Slip ring motor conversion to VSD driven standard squirrel cage ac motor

By J van Niekerk, Zest WEG Group

Over a number of years slip ring motors have largely been replaced by standard squirrel cage ac induction motors, often in conjunction with ac Variable Speed Drives (VSDs). Selecting the correct squirrel cage motor to replace a slip ring motor has been challenging for those doing the selection.

Slip ring motors were traditionally the ‘stalwarts’ of industry in certain applications such as crushers, cane knives, large pumps and crane hoists. These motors are applied where the starting torque must be controlled, either to achieve high starting torque or to reduce starting torque and current. Additionally slip ring motors are able to produce high starting torque with a starting current that is much lower than a squirrel cage motor of similar torque capability. Typically, slip ring motors have starting torques of 200 to 250% for a starting current of 250 to 350% whereas a squirrel cage motor for similar torque would have 600 to 700% starting current. See curves below.

Standard squirrel cage motors have a fixed value of starting and breakdown torque, whereas slip ring motor characteristics can be changed by adding or removing rotor resistance.

Standard squirrel cage motors also have a fixed nominal rating that is almost always based on S1 duty. Slip ring motors can have many different ratings depending on the duty cycle for which they are specified.

If the standard squirrel cage motor is selected purely on nominal power, for example a 37 kW to replace a 37 kW slip ring motor, then the starting torque may not be sufficient. Alternatively, if one is overly conservative and selects a 45 kW or 55 kW standard motor the costs may be unnecessarily high. This is especially true when dealing with larger motors such as 1 000 to 1 500 kW.

The question then is how to correctly select a replacement squirrel cage motor and VSD combination.

A synopsis of relevant points and a detailed explanation follows. When reading these, some readers may immediately notice that some of this information is difficult or impossible to obtain. For this reason, alternative methods are also presented. The best method is to know the application requirements. In this way the ac motor is Application Engineered for the application and it is not merely selected as hopefully a suitable replacement.

- Method A: Establish the application and load requirements
  - Type of load (fan, crusher, pump, etc)
  - Absorbed power
  - Speed
  - Starting torque required
  - Maximum torque required
  - Load inertia referred to the motor shaft
  - Duty cycle (number of stops and starts per hour and actual load while running)
  - Current limit or maximum current acceptable at start up
  - Supply voltage
  - Supply voltage variation
  - Ambient and altitude
  - Mechanical limitations, i.e frame size and shaft size of motor to be replaced.

- Method B: Obtain the full details of the existing motor, starter, application and mechanical equipment.
  - Existing motor nominal values:
    - Power
    - Speed
• Stator voltage
• Stator amps
• Rotor voltage
• Rotor amps
• Starting torque
• Breakdown torque
• D duty cycle rating (eg S4 150 starts/hr ED 40%)
• The full motor data sheet or manual is best for this
• Type of starter, eg liquid resistance or resistance banks
• Value of starting resistance and the resistance steps for acceleration
• Frame size of the existing motor
• Shaft size of the existing motor
• Space constraints
• Any known application data as per Method A

Method C: Replace based on measurements and estimation due to the foregoing information of methods A and B not being available.

Method A
Using Method A is not based on doing a slip ring replacement but rather on doing a correctly engineered selection. This is the best option but will not be dealt with in this article.

Method B
Each slip ring motor has a resistance value that when connected to the rotor will result in a starting torque of 100%. This value is known as K. The value for K is different for each slip ring motor. Using the motor nominal data, K can be calculated.

Using the values of the starting resistors used, actual starting torque can be calculated. An ac motor that can provide starting torque and running torque equal to or greater than the existing motor must be selected (see example).

In addition to this mechanical constraints such as available space, shaft size and motor frame size must be considered. Ambient and altitude must also be taken into account.

Applicable formulae:

\[ K = \frac{\text{Rotor volts}}{\text{Rotor amps} \times \sqrt{3}} \text{ and } T_{\text{start}} \propto \frac{K}{R} \]  
(\( R \) = Resistance)

\[ P_{\text{motor}} = \frac{N \times T}{9550} \text{ and } T = \frac{P \times 9550}{N} \]

\[ P = \sqrt{3} \times V \times I \times \cos \phi \times \eta \]

Method B example:

• Existing motor nominal values:
  o Power – 420 kW
  o Speed – 1 490 rpm
  o Stator voltage – 380 V
  o Stator amps – 754 A
  o Rotor voltage – 600 V
  o Rotor amps – 416 A
  o Starting torque – unknown
  o Breakdown torque – 2,8
  o D duty cycle rating – S4 300 starts/hr ED 40%

• Type of starter - resistance banks
• Value of starting resistance and each resistance step for acceleration – \( R_1 = 0,2 \), \( R_2 = 0,13 \), \( R_3 = 0,12 \)
• Frame size of the existing motor - 450
• Shaft size of the existing motor - 120 mm
• Space constraints - none
• Application:
  o Crusher
  o Absorbed power while running – 300 kW to 350 kW
  o No of starts per hour – six maximum
• Ambient and altitude – 1 500 masl and 45ºC

Solution

The application being a crusher is an immediate indication that high torque is required.

