Fault Zone Analysis “ROTOR”
Presented by: Luis Leon at the 2007 Motor Reliability Technical Conference
Company: PdMA Corporation
Department: Technical Support & Training

INTRODUCTION
The rotor is the most stressed component of a Three Phase AC Induction Motor. The purpose of this article is to identify causes of rotor and rotor bar failure and possible testing methods used to find such faults. Although written for three phase squirrel cage induction motor, this article can be applied to other motor types.

Various stresses can cause rotor failures: thermal, magnetic, dynamic, environmental, mechanical, and residual. When installed and operated as designed, the stresses remain within tolerance and the motor operates properly for years. When any of these stresses are above allowable levels, the life of the motor is greatly reduced.

THERMAL STRESS
Thermal overload for the rotor can occur during starting, running, or stalled conditions. When the motor is stalled or locked, there is a very high potential for damage to the rotor in the shortest amount of time. The best way to protect the rotor from thermal overload and damage is with current sensing devices, which measure the currents and can trip the motor power supply. The following are causes of some of the most common thermal overload problems:

- Excessive number of motor starts
- Rotor stalling
- Bearing failure or misalignment resulting in rotor rub
- Insufficient airflow
- Unbalanced phase voltage causing negative sequence currents

Thermal overloading can be detected by inspecting the rotor for signs of overheating. An obvious indication is melted cage material.

Thermal imbalances also exist in rotors and can be caused by starting or running conditions. Some imbalances are due to design or operation of the motor outside the design parameters. Some causes of imbalance are:

- Frequent starting
- Uneven heat transfer between rotor core and bars
- Rotor bowing due to thermal cycling
- Vibration from uneven fit between shaft and rotor
- Hot spots on the rotor
- Uneven circulating currents caused by broken bars

Thermal imbalances are difficult to correct since test data is not always repeatable. It is fairly easy to measure vibration levels and determine if the machine is temperature sensitive, but it is hard to determine the exact reason.

Tests performed to find rotor problems might consist of:

- Rotor Influence Check (MCE)
- In-Rush/Start-Up (EMAX)
- Rotor Evaluation Test (EMAX)
- Advanced Spectral Analysis (EMAX)
- Growler
- Single-Phase
- Ultrasonic
- No Load Saturation
- Motor monitoring during operation on test stand
Rotor sparking is another failure mechanism for fabricated rotors when the condition is severe. During across the line starting, the current in the rotor is from five to ten times normal and in some designs is even higher. The magnetic force resulting from this high starting current causes the rotor bars to vibrate radially. This vibration in the rotor slot may cause breaks in the current flow between the rotor and laminations, which results in sparking. When motor sparking occurs during startups, the sparking period is brief and doesn’t normally reduce the life of the motor. Destructive sparking occurs with broken rotor bars or with defective connections in the end rings. The tests used to determine if a rotor may have sparking problems are the same tests used to find broken rotor bars or cracks in the end rings.

**MAGNETIC STRESS**
Dynamic forces are generated due to slot leakage flux, which are proportional to the rotor current squared. These magnetic forces vibrate the bar and displace it radially. This magnetic force will cause the rotor bar to bend and could result in fatigue failure. When the magnetic field is unbalanced the rotor will tend to be pulled out of center and could hit the stator causing severe damage to the motor. When the motor is started, the currents are highest and therefore the magnetic forces are highest. The probability for the rotor to be pulled out of center is highest during motor startup. Eccentricity can also cause problems such as noise and vibration. There are several causes of eccentricity that may be encountered such as the rotor outer diameter being eccentric, stator bore eccentricity, different axis of rotation between the rotor and the stator, or shaft out of round.

**DYNAMIC STRESS**
Rotor shafts undergo a tremendous amount of torque and must be designed for continuous operation with the resultant stress. Excessive torque levels above design will shorten the life of the motor. Some examples of excessive torque are those that occur during starting or bus transfers. Another dynamic stress occurs when the rotor rotates. Excessive centrifugal forces in the rotor can cause the rotor to fly apart during operation. Motors designed within NEMA limits should be able to handle up to 20% overspeed for two-pole motors and 25% for slower motors.

**ENVIRONMENTAL STRESS**
Environmental stress can be anything in the motor environment that affects the life of the motor. Such stresses are poor ventilation, chemical attack, high humidity or moisture, or anything in the environment that attacks the rotor and breaks down the rotor material. If the motor application will be in a harsh environment, the motor manufacturer can apply additional protection for the motor.

**MECHANICAL STRESS**
There are many common stresses, which fall into the mechanical stress category. These stresses include casting defects, loose laminations, broken parts, incorrect fitting, incorrect air gap, bent shafts, bearing failure, misalignment, and incorrect materials.

