

NEW ADVANCES IN PULSE WIDTH MODULATED SLIP POWER RECOVERY DRIVES FOR PUMPS

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Abstract - Since its invention by Nikola Tesla in 1888, the alternating-current (AC) motor has been a critical driver for the industrial age. One of his original three patents was the wound rotor induction motor (WRIM). Later, Westinghouse refined the design of the wound rotor motor to permit control of the speed-torque characteristics of the machine. This paper discusses a new advancement in Pulse Width Modulated slip power recovery drives (PWM-SPR) application for pumps. By using sophisticated adjustable speed drive control, a significant amount of slip power can be fed back to the utility line, hence resulting in energy savings. Also, application examples are discussed to enhance understanding.

I. INTRODUCTION & HISTORY

Large wound rotor induction motors (WRIM) have been used in industries for decades. In pumping applications, high horsepower WRIM(s) are used on both vertical and horizontal pumps, where they have the advantage of controlled starting characteristics and adjustable speed capability.

Although the WRIM offered many benefits to rotating machinery applications, it also had two major weaknesses. First, there is a significant cost of maintenance of the brushes and slip rings due to wear and tear. Second, adjustable speed operation required converting rotating energy into waste heat via a resistor bank. To avoid the cost of maintenance and energy losses; the WRIM has been replaced by modern pulse width modulated (PWM) adjustable speed drives (ASD) and squirrel cage induction motors (SCIM).

However, there is a sizable base of WRIM still in use and there are many applications where the starting torque capability of the WRIM makes it the preferred type of motor. This paper discusses WRIM fundamentals, legacy methods of WRIM controls and explores a new method of providing rotor control to wound rotor induction motors. A practical example of wastewater pump is used to illustrate.

II. WOUND ROTOR INDUCTION MOTOR BASICS

A. Wound Rotor Motor design

A wound rotor induction motor has a stator with a three-phase winding just like the conventional squirrel cage induction motor (SCIM). The difference between WRIM and SCIM lies in the rotor design. In an SCIM, the rotor windings are permanently shorted and there is no mechanism to control rotor resistance. In induction motors, the torque capability of the motor can be altered by changing the rotor resistance. In the case of WRIM, the rotor also has a three-phase winding usually connected in a

wye (star) configuration, and brought out to slip rings on the shaft as shown in Figure 1 & 2. With appropriate brushes and brush rigging, external circuits can be connected to the rotor circuit to alter the performance and torque characteristics of the motor. The stator of a WRIM is a 3-phase wound design that is usually connected directly to the utility supply.

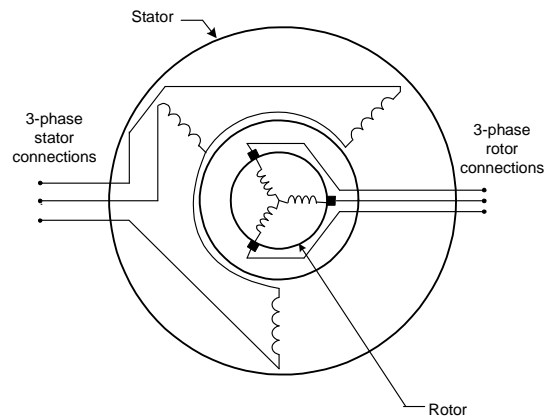


Figure. 1. Wound rotor motor circuit

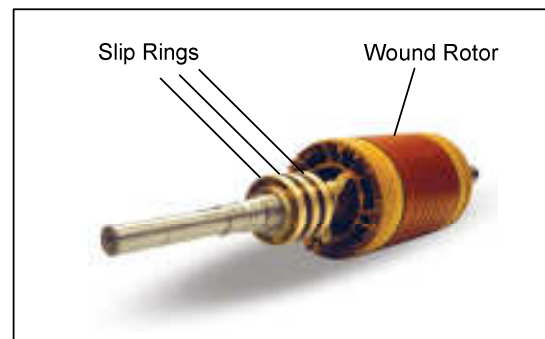


Figure. 2. Wound rotor motor with slip rings (Courtesy of TMEIC)

B. Comparison between wound rotor and squirrel cage induction motor (WRIM vs. SCIM)

Figure 3 shows a comparison in the speed-torque characteristics between a SCIM and a WRIM. Typically a WRIM can supply a higher starting torque to the driven machinery by adjusting the rotor resistance, whereas in the case of SCIM, the starting torque capabilities are fixed as

dictated by the rotor construction, resistance and inherent motor design at the factory.