Existing motor:

\[ K = \frac{600}{(416 \times 2,3)} = 0,83 \]

Starting resistance = \( 0,2 + 0,13 + 0,12 = 0,45 \)

\[ T_{\text{start}} = \frac{0,83}{0,45} = 184\% \]

\[ T_{\text{motor}} = \frac{420 \times 9 550}{1 490} = 2 692 \text{ Nm} \]

\[ T_{\text{start}} = 1,84 \times 2 692 = 4 953 \text{ Nm} \]

Standard VSD motor \( T_{\text{start}} = 150\% \) therefore motor torque required \( \geq 4 593/ 1,5 = 3 062 \text{ Nm} \)

Therefore motor power \( \geq 1 490 \times 3 062/ 9 550 = 478 \text{ kW} \)

Oversized VSD \( T_{\text{start}} = 200\% \) therefore motor torque required \( \geq 4 593/ 2 = 2 297 \text{ Nm} \)

Therefore motor power \( \geq 1 490 \times 2 297/ 9 550 = 358 \text{ kW} \)

Derating for ambient and altitude: 45ºC = 0,95  1 500 masl = 0,96

Total derating = 0,95 x 0,96 = 0,91

\[ P_{\text{abs}} \leq 350 \text{ kW} \]

Therefore motor power \( \geq 350 / 0,91 = 384 \text{ kW} \)

Therefore to provide normal running power 384 kW is needed and to provide starting torque a motor of 478 kW is needed, or alternatively when using an oversized VSD, a motor of 358 kW is needed. The
choice then would be between the nearest standard motor sizes and corresponding VSDs. Therefore, either a 500 kW motor with matching VSD or alternatively a 400 kW motor with oversized VSD. The final choice would depend on cost and customer preference. Either would be suitable. In this example a 500 kW motor and matching VSD are more economical. This motor when VSD driven can supply all of the known capabilities of the existing motor. A 500 kW motor is in a 355 frame with a 100 mm shaft. It will therefore be necessary to check if a base plate adaptor and new coupling will be needed to couple to the existing load. To match the existing frame and shaft size, an 800 kW motor would be needed. This is not economically viable.

**Method C**

This method is the least preferred due to various values being unknown and assumptions having to be made. The reader can see though that the assumptions are not unreasonable and a generally safe selection is possible using this method.

**Known information**

- Existing motor nominal values:
  o Power - 1 000 kW
  o Stator voltage - 550 V
  o Stator amps - 1 275 A
  o Speed – 6 pole, approximately 980 rpm
- Type of starter – liquid resistance. Resistance value unknown
- Current limit or maximum current acceptable at start up – ± 3 500 A approximately
- Application
  o Mill
  o No of starts per hour – six maximum
- Ambient and altitude – 1 600 masl and 40°C

**Measurements**

- Supply voltage – 550 V
- Current while running – 720 to 880 A
- Maximum current while starting – ± 2 850 A
- Shaft height to shaft centre – 500 mm
- Shaft diameter – 100 mm

**Solution**

The application being a mill is an immediate indication that high torque is required.

Existing motor

\[
P_{\text{absorbed}} \geq \sqrt{3} \times 550 \times 880 \times 0.85 \times 0.9 = 641 \text{ kW}
\]

(Power factor and efficiency are assumed at typical values)

\[
T_{\text{nominal}} \geq 1 \,000 \times 9 \,550 / 9 \,745 = 9 \,745 \text{ Nm}
\]

\[
T_{\text{starting}} \geq 2.5 \times 9 \,745 = 24 \,363 \text{ Nm}
\]

(T starting is normally < 200% of T nominal (however because of the lack of information a conservative value of 250% is used here)

Standard VSD motor \( T_{\text{start}} = 150\% \) therefore motor torque required

\[
\geq 24 \,363 / 1.5 = 16 \,242 \text{ Nm}
\]

Therefore motor power

\[
\geq 980 \times 16 \,242 / 9 \,550 = 1 \,667 \text{ kW}
\]

Oversized VSD \( T_{\text{start}} = 200\% \) therefore motor torque required

\[
\geq 24 \,363 / 2 = 12 \,181 \text{ Nm}
\]

Therefore motor power

\[
\geq 980 \times 12 \,181 / 9 \,550 = 1 \,250 \text{ kW}
\]

Derating for altitude: 1 600 masl = 0.96

Therefore motor power

\[
\geq 641 / 0.96 = 667 \text{ kW}
\]

Therefore to provide normal running power 671 kW is needed and to provide starting torque a motor of 1 667 kW is needed, or alternatively using an oversized VSD, a motor of 1 250 kW is needed. The choice then would be between the nearest standard motor sizes and corresponding VSDs. Therefore, either a 1 700 kW motor with matching VSD or alternatively a 1 250 kW motor with oversized VSD.

