Driving Forward

Barry Dick, TM GE Automation Systems, USA, introduces new PWM drive technology for wound rotor motors.

Introduction

Wound rotor induction motors have been popular in some industries, particularly cement, for decades. Until about 1985, a wound rotor induction motor (WRIM) was the only large ac motor that allowed practical controlled starting characteristics and adjustable speed capability.

In the context of this article, a WRIM is a machine with a 3-phase wound stator that is usually connected directly to the power system (Figure 1). The rotor also has a 3-phase winding, usually connected in a wye (or star) circuit. The three terminals of the rotor winding are connected to separate slip rings, while the neutral point is usually terminated internally and not brought to a slip ring. Appropriate brushes and brush rigging and conduit box terminations permit the rotor windings to be connected to external circuits.

Connecting external circuits to the rotor terminals allows a drive system designer the flexibility to control the motor starting characteristics and to control speed. The simplest form of external circuit is resistance, which when inserted into the rotor circuit adds to the rotor resistance and reduces starting currents. Adding resistance to the rotor circuit also changes the speed at which maximum torque occurs for the motor, so high torques can be produced at low speed for starting loads with high breakaway torque requirements.

Having access to the rotor circuit of the WRIM has given rise to many different circuits for controlling the motors. Reactors have been used to modify the rotor impedance and not just add resistance. Saturable reactor circuits have been applied for speed control. Slip power recovery circuits were developed about 25 years ago to provide a more energy efficient means of controlling the speed of the WRIM. Previously, the circuits with passive elements simply dissipated energy from the rotor circuit to control speed.

The general principle of speed control of a WRIM using an external circuit connected to the rotor is easily explained. The WRIM is essentially a transformer with a rotating secondary winding. Power going into the stator from the utility supply is magnetically coupled to the rotor. The rotor power can be divided between mechanical power applied to the load and electrical power handled by the external circuit. A controllable external circuit allows the electrical power handled to be varied, and so the mechanical power applied to the load will change. If the external circuit is set to absorb a small percentage of power, more mechanical power is applied to the load, and the motor runs at near its rated speed; if the external circuit absorbs more power, the motor will slow down. The design of the external circuit determines whether the electrical power is dissipated in passive devices (such as resistors) or is recovered to the power system.

Slip power recovery drives

The slip power recovery (SPR) drive is an external device connected to the rotor circuit that can recover the power taken off the rotor back into the power system to avoid energy waste. In usual practice, an SPR drive consists of two interconnected power converters. The rotor converter is connected to the 3-phase rotor winding. The feedback power converter is connected to the power system, usually through a transformer that matches the output voltage of the converter to the power system. The regenerative or feedback power converter is controlled to modulate the amount of power put back into the power system, allowing control of the motor speed.

One form of past practice with SPR drives from the 1980s used the power conversion devices available at

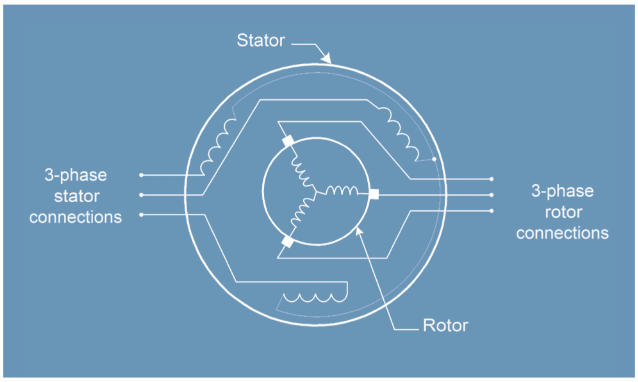

Figure 1. WRIM circuit diagram.

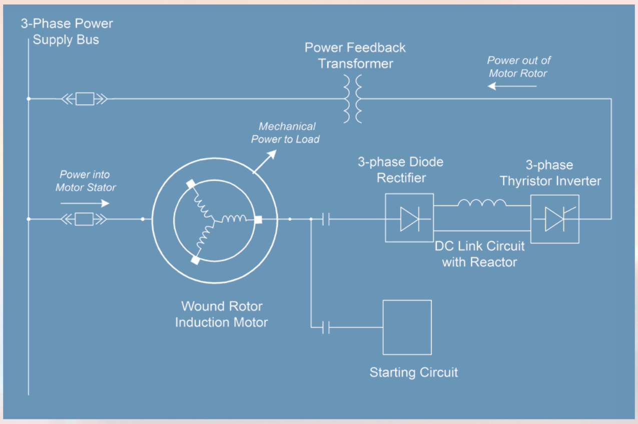

Figure 2. Current source SPR drive.

