Impact of Rotor Bar Bridge on Torque Development in Integral Horsepower Machines in PWM Inverter Environments

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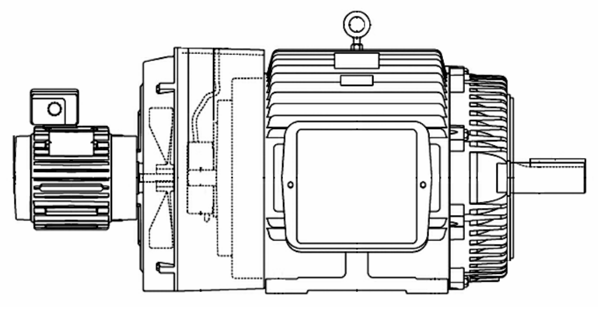
Abstract: The impact of rotor bar bridges in closed-slot induction motor rotors has been simulated using Finite Element Analysis (FEA) and single phase equivalent circuit methods in 60 Hz sinusoidal environments. In this paper we will discuss a study on a 455HP, 90Hz, 380 Vac machine utilizing a rotor with a deep bridge, then the impact on output torque once the diameter of the rotor was turned down, reducing the bridge depth. The research performed allowed for optimizing optimal bridge depth and air gap sizing based upon machine design for peak torque development.

Introduction

A specialty machine was designed to operate on a constant V/Hz curve to 380Vac, 90Hz, 658 Amp with a constant torque to 455 Horsepower at 5400 RPM. A key consideration in the development of the machine was the decision to utilize a cast aluminum alloy in a closed slot rotor. The PWM Variable Frequency Drive (VFD) was a 500 horsepower Yaskawa P7 Drive with a 675 Amp maximum current. The stator was designed and wire sizes selected with a single circuit wye, two-pole, lap winding with an 80% slot fill. The bore of the stator was 0.2667 Meters (10.5 inches) in diameter and 0.4318 Meters (17 inches) in length.

Figure 1: Drawing of Complete Motor



As the machine was being employed in a VFD environment and the rotor slots were closed, creating a slot bridge, consideration is required for the bridge depth and optimal air gap for operation of the machine. Challenges included air gap harmonics, rotor slot permeance, starting torque on the inverter, bridge saturation, and other conditions such as power factor and efficiency.

As the original design was in metric and drawings were in English, both will be presented in this paper with drawing dimensions in English.

Initial Rotor Design

The initial rotor design was based upon an optimal air gap for a 50 Hz machine. As there are no hard and fast rules for optimal air gap, a standard formula was employed as shown in equation 1. The result was an air gap of 1.16 x 10^{-3} m (4.56 x 10^{-2} inches) or 0.0456 inches.

Equation 1: Optimal Air Gap

$$\delta = \frac{0.18 + 0.006 * P^{0.4}}{1000} m$$

Due to mechanical considerations, the rotor diameter was selected as 0.2642 m (10.400 in), which resulted in an initial air gap of 1.25 x 10^{-3} m (5.0 x 10^{-2} in). The rotor bars were selected to be placed as shown in Figures 2 and 3.

Figure 2: Rotor Slot Dimensions

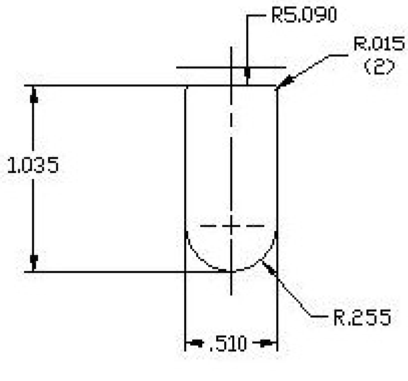
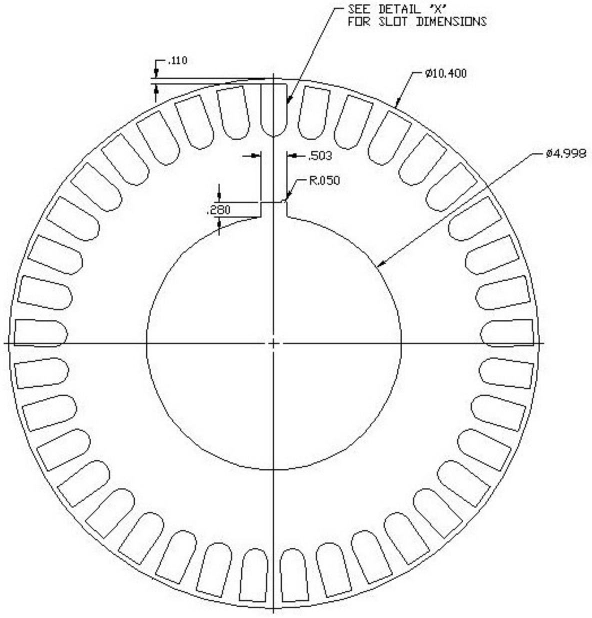


