more experience has been gained and it is now clear that the PP-EAR holds more information regarding the health of turn insulation. This new information allows the surge test to be considered a predictive test as opposed to a basic pass/fail or go/no go test. Users of the PP-EAR equipped instruments can now identify weakening turn insulation before a full turn-turn arc occurs as demonstrated by the test results shown in this paper.