Table 1. Comparison of SPR drive technologies

Characteristic	PWM SPR drive	Diode-thyristor SPR drive
Power factor at utility	High (1.0)	Low (<0.7)
Harmonics at utility	Low	Higher
Torque pulsations in motor	Low	High
Controlled speed range	Higher	Lower
Modern technology	Yes	No

the time, e.g., diode and thyristors. (Figure 2). The 3-phase diode rectifier is connected to the rotor circuit and the thyristor inverter is connected to the power system through the feedback transformer. The two converters are connected with an inductor in series, thereby forming a current source type of drive system. Commonly, the motor stator is powered from a medium voltage source (2.3 kV, 4.16 kV, 6.6 kV, etc), but the operating voltage of the SPR drive would be 600 Vac or less. Therefore, a means to start the motor and get it to minimum operating speed is needed. This starting means usually consisted of contactors and resistors or a liquid rheostat. The direction of power flow is labelled in Figure 2, showing power flow from the system, and into the load and SPR circuit.

While these older SPR drives provided speed control functionality with high efficiency, they also had some significant performance drawbacks. These include: inability to run at rated motor speed, significant torque pulsations near maximum speed, and low power factor operation of the inverter. The remainder of this article describes PWM technology being applied to SPR drives that promises to overcome all these problems.

PWM SPR drives

An SPR drive based on PWM power converters operates in a similar manner as the older drives based on diodes and thyristors. That is, a rotor converter and a feedback converter are connected through a dc link. In the PWM SPR drive system, the dc link uses capacitors, so the drive is a voltage source type (Figure 3). To operate the motor below rated speed, the PWM converter-based also takes power off the rotor and puts it back into the power system. The power flow in the PWM SPR system is shown in Figure 3. Like the current source SPR drive system, the rotor power is divided between the mechanical power applied to the load and the electrical power returned to the power system.

The performance advantages of the PWM SPR drive system derive from the inherent capabilities of the PWM converters. For example, the converter connected to the rotor performs functions similar to an inverter connected to the stator of a squirrel cage induction motor. The high switching frequency of the inverter produces no low frequency pulsating torques to excite mechanical resonances. Therefore, the PWM SPR can operate near the motor rated speed and not require special damped couplings to attenuate the torque pulsations. The low power factor operation of the converter connected to the power system is corrected by using a PWM converter that operates at unity power factor at all times. This converter is the same hardware as that used for a regenerative squirrel cage induction motor drive.

This new PWM implementation of the SPR drive can operate the motor below rated speed, but can also operate the motor above rated speed. It has motor control capability that is equal to that of SPR drives implemented in the past with cycloconverters, but without the harmonics or low power factor of that system. The PWM drive can operate the motor above synchronous speed by injecting power into the rotor at the right frequency and phase rotation. This causes the rotor operating frequency to add to the power system frequency, so the motor speed becomes higher than rated (or synchronous speed). The limits on motor speed are mechanical (maximum speed of the motor, maximum torque capacity of the shaft) and electrical (maximum power the SPR can deliver).

PWM SPR drive operation

In practice, a PWM SPR drive generally will need a starting system that provides a controlled start for the motor and load. The starting system will operate until the motor reaches minimum controlled speed. The minimum controlled speed is determined by the rotor voltage of the motor and the maximum input voltage of the PWM inverter connected to the rotor. The rotor voltage of the WRIM decreases linearly from the open circuit voltage (or locked rotor voltage) to zero as the motor speed increases (Figure 4). The SPR drive cannot be connected to the rotor if the voltage is higher than the drive's rating. For example, if a WRIM has an open circuit rotor voltage of 1200 Vac line-line, and the SPR converter is rated for 460 Vac, the motor operating speed range is 38%, which means the motor can be controlled from 62% to 100% speed. With proper component sizing, the PWM SPR drive can be used for variable torque or constant torque loads.

While operating on the SPR drive, the power converter connected to the rotor injects a voltage with a phase rotation that opposes the power system voltage phase rotation so the rotor slows down relative to the rated speed of the motor. Because the WRIM stator is connected to a fixed frequency bus, there is a direct relationship between the rotor voltage frequency and the reference speed. In applying this voltage, the rotor converter must also absorb power from the rotor generated by the frequency difference (slip) between the rotor and stator - hence the name slip power recovery drive.