Figure 3: Rotor Dimensions



The bridge depth above the center of each rotor bar was 2.794 x 10^{-3}m (0.110 in) with the aluminum alloy being pressure cast to reduce casting voids in the rotor bars. See Figure 4 for a cutaway of the completed rotor with the bridge and shorting ring.

Figure 4: Sectioned Rotor

Consideration of Bridges in Rotor Design

According to the literature, an open rotor slot will result in parasitic torque and harmonics in a machine operating in a VFD environment. However, a closed slot rotor will generate permeance harmonics until the bridge saturates at which point the harmonics are linear as in an open slot design. The primary difference is that the closed slot bridge will become saturated by fields induced by the currents within the rotor bars, requiring additional energy.[1]

The bridges will cause increased leakage reactance resulting in reduced radial pressure waves which reduces audible noise during operation. Deeper bridges result in even lower noise, but also reduce power factor and require more energy to saturate. This effects starting but will have a limited effect on full load torque. “In terms of performance, the closed slot machine shows a deterioration in power factor as the slot bridge depth is increased, and there is also a very slight fall in efficiency. On the other hand, a closed rotor slot provides extra rotor leakage reactance, which reduces the starting current and torque. These features may be desirable for direct-on-line starting.” [2]

It is known from Flack and Williamson that due to the saturation, the deeper the bridge, the lower the starting current and starting torque. In high speed machines that require VFD control for operation, this can mean that the supplied current at starting can be absorbed, tripping the drive on high current.

A small air gap will increase the permeance harmonics seen in enclosed slots. A larger air gap will decrease power factor and will result in a change in motor efficiency. Therefore, in a machine with closed slots, a slightly increased air gap and thinner bridge can balance the use of the bridge for mechanical strength.

Evaluation of Machine

The 455hp machine was evaluated with the combination of deep bridges (0.110 in) and small air gap (0.050 in). With no load and uncoupled, the machine would trip on ‘Output Phase Loss,’ which is defined by the drive manufacturer as:

1. An output open-phase;
2. An open-phase occurred at the drive output; or,
3. The fault is detected when output current has exceeded 5% imbalance or a low impedance motor was used.

Under the low impedance definition the manufacturer states: “The motor being used has a capacity less than 5% of the drive’s maximum motor capacity.”[3] It was determined that the motor would have to be started with a light load (100 lb-ft or 135.6 n.m). It was concluded that the extremely low starting torque of the deep bridge tricked the drive into recognizing that the motor was smaller than it was. When the load was removed, the drive would run at 40 Amps before tripping on the ‘Output Phase Loss’ error.

Figure 5: No-Load Testing Machine

The drive was used to self-tune the motor and recognized it as 131 Amp and 0.012 Ohms terminal resistance. At 100 lb-ft, the running current was 138 Amps. The bearing temperatures stabalize at 123^{o}F (50.6^{o}C). The motor was loaded up to 500 lb-ft (678 n.m) at 45 Hz (2660 RPM) the motor operated at 670 Amps and the temperature rise increased rapidly and did not stabalize. The machine was shut down prior to thermal overload. The Power Factor was measured at 0.598.

It was determined that the optimal rotor diameter would be 10.250 in (0.2604 m) at which the estimated Power Factor would be 0.60, equivalent to the deep bridge. The air gap was increased by 0.075 in (1.90 x 10^{-3} m) per side resulting in a total air gap of 0.125 in (3.17 x 10^{-3} m) and a bridge depth of 0.035 in (8.89 x 10^{-4} m).

