ROTATING MACHINES WORKING GROUP

MINI SURVEY ON CRACKED/BROKEN ROTOR BARS

CONTRIBUTION BY DAVID BRAUDE

At the Meeting of the Rotating Machines Working Group held on 2 November 2005 at the University of the Witwatersrand, Mr. Herman van der Merwe of Marthinusen & Coutts and Mr. Kahesh Dhuness of the University of Johannesburg delivered presentations on their research work on cracked/broken rotor bars. The discussion on these presentations reached the conclusion that the problem deserved more attention. Therefore, the Chairman proposed, and those present agreed, that a mini survey be conducted amongst the members of the RMWG to ascertain the extent of the problem and possibly identify causes with greater clarity.

The following response is based on my personal experience.

After graduation at UCT and a two-year period in manufacturing in the electrical engineering industry in England, I joined the South African gold mining industry in 1954. As early as the late 1950's, I experienced cracked and broken copper rotor bars in the single cage squirrel cage rotors of 2200 volt induction motors. These motors were the drives for main clear water mine dewatering pumps. Apart from the rotor bars having burnt partly through the rotor laminations in several cases, there was at least one case where a broken rotor bar had moved axially along the slot with its end protruding outside the slot. This end of the rotor bar had also bent radially outwards and had cut into the stator windings. This, of course, resulted in the complete failure of the motor. At that stage, nobody on the mine or in the mining group head office had any idea as to the cause of this type of failure.

To put this type of failure in context, it must be noted that, although this type of failure was experienced over the years from time to time in 2200 volt and 6600 volt squirrel cage induction motors, it did not happen frequently.

Regarding low voltage motors, that is, 500/550 volt (525 volt), 380 volt and 220 volt motors, rotor failures, if any, were not the focus of attention in those early years and for many years after that, because we were very involved with, and concerned by, the high rate of stator winding failures and bearing failures in these motors.

From the late 1960's the trend in our mining group was to purchase new 6600 volt motors rather than 2200 volt motors. As already stated, failures due to cracked/ broken rotor bars in 6600 volt squirrel cage induction motors did not happen frequently. Although such a failure could lead to a catastrophic failure of the motor, the frequency of such an occurrence was so rare that it was not a major concern. However, in the 1970's we introduced major improvements to the designs of new

6600 volt squirrel cage induction motors purchased for mines in our group. Over the years that we used such improved-design motors, we never experienced any cracked/ broken rotor bars, let alone any subsequent motor failure. In order to understand how this came about, it is necessary to explain the circumstances that led to this development.

From the late 1960's major motor failures of 6600 volt squirrel cage and slipring induction motors (other than failures due to cracked/broken rotor bars) became ever more frequent and began to occur earlier in the lives of these motors. We began to experience very early failures of brand new 6600 volt induction motors driving large and important machines. We were losing production. This was extremely serious. We had a crisis on our hands.

In that era, our mining group's enquiries for such large motors had been made on the basis of very brief specifications, with reliance on BS2613, and motor selection was based on price alone. The motor manufacturers were able to exploit the gaps in this poor enquiry procedure and selection process. Consequently, the motor manufacturers supplied motors of poor design and manufacturing quality. It is arguable that the motor manufacturers were forced to drive quality out of the motors through price competition.

Our mining group was not alone in suffering these problems. Such problems were widespread in South African heavy industries. Incidentally, a consequence of this troubling situation was that the Rotating Machines Working Group was established at that time as a forum for the discussion of these problems.

The reaction of our mining group to these serious motor failures was to become far more careful and circumspect in making enquiries for 6600 volt motors and in adjudicating the tenders offered for such motors. Detailed enquiry documents for 6600 volt motors were developed. These enquiry documents required tenders to include detailed technical and design information regarding the motors offered. Selection was based on both technical merit and price.

One consequence of this improved enquiry and adjudication process was the selection of induction motors having comparatively high D/L ratios, where
D = Rotor core diameter, and
L = Rotor core length

In other words, we avoided "sausage" machines.