The rotor converter is connected by a dc link capacitor bank to the feedback PWM converter, which is connected to the power system. A transformer matches the operating voltage of this line converter to medium voltage (usually 4.16 or 6.6 kV) of the system. The feedback converter is a standard regenerative PWM converter that regulates the dc link capacitor voltage by passing power to the utility system at the power system frequency (50 or 60 Hz). In this manner, the slip power is recovered to the power system and not wasted.

The WRIM drive system can include a complete package to coordinate starting the motor and transferring it to the SPR for speed control. The starting means can be either a contactor/resistor arrangement or liquid rheostat system, depending on customer preference and load torque starting requirements. This complete system integrates the starting and speed control functions into one drive system. On the other hand, it is also possible to retrofit the SPR drive system to an existing motor and retain the existing starting means. The level of coordination between the SPR and the starting means can be determined on a project basis.

Advantages of the PWM SPR drive

Table 1 summarises the differences in important characteristics between the PWM PSR drive and older diode-thyristor SPR drives. The PWM SPR drive can address all of the shortcomings of the older technology. Cycloconverters have also been used for SPR drives, but are left out of this comparison because they constituted a very small niche market.

Better power factor at utility

From the SPR system diagrams, the connection to the utility interface transformer is clear. The operating power factor at that connection determines whether pf correction and harmonic filtering may be needed. The source converter in the PWM system (Figure 3) operates over all load ranges at unity (1.0) pf, so it does not need any pf correction capacitors. In fact, the source converter of the PWM SPR drive can be configured to deliver VARs to the power system, meaning it can operate at leading power factor within its rating.

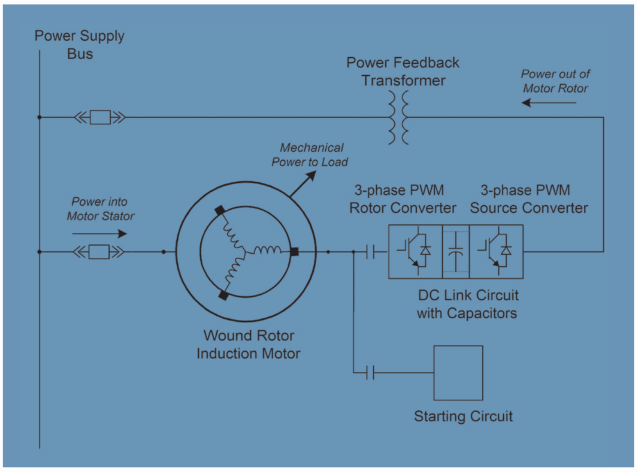

Figure 3. PWM SPR drive.

In contrast, the diode-thyristor SPR drive (Figure 2) is a current source drive system that operates at variable power factor related to motor speed. The pf of the current source SPR system at the utility connection will decrease as the motor speed increases and the rotor voltage decreases. The VAR demand of the inverter is related to the rotor current magnitude because the full rotor current must circulate through the drive and transformer. This results in a high VAR loading on the system with the motor near full load because the rotor voltage is near minimum while the rotor current is near maximum. The inverter VAR load in addition to the motor VAR load can be significant. For example, a 5000 HP (3750 kW) motor may draw 1800 kVAR for magnetising and a current source SPR with a 30% speed range may require more than 1000 kVAR near full load, thus contributing significantly to the VAR demand by the motor. While this VAR loading will decrease as the motor speed decreases, the power system must be designed to support the full load VAR load.

In a new installation, the PWM SPR drive would not require any pf correction capacitors. In a retrofit installation, any pf correction equipment dedicated to the current source SPR could be removed, or left in place to add VARs to correct other loads.

Lower harmonics at utility

A typical implementation of a current source SPR in the past would have a 6-pulse thyristor inverter. Higher power thyristor-based SPR drives might have 12-pulse drives for harmonic reduction. These thyristor converters make harmonic currents that are multiples of the power system frequency (5^{th}, 7^{th}, 11^{th}, 13^{th}, etc). Use of large, expensive harmonic trap filters to prevent excessive harmonic currents in the power system and to add reactive power to the system was common. These filters can be designed appropriately, but even filters that have given no trouble for a long time can become problematic if a new harmonic source is added to the system or a change in the system impedance causes a parallel resonance.

On the other hand, the harmonic current signature from a PWM converter is much easier to manage. A PWM converter is switched at a much higher frequency (usually 1500 Hz or higher). The harmonic currents from this type of converter are centered around the switching frequency and multiples of it. These currents are easy to suppress with the impedance (15 - 20% on the drive rating base) in a reactor. If a harmonic study revealed that additional filtering was needed, a simple high pass filter can reduce the high frequency harmonics. This type of filter is not sensitive to changes in the power system because it is closely connected to the PWM converter, so future changes are not likely to disturb it. As noted previously, the PWM converter needs no reactive power support, so the filter is not sized to provide that.