III. METHODS OF WRIM STARTING & CONTROL

There are three ways of starting and controlling a wound rotor induction motor. They are as follows:-

- Stator DIRECT ON-LINE, with slip rings connected to a stepped resistor to control rotor current up to top speed and then short the rings.
- Stator DIRECT ON-LINE, with slip rings connected to a liquid rheostat to control rotor current up to top speed and then short the rings.
- Stator DIRECT ON-LINE, with slip rings connected to a converter or Adjustable Speed Drive (ASD) to control rotor current

A. Starting with slip rings connected to stepped resistance
Adding external resistance to the rotor has the effect of reducing the inrush current for soft starting and changing the speed at which the motor develops maximum torque. With the proper resistance, very high torque can be developed at low speeds. The stepped resistance starting method to control the rotor current is one of the easiest ways to start a wound rotor motor. In this control strategy, different rotor resistances can be switched by current level control or simple timers. Figure 5 shows an electrical one-line connection diagram of stepped rotor resistance. A family of speed-torque curves is also shown.

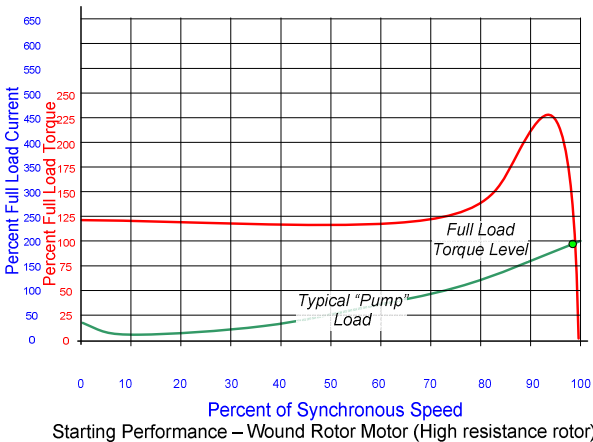
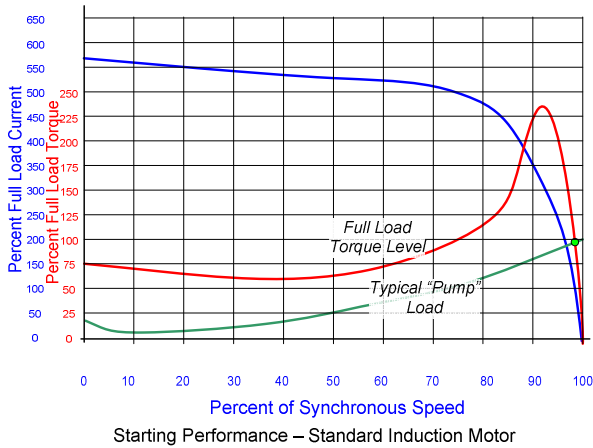


Figure 3. Starting performance between standard motor (SCIM) and wound rotor motor (WRIM)

In fact, with the help of adjustable or stepped rotor resistances, a family of speed-torque curves can be obtained for a WRIM. Based on a given pump application, the WRIM can be operated on any one of the curve characteristics. Figure 4 shows a sample family of curves for a WRIM.