**RESIDUAL STRESS**
Residual stresses do not normally damage the rotor as long as they do not change the geometry of the rotor. Some of the most common of these stresses are due to welding, casting, machining operations, and brazing. These stresses can result in changing the rotor geometry in the transition from cold iron off condition to full-load running condition as the rotor thermal condition changes.

**DETERMINING CAUSES of ROTOR FAILURE**
Finding the cause of rotor failures can be a long, detailed process. Many things such as how the rotor failed, the rotor appearance, application, and the history of the motor must be taken into consideration. Many times some of the information needed such as the motor’s maintenance history will be difficult, if not impossible, to find. When analyzing a rotor failure, inspect the shaft, bearings, lamination, rotor cage, ventilation system, and, of course, the stator. Any information gathered during the inspection process will help in determining the method of failure.
Looking at Figure 1, what is the possible cause of rotor failure?

The end result in this picture is that the rotor is falling apart, but what started it? Was it a bearing fault, excessive starts, or a poor ventilation system? In this example, the rotor was started an excessive amount of times. The continuous stress from the starting currents overheated the rotor causing the rotor bars, shorting ring, and laminations.

Figure 1: Squirrel Cage Rotor

BROKEN ROTOR BARS
Broken rotor bars do not normally result in an immediate failure of the motor. Broken bars can cause a loss of torque and increased heating and stressing of adjacent bars. Being able to detect broken bars early reduces down time and lowers repair costs since the repairs are usually only for the rotor. If the bars are not repaired and the motor continues to operate additional bar breakage is likely as well as damage to other components in the motor. The more rotor bars that break, the larger the loss of torque and the higher the current in adjacent bars. The higher current causes higher temperatures in the area near the broken bars and will also cause stator damage due to excessive heat. Oscillations in speed and torque are indications of broken rotor bars, which can cause increased wear of other motor components. Use of the MCEmax tester can provide for early detection of rotor problems.

MCE ANALYSIS
The MCE tester has two tests that address the rotor fault zone. The Rotor Influence Check (RIC) and the AC Standard Test.

The MCE RIC utilizes inductance measurements to create a graphical representation of the rotor-stator relationship. Figure 2 is an example of satisfactory results for a RIC test. Positioning the rotor through 18 points of one complete pole face, allows for analysis of winding condition, rotor condition, and air gap eccentricity. These points are at specific increments, determined by the amount of poles of the motor.

Figure 2: Satisfactory RIC Results
High resistance and broken rotor bars will reveal themselves as repeated distortions in all three phases of the RIC graph. An example of this is shown in Figure 3. This is the result of the distorted residual magnetic flux that develops in the area of the cracks or high resistance connections of the squirrel cage rotor.

![Figure 3: Broken/High Resistance Rotor Bars](image)

**A note about RIC testing:**

With regard to 3-phase AC induction motors, there are two basic types of rotor construction. There is a cast aluminum/alloy type and a copper/alloy bar fabricated type. Along with being different types of construction, they also have different characteristics when testing.

**Cast rotor:**
- Rotor holds a strong residual magnetism
- Rotor develops a sinusoidal graph of inductance (RIC)
- Some defects (porosity) are common from the manufacturing process

**Fabricated rotor:**
- Rotor does not hold a strong residual magnetism
- Rotor develops a straight line graph of inductance (RIC)
- Very high quality from the factory, but more susceptible to failure from external stresses

**AC Standard Test**

Variations in a motor’s Inductive Imbalance over time, coupled with a steady upward trend in Average of Inductance in the MCE Standard Test indicate the possibility of rotor cage degradation. Such changes should be an indication to perform or increase the frequency of the RIC testing on the specific motor. Figure 4 shows an example of an upward trend of Average Inductance on an AC Standard Test.
Figure 4: Standard Test History

**EMAX Analysis**

The EMAX tester has several additional tests addressing the rotor fault zone. The Rotor Evaluation Test, Advanced Spectral Analysis, and In-Rush/Start-Up capture help us determine the condition of the motor’s rotor.