In this example a 1 250 kW motor and oversized VSD are more economical. A 1 250 kW motor is in a 500 frame with a 120 mm shaft. It will therefore be necessary to check if a new coupling will be needed to couple to the existing load. The VSD must be selected in order to provide > 250% of the 1 250 kW motor nominal current.

For a 550 V 1 250 kW motor is 1 550 A

Therefore VSD

\[
P_{\text{nominal}} \geq 1 \,550 \times 2.5 / 1.5 = 2 \,583 \text{ A}
\]

VSD derating for 1 600 masl is 4%, however the absorbed power is far below the installed power and therefore this is not a consideration.

The combination of VSD and motor can supply all the known capabilities of the existing slip ring motor.

As can be seen from the foregoing examples, where sufficient information was available, a 420 kW slip ring motor could be replaced with a similar size of ac motor whereas in the second example a larger ac motor should be chosen.

**Crane specific selection**

When selecting standard squirrel cage ac motors to replace slip ring motors on cranes, additional considerations are needed. In addition to the information for Method B, the following should also be known:

- Crane method additional information required:
  o Crane hoist working load in tons or kg
  o Crane hoist speed in m/s

**Known information**

- Existing motor nominal values:
  o Power - 1 000 kW
  o Stator voltage - 550 V
  o Stator amps - 1 275 A
  o Speed – 6 pole, approximately 980 rpm

- Type of starter – liquid resistance. Resistance value unknown
- Current limit or maximum current acceptable at start up – ± 3 500 A approximately
- Application
  o Mill
  o No of starts per hour – six maximum
- Ambient and altitude – 1 600 masl and 40°C

**Measurements**

- Supply voltage – 550 V
- Current while running – 720 to 880 A
- Maximum current while starting – ± 2 850 A
- Shaft height to shaft centre – 500 mm
- Shaft diameter – 100 mm

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This information can be used to calculate the crane absorbed power to confirm motor size selection. The value for efficiency is seldom
known, however a value of 70% is conservative and safe to use. When selecting a motor and VSD combination for a crane, assumptions are not recommended. This is because a hoist that does not function correctly can have potentially catastrophic consequences. As per method B, a suitable motor must be selected. The ac motor must be able to supply the maximum torque that the slip ring motor supplied. When used on a VSD, motor torque is proportional to motor current. This is termed a linear relationship. This holds true until breakdown torque is approached. Close to breakdown torque the relationship between torque and current is no longer linear. It must be ensured that this area of non linearity is not within the required torque range of the application. This should be established from the selected motor data sheet. A typical value for this is ≤ 70% of breakdown torque.

### An example

**Given information:**

Motor: 110 kW, 380 V, 205 A, 1480 rpm, 435 V rotor, 154 A rotor, 315 frame, S4 150 starts/hr 60%

Starter: Thyristor controller with resistor banks and 80% starting voltage

R total = 0.65 Ω

Environment: 800 masl and 30ºC

Crane: 12 ton, 0.5 m/sec.

\[ K = \frac{435}{\sqrt{3 \times 154}} = 1.63 \, \Omega \]

\[ T \text{ start} = 1.63 \times 0.65 = 251\% \]

\[ T \text{ motor} = 110 \times 9.550 / 1480 = 710 \text{ Nm} \]

Reduced voltage T start = 0.8 \times 0.8 \times 2.51 \times 710 = 1411 Nm (161%)

**Standard motor** T start = 1411 / 1.5 = 761 Nm

Standard motor power = 1480 \times 761 / 9550 = 118 kW

Nearest standard motor power = 132 kW

**Motor power check**

Hoisting power required = 12,000 \times 9.81 \times 0.5 / (0.7 \times 1000) = 84 kW

In this example then, a 110 kW slip ring motor would be replaced with a 132 kW standard ac motor. Considering the actual hoist power required of 84 kW, this selection is slightly conservative, however it ensures that the replacement motor has the same performance and torque capability as the slip ring motor.

### Conclusion

Replacing slip ring motors with standard ac motors is therefore practical and possible without risk provided the selection is correctly engineered.

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### About the author

As drives and automation manager for Zest Electric Motors, Johan van Niekerk has successfully established a dedicated drives department – making Zest WEG Group one of the major players in this field. Under his guidance, the company has successfully completed a spectrum of projects in the VSD industry.

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