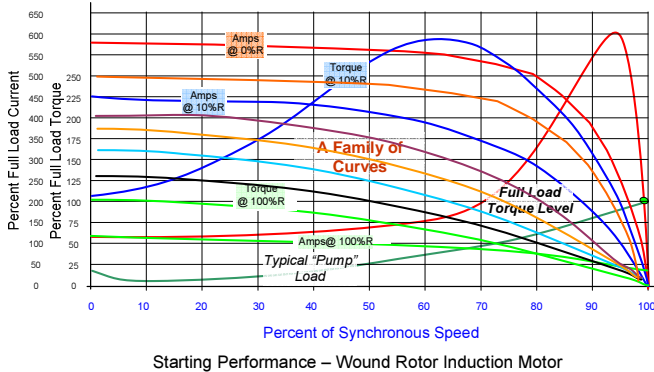


Figure 4. Starting performance of WRIM for various rotor resistances

Utility
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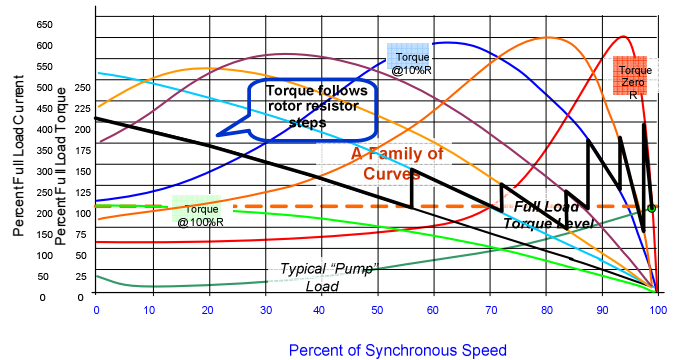
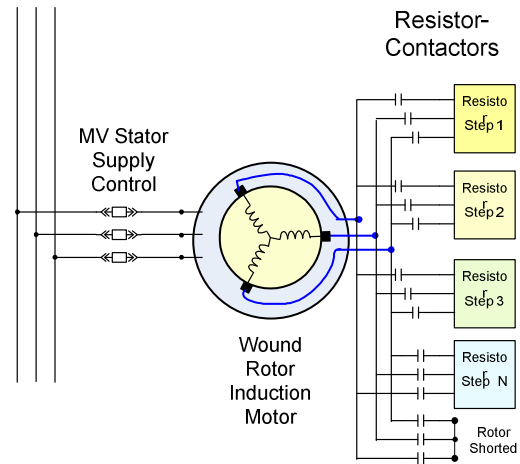


Figure 5. Connection one-line & family of curves for WRIM stepped resistor rotor current control

From Figure 5, the stepped resistance rotor control method requires lot of hardware to operate. Devices like contactors are needed which wear out over time and maintenance can become cumbersome. Also, since the resistance of the rotor is changed instantaneously, torque delivered is changed rapidly that might be unacceptable to the driven machinery and will induce mechanical stress. Also, rotor power is lost if the motor operates below top speed. A better method of overcoming this shortcoming is by using a liquid rheostat for rotor resistance control which is discussed next.

B. Starting with slip rings connected to a liquid rheostat

The liquid rheostat starting method is similar to the stepped resistance control strategy but provides smoother rotor resistance to control current and torque. Figure 6 shows the electrical illustration of this set-up. A family of speed torque curves is also presented.

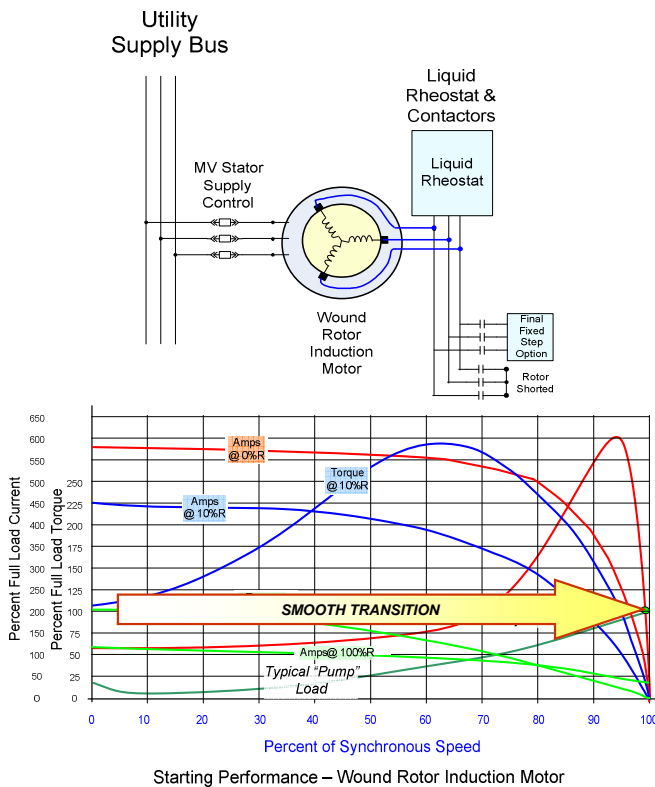


Figure 6. Connection one-line & family of curves for WRM liquid rheostat rotor current control

In the liquid rheostat control strategy, the rotor resistance is changed smoothly in order to produce a certain starting torque based on process conditions and within the capabilities of the motor. Once the motor is accelerated, the rotor slip rings may be shorted out and the WRIM operates like a regular induction motor or the liquid rheostat can be left connected to the circuit for adjustable control. However, slowing the motor down will result in all the rotating energy being lost to the liquid rheostat in the form of heat.

Due to the short comings of using resistor control (stepped or rheostat) for rotor current and torque; adjustable speed drives can be applied to the rotor slip rings which can recover the lost energy in the rotor and feed power back to the utility line when

running the motor at below rated speed. This results in significant energy savings. This is new methodology is discussed in the next section.