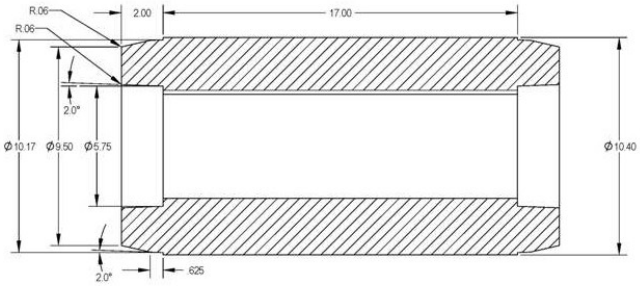
Motor no-load current was now measured at 84 Amps. The tuning identified the terminal resistance the same at 0.012 ohms, and the current was identified as 171 Amps no load. The bearing temperatures stabalized at 106^{o}F (41^{o}C). At 500 lb-ft (678 n.m) and 45 Hz (2660 RPM), the motor operated at 620 Amps and remained cool to the touch. The maximum stabalized bearing temperature was 100^{o}F (37.8^{o}C) and winding temperature steadied at 115^{o}F (46.1^{o}C). The ambient temperature for both tests was 70^{o}F (21.1^{o}C).

Table 1: Comparison of Rotor Diameters and Operating Characteristics

Characteristic	Value 10.4 inch rotor	Value 10.25 inch rotor
Start at no load	Tripped	Yes
No Load Current Tuning	131 A	171A
No Load Current Actual	40 A	84A
Bearing Temps	123F	100F
500lbft at 45 Hz Current	670 A	620 A
Power Factor	0.598	0.589

Based upon the operating characteristics of the drive and the current at no load, and the machine should have had a slightly higher torque with a smaller air gap, the deeper bridge had a noticeable affect.

Figure 6: Remaining Rotor Dimensions



The total area of each rotor bar bridge was:

Equation 2: Calculated Area of Rotor Bar Bridge

$$A = 0.510''*0.075''*17.0'' = 0.65in^3$$

With a total of 37 bars, and the permeance affecting only the area of the bridge above each bar, the total area affected is 24.1in^3. At the 500 lbft at 45 Hz, the current absorbed by the bridges would be approximately 50 Amps, or 2.1 Amps/in^3. At starting, the current absorbed by the bridges was similar, or 1.8 Amps/in^3, preventing enough starting torque to operate the motor. However, it was found that by adding a slight load to the motor that the drive would be able to start it but with much higher operating losses.

Additional studies are ongoing to determine the effect of the steel between bridges and the affect at sinusoidal 60 Hz versus the 2 kHz carrier frequency of the drive used in this study.

Conclusion

It has been confirmed that additional bridge depth causes the starting torque to be much lower and losses to increase as the machine operates. The losses are seen in the motor stator and rotor with increased bearing temperatures and stator temperatures. Under full 90 Hz operation, with the smaller rotor, temperature rise maintained constant. At 90 Hz full load operation, the machine operated below 600 Amps while providing 455 hp of torque (Figure 7) while maintaining a temperature rise less than 25°C.

Figure 7: Pump System Setup for Full Load High Speed

Therefore, finding an optimal bridging that will maintain mechanical strength at design speed and an optimal air gap is necessary to maintain good operating characteristics of large, high speed machines. Bridging does have a significant impact on starting torque, current and operating characteristics and the air gap does have a significant impact on power factor. In this study it was observed, but not measured, that the deep bridge motor test and small air gap had a higher level of noise than the shallower bridge and larger air gap. Such measurements will be considered in future studies of these phenomenon.

Biographies

Howard W Penrose, Ph.D., CMRP is the Vice President of Engineering and Reliability Services for Dreisilker, the Web Editor-in-Chief of the IEEE Dielectrics and Electrical Insulation Society, the Director of Membership for the Society for Maintenance and Reliability Professionals (SMRP) and is the Treasurer for the Autism Society of Illinois and the SMRP Chicagoland Chapter. He has won five consecutive UAW and General Motors People Make Quality Happen Awards (2005-2009) for energy, conservation, production, and maintenance programs developed for GM facilities globally and is an SMRP Certified Maintenance and Reliability Professional (CMRP). Dr. Penrose is the author of the Axiom Business Book Award (2008 Bronze and 2009 Bronze) winning “Physical Asset Management for the Executive (Caution: Do Not Read This If You Are on an Airplane),” and the 2008 Foreword Book of the Year Finalist textbook, “Electrical Motor Diagnostics: 2nd Edition.”

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