By comparison with a high D/L ratio induction motor, the low D/L ratio induction motor has lower manufacturing cost, and so a lower purchase price. From the user's point of view, the low D/L ratio induction motor comes at a lower first cost, but its reliability is low, sometimes catastrophically low, so that its total lifetime cost is high. The high D/L ratio induction motor has higher first cost, but a low total life cost.

It is important to note that these criteria were based on considerations other than overcoming rotor bar failures.

However, the concept of selecting high D/L ratio induction motors matched well with the concept that double cage squirrel cage rotors were sounder than single cage squirrel cage rotors. Therefore, the vastly improved and, in fact, completely reliable generation of high D/L squirrel cage induction motors incorporated double cage squirrel cage rotors in their design and construction. In the period of up to about 15 years that these motors were in service until I retired in 1992, no rotor bar failures were experienced in these motors. In fact, none of these motors failed or gave any trouble of any sort whatsoever.

It is most important to bear in mind that the double cage squirrel cage rotor is a basic textbook design fundamental. To quote one alternating current machine textbook (Puchstein and Lloyd):

" Two squirrel cages are used on the same rotor core: one of high resistance and low reactance close to the rotor surface; the other of low resistance and high reactance (deeper, further from the rotor surface). At starting, the rotor frequency is high and the high-resistance winding carries most of the current; the low-resistance winding is ineffective because of its high reactance. This gives good starting torque. When running, more of the current is carried by the low-resistance winding and the copper loss is not excessive. "

Putting it in other words, in a squirrel cage induction motor two significantly different conditions must be satisfied. In order to satisfy these two conditions two solutions are necessary, that is, two separate squirrel cages, each correctly designed for its duty, are necessary. One solution, that is, a single cage squirrel cage rotor cannot properly satisfy both the starting and running conditions no matter how the single cage rotor is designed and configured dimensionally and materially.

Any single cage squirrel cage rotor must be recognized for what it is: a compromise between the starting requirement and the running requirement. Such a compromise is done in by far the majority of induction motors in order to achieve low first cost. However, it is no good crying when we have to pay the penalties.

In the presentations delivered on 2 November 2005 on research work on cracked/broken rotor bars, mention was made of the drive applications and the sizes of some of the motors involved. Certainly, the motors mentioned are of such importance and calibre that they should never have been designed, ordered, manufactured and used as single cage squirrel cage induction motors.

As already mentioned above, the improved generation of squirrel cage induction motors in our mining group incorporated double cage squirrel cage rotors in their design. However, the design of the double cage rotor included a special and important feature. This can be seen in the diagram on Page 6, showing a sectional view of a rotor slot.

The material of the outer starting squirrel cage rotor bar is copper alloy having a high resistivity. On the other hand, the material of the deeper running squirrel cage rotor bar is near-pure copper having a high conductivity. It can be seen that the cross-sectional area of the outer starting squirrel cage rotor bar is considerably greater than the cross sectional area of the deeper running squirrel cage rotor bar. The large cross–sectional area of the outer starting squirrel cage rotor bar provides the thermal capacity to absorb the heat generated during starting and so keeps down the temperature rise of that rotor bar during starting. Another advantage of the large cross-sectional area of the outer rotor bar is that it provides great mechanical and structural strength to that bar.

It may be noted that in many poorly designed double cage squirrel cage rotors the outer starting squirrel cage rotor bar has a cross-sectional area ***less*** than that of the deeper running squirrel cage rotor bar.

Also, in many single cage squirrel cage rotors, the bar material is high conductivity copper, but the outer part of the bar is ***reduced*** in cross-sectional area to provide greater resistance for the purpose of starting. This is a formula for eventual bar failure.

In 1992 I retired from the mining group I had worked for since 1954. I then began to work in a private consulting capacity. In 1993 I was approached by a large South African mining and mineral processing company to investigate squirrel cage induction motor failures, particularly involving broken rotor bars in motors made by a local manufacturer. These failures involved copper rotor bars broken through at the end rings. Other failures involved casting problems with cast aluminium rotors. The client mining company reported that it had been in contact with two other large South African industrial companies that had experienced similar problems.