IV. NEW TECHNOLOGY IN PULSE WIDTH MODULATED SLIP POWER RECOVERY WOUND ROTOR INDUCTION MOTOR CONTROL

Pulse Width Modulated (PWM) adjustable speed drives (ASD) are presently widely available for both low voltage and medium voltage squirrel cage induction motors. These ASDs power the motor through the stator for adjustable speed and torque control. However, low voltage PWM drives are suitable for use as a Slip Power Recovery. These drives are called Pulse Width Modulated - Slip Power Recovery (PWM-SPR) drives because they have the ability to recover or regenerate the lost energy in the rotor (when run below rated speed) and feed it back to the power system. The inherent characteristics of the PWM converters can overcome the disadvantages of the previous SPR drives.

A. Major components of a PWM-SPR system

A PWM based system for slip power recovery consists of a wound rotor induction motor, a simple starting circuit, inverter, converter and a power transformer. A simplified illustration of a PWM-SPR drive is shown in Figure 7. Both the power converters use switching devices like Insulated Gate Bipolar Transistor (IGBT). One converter has its AC input terminals connected to the motor rotor, while the other converter has its AC terminals connected to the feedback transformer. In most applications, a starting circuit will be necessary to accelerate the motor to the PWM-SPR minimum operating speed.

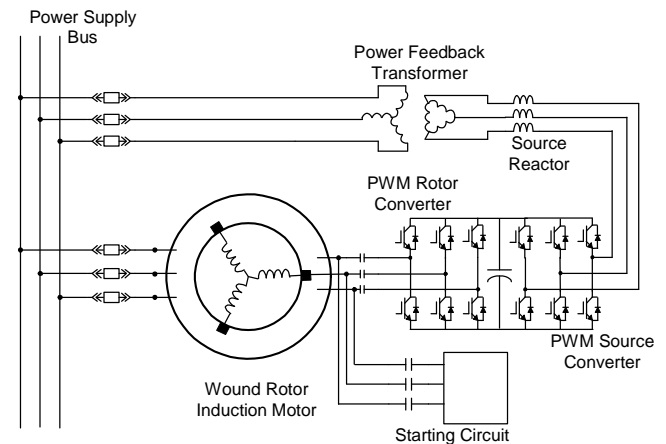


Figure 7. PWM SPR Circuit Diagram (Dick 2006)

B. Operation of a PWM SPR system

To operate the motor, it must first be started from standstill and accelerated to a speed at which the PWM-SPR drive can take over operation. Most loads require operation over a limited speed range, e.g. 50 – 100%. The starting circuit, either resistors and contactors or a liquid rheostat, are sized for the required starting torque and duty. The control system sequences the contactors to accelerate the motor in a controlled manner up to the operating speed of the WRIM. The starting circuit is then taken out of operation and the PWM-SPR drive is enabled. Once the motor is operating on the PWM-SPR

drive; all the rotor current passes through the drive and the feedback transformer to transmit power back to the utility system. Figure 8 is a representation of this balance between mechanical output power and regenerated power.

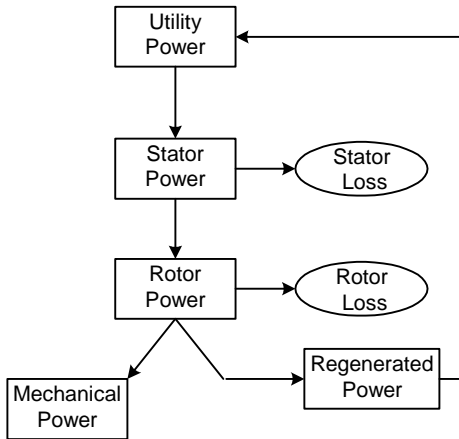


Figure 8. PWM-SPR drive power flow diagram (Dick 2006)

In practice, the converter connected to the rotor is like an inverter that is connected to the motor stator in a standard motor-drive installation. The converter connected to the feedback transformer is a PWM source converter that is used in any regenerative drive application.

The power conversion hardware used for the PWM-SPR is very similar to the drives that supply power to a squirrel cage induction motor (SCIM). However, the direction of power flow is reversed. In the PWM-SPR, when the motor speed is reduced below rated speed, power is taken off the rotor and passed back to the power system. Therefore, the 'inverter' connected to the rotor is actually taking AC power off the rotor and passing it to the direct current (DC) link. At the other side of the DC link, the regenerative source converter takes the power off the DC link and makes it into constant frequency ac power at the utility frequency. So, the PWM-SPR drive operates in regeneration mode anytime the motor is operating below rated speed.