Motor torque pulsations eliminated

A WRIM operated on a current source SPR drive usually has a 6-pulse diode converter connected to the 3-phase rotor winding. This converter makes current harmonics in the rotor circuit that are multiples of the rotor current frequency (5^{th}, 7^{th}, 11^{th}, 13^{th}, etc). These harmonics interact with the stator flux to make torque pulsations at 6 times and 12 times the rotor current frequency, which is also the slip frequency of the motor. (The slip frequency is the difference between the constant power system frequency and the frequency that corresponds to the rotor rotating speed.) Mechanical resonances within the motor and load equipment can occur at almost any frequency, but those causing the most serious concern are usually below 20 Hz. The torque pulsations of the current source controlled SPR motor can excite the mechanical resonances at high speed (3 Hz and lower rotor frequencies). The potential for damage to the motor or load equipment has required the use of damped resilient coupling and speed avoidance strategies in the SPR drive control.

In contrast, a PWM SPR drive does not create torque pulsations in the motor. The current in the rotor circuit has very low harmonic currents, just like a standard induction motor power by a PWM drive on the stator. With the smooth rotor current, the torque output from the motor has very low ripple. Therefore, there are no requirements for special damped couplings or banned speeds due to mechanical resonance.

Wider controlled speed range

The controlled speed range the PWM drive can provide is also increased by being able to actively control the frequency of the voltage applied to the rotor. In the current source SPR drive, the diode rectifier connected to the rotor is passive and depends on the rotor voltage to drive it. As the motor speed increases and the rotor voltage decreases, there comes a speed at which there is insufficient rotor voltage to increase the current in the rotor circuit, and the motor stops accelerating. With the PWM SPR drive, this is not a problem. The PWM converter connected to the rotor can make a voltage of desired frequency and magnitude, even down to near 0 Hz. Therefore, the motor can be run very close to synchronous speed.

When the motor is running below synchronous speed, the SPR drive is returning power to the power system. To the run the motor above synchronous speed, the SPR drive can take power off the system and deliver it to the rotor. This does provide some interesting potential to control a WRIM through synchronous speed and to supersynchronous speeds. The limitations for this operation are the overspeed capability of the motor and the torque capability of the motor shaft.

Modern technology

The PWM SPR drive is based on state-of-the-art, proven low voltage induction motor drive equipment. These are in volume production at this time and support will be available for years to come. For example, TM GE Automation Systems and TMEIC (Toshiba Mitsubishi-Electric Industrial Systems Corp) manufacture PWM SPR drive systems based on a line of very successful low voltage motor drive hardware, the TMdrive-10. This line of low voltage drives operates at rated voltages of 460V, 575V, and 690 Vac. A range of current ratings is available to support very high power levels. A lineup of TMdrive-10 hardware is shown in Figure 5.

Diode and thyristor devices are still available, but the market for SPR drives using them is nonexistent. Getting renewal parts for these drive products can be very difficult, especially if the need is for electronic parts, such as printed circuit boards.

Summary

The application of proven, high production low voltage drive power converter hardware in controlling the speed of WRIMs has been shown to be superior to older technology with diode-thyristor (current source) SPR drives in several areas. The significant application issues that can arise with the older technology are solved with PWM technology. The PWM SPR drive technology provides an effective way to upgrade an existing SPR drive to solve obsolescence problems. For WRIMs without slip power recovery, a PWM drive can provide energy savings, effective adjustable speed operation, and high reliability.

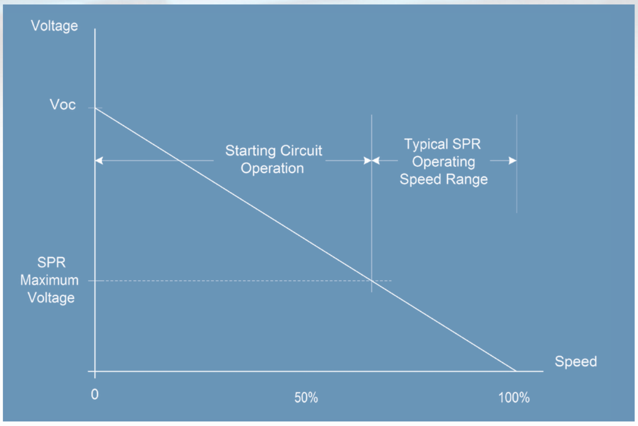

Figure 4. WRIM rotor voltage characteristic.

Figure 5. An example drive system lineup.