I conducted a detailed investigation and submitted three lengthy reports to my client. This work revealed much which would be of interest to members of the RMWG. However, these reports were confidential. For the present purpose, what is significant is that the client company had experienced many problems with cast aluminium rotors, particularly broken rotor bars, bars not bonded to the rotor core, bars of reduced cross-sectional area, blow holes and signs of porosity. The client company had experienced great difficulty in understanding what was going on, and it had taken the client company three years to focus on the problem. This was before I came into the picture. The client company reported that it had lost 43 cast aluminium rotors in the period between 1991 and 1993, and that in several cases the motors did not actually fail due to defective rotor bars, but the defects were picked up during routine inspections, bearing changes and the like. Most of the rotor failures occurred within three years, but one rotor failure had occurred in five months.

My investigations into the possible causes of cast aluminium rotor failures involved inspections of the factory concerned and gave me an insight into the considerable manufacturing problems and testing problems involved at that time. It would be interesting to know the present state of the art in these areas. This is relevant because cast aluminium rotors are so widespread. It was reported in a paper published in the IEE Power Engineering Journal April 1995 that " until recently aluminium die-cast rotors were used only on low power motors (<200kW), but they are now found in motors rated up to 3000kW. "

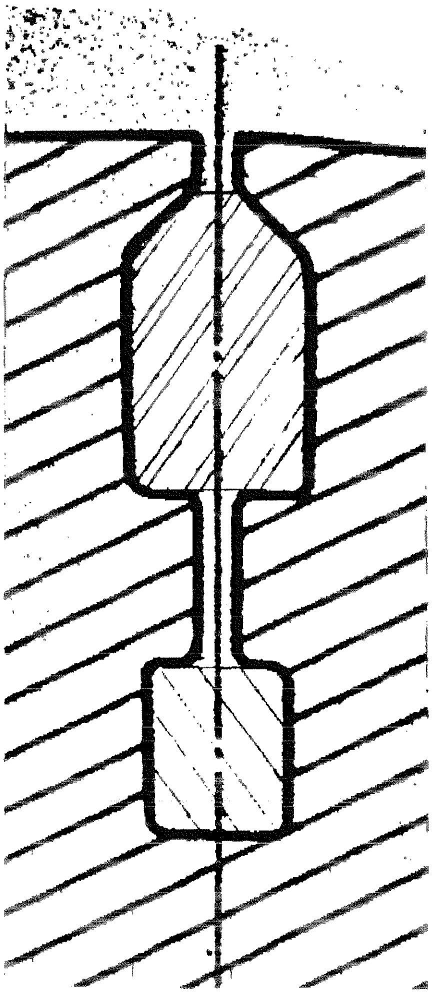
For copper bar rotors of the client company, only one rotor was available for inspection. The failure of this rotor had definitely been caused by very loose bars in the slots, a glaring mismatch between the bar dimensions and the slot dimensions. This was clearly a manufacturing defect.

There was a discussion between the manufacturer, the client company and myself on copper bar rotor failures that may have been caused by undesirable chemical inclusions in the copper bar material. The possible effects of different brazing materials was also discussed. I mention this because metallurgical tests on failed rotor components do not seem to be reported on in the research reports and papers that I have seen. However, my review of the literature is certainly superficial.

During the course of my investigations for this client company, I raised the question as to whether a literature survey had been done on the subject of cracked/broken rotor bars. I suggested that Professor Charles Landy may be able to assist in this direction. Consequently, the client asked me to approach Professor Landy , which I did. Professor Landy submitted a quotation to me for producing what he called a " Reference List " on publications relating to the detection of broken rotor bars in squirrel cage induction motors. I sent Professor Landy's quotation to my client, but I do not know whether my client accepted Professor Landy's quotation or not.

In 1995 I saw a very interesting paper published in the IEE(UK) POWER ENGINEERING JOURNAL, APRIL 1995, Pages 77 to 84 inclusive,
Title: " The Industrial application of phase current analysis to detect rotor winding faults in squirrel cage induction motors "
Author: David R. Rankin
10 references are listed at the end of this paper.
In May 1995 I phoned Professor Landy and drew his attention to this paper.

I commend the presenters who reported on their research work on cracked/broken rotor bars on 2 November 2005 at the Meeting of the RMWG. I hope that the information I have provided in this contribution to the mini survey on this subject will be of interest to the members of the RMWG.



Sectional view of rotor slot