In the Rotor Evaluation Test Spectrum, we must first determine pole-pass frequency ($F_p$). Pole-pass frequency is directly related to the operating speed of the induction motor. Simply put, pole-pass frequency is the rate at which the rotor bars are being passed by the synchronous magnetic pattern developed by the stator. The more slip as the load increases, the higher the pole-pass frequency. The formula below shows this relationship.

$$F_p = \frac{(\text{Syn RPM} - \text{RPM}) \times (\# \text{POLES})}{60}$$

By identifying the speed of the motor, either through Demod or the use of a tachometer, the system determines the $F_p$. Rotor bar issues reveal themselves as $F_p$ sidebands at the fundamental line frequency. Figure 5 shows these $F_p$ sidebands at the 60 Hz line frequency peak for a 4-pole induction motor. The $F_p$ in this test was 1.20 Hz. Once identified, the amplitude of these sidebands in relation to the line frequency peak is used to diagnose rotor condition.
Swirl Effect

In addition to evaluating the amplitude of the $F_p$ in relation to the line frequency to determine rotor health, a damaged rotor will also cause a phenomenon called swirl effect. This swirl effect is an additional indication of a damaged rotor and appears in the spectrum just below the 5th harmonic. It appears as three evenly spaced spikes in the current spectrum to the left of the 5th harmonic. The spacing between these spikes will be the same as the pole-pass frequency. There is no specific amplitude evaluated.

The presence of the swirl effect is an additional indication of possible rotor problems. Note the swirl effect in the motor current spectrum shown in Figure 6 from the same 4-pole motor discussed earlier. The frequency span between the swirl peaks is 1.20 Hz, which is equal to the $F_p$ identified in Figure 5.
**In-Rush**

With the In-Rush capture, over time and with trended information, we look for changes in the In-Rush current characteristics. Increases in acceleration time for the same load, current modulation at the crest of the graph, and the increase in running current are all possible signs of rotor degradation. Figure 7 shows an In-Rush current capturing showing the current modulation at the crest of the graph.

![Figure 7: In-Rush Tests Results](image)

**ROTOR FAILURE ANALYSIS**

We have examined several different types of rotor failures and generally it is difficult to determine the exact initial cause of the failure. By examining all the data available for the motor in question, it becomes easier to find the cause of the failure and determine how to prevent it in the future.

Thermal failures are probably the easiest to find since heat damage can be found with a visual inspection of the rotor and stator. When inspecting the rotor, check for melted metal in the rotor and stator, hot spots on the rotor (indicated by blue spots), melted paint on the rotor surface, melted air passages, and perhaps even rotor bowing due to excessive heating.

Magnetic failures are harder to determine due to the nature of the failure. Items to examine as possible causes are rotor pull-over, circulating currents, lamination saturation, and uneven magnetic pull on the rotor. Performing an eccentricity test using the EMax will help in the analysis for magnetic failures. A Rotor Influence Check using the MCE will also provide useful data for determining if the motor has a magnetic failure. Physical evidence of magnetic failure is a rub spot where the rotor comes in contact with the stator during motor operation. If the magnetic failure does not cause physical contact between the rotor and stator, the problem is very difficult to visually detect and will require measuring clearances and analyzing magnetic forces in the motor. Magnetic failures can sometimes be detected by listening to the motor during startup and normal operation, since loose rotor bars may exhibit noise.

Dynamic failures fall into several categories such as vibration, rotor rubbing, over-speeding the motor, cyclic stress, loose rotor bars, and high transient torque. Broken shafts and possibly failed bearings are the result of transient torque, vibration, and cyclic stress. Over-speeding the motor usually results in broken fans, high vibration level, and failed couplings. These are just a few examples; there are many more possibilities. These dynamic failures usually destroy the motor due to their catastrophic nature. Finding the cause of dynamic failures can be very difficult since these forces are usually external to the motor and not available for analysis after the motor has been removed for repair or replacement.
severe bearing failure allows the rotor to come in contact with the stator resulting in extensive damage to both. Over-speeding the motor damages the entire motor. Finding broken bars can be accomplished using data obtained from the Rotor Influence Check and Low/High Resolution tests. The single-phase voltage test looking for current changes of more than 5%, which usually indicates a broken rotor bar, can also be used to find broken rotor bars.

Environmental failures are also easy to find and this usually consists of a visual inspection. Some issues to look for are contamination, high temperatures, restricted cooling to the rotor/motor, debris, and abrasion. An environmental failure can be caused by lack of maintenance or the wrong motor for the job. Should an open frame motor be used in an industrial area with high contamination? Dirt, debris, dust, and other foreign materials will clog filters and air passages in motors/rotors.

Mechanical failures are also difficult to identify since the failure can look like many other failure causes. Porosity or casting voids in the rotor, loose rotor bars or laminations, improper alignment or mounting of the motor, or perhaps the wrong motor for the application can cause some mechanical failures.

**SUMMARY**

Motors can fail for many reasons; sometimes the cause of the failure isn't determined until the failure has occurred several times. For this reason, it is imperative that as much investigation as possible be performed to determine the cause of the failure in order to prevent future failures and lost revenue. By examining all of the evidence gathered, the cause of the failure should be identified, corrected, and prevented from re-occurring.