This regeneration mode is a standard operation mode for certain high performance conventional ASD that feed the stator of an induction motor. When a squirrel cage motor must be stopped quickly due to an overhauling load, power must be taken from the motor and passed back to the power system or dissipated in resistors. When an application repeatedly requires such braking, a regenerative converter is used that can pass the power back and forth from the power system. The application of regenerative type of ASD is also very commonly found in steel mills, conveyors, mine hoists and other applications that require them.

The PWM-SPR drive hardware has been in use for many years on low voltage (<690V_{ac}) induction motor drives. The power circuits are similar, but the control in the rotor converter is special for this application.

One method for visualizing the operation of the PWM-SPR drive is to understand that power is taken into the stator of the motor and passed to the rotor. The PWM-SPR drive makes it possible to control the power that is returned to the power system from the rotor and thereby reduce the torque the motor can deliver to the driven equipment. When the output torque is reduced on a variable torque load, the motor speed decreases.

V. ADVANTAGES OF PWM SPR DRIVES

The PWM-SPR drive controls the motor speed in a similar manner to the previous SPR drives. That is, the PWM-SPR drive returns a portion of the rotor power to the power system, thus controlling the power available for making torque to drive the load. However, the characteristics of the PWM converters give this implementation significant advantage over previous drives, as shown below.

A. Optimized hardware

The PWM-SPR drive operates as a voltage source converter with capacitors in the DC link between the rotor converter and the source converter. The presence of the capacitor bank means the rotor current can circulate in the rotor converter and capacitors, and does not have to pass through to the source converter. Therefore, the source converter can be sized for the actual power to be regenerated to the power system, not for the rotor current. Also, the source converter can supply the power at unity power factor instead of low power factor. The proper rating of the source converter also implies that the feedback transformer can be rated for the power it must transmit, not for the rotor current. This change is a significant shift in reducing the cost of the system and making the PWM-SPR drive a better load on the plant power system.

B. Lower harmonic impact and smooth operation

The harmonic impact of the rotor converter and source converters are reduced compared to previous drives. On the rotor, the elimination of 6-pulse harmonics means damped couplings are not needed between the motor and load. Rotor winding heating is also reduced compared to operation with 6-pulse currents with 30% total harmonic current distortion. The expected rotor harmonic currents are 4% or less with the PWM-SPR. On the power system side, the source converter has a higher frequency harmonic spectrum than the previous thyristor inverter. The harmonic currents are controlled with impedance and can be filtered with relatively simple filters compared to the 6- or 12-pulse thyristor inverters.

Also, since PWM-SPR drives are used to control rotor current, there are no torque pulsations. Motors can also be operated above base speed within loading and mechanical limits.

C. Modern trusted technology

A practical advantage of the PWM-SPR drive is its reliance on state-of-the-art power conversion hardware that is in wide production. Most previous drives are becoming quite old and hard to repair. The PWM-SPR drive offers a replacement that will be current technology for some time to come.

D. Proven energy savings

The PWM-SPR drive can provide significant energy saving benefits when compared to a liquid rheostat or stepped resistor for speed control. Consider a comparative study between liquid rheostat and PWM-SPR drive as shown in Figure 9. It is observed that the power P_4 is recovered via the PWM-SPR drive and fed back to the line via a transformer, whereas, in the case of a rheostat solution, the power P_4 is lost to the resistors in the form of waste heat. Appendix A gives a detailed calculation of the energy savings between PWM-SPR drives and rheostat.

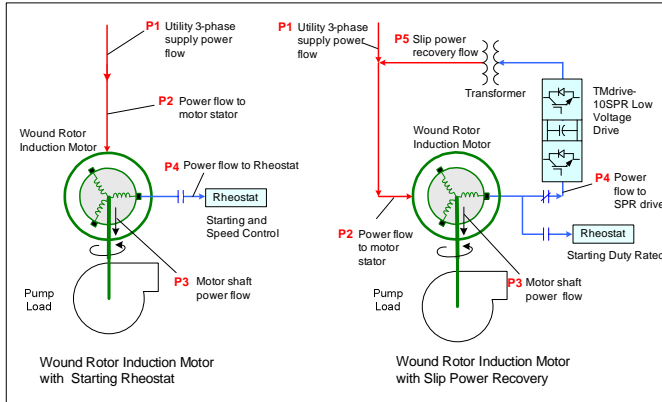


Figure 9. Comparison of WRIM control systems

VI. APPLICATION EXAMPLE OF PWM-SPR CONTROL IN PUMPS

This section describes a case study of the application of the PWM-SPR drive. This project was a retrofit to replace existing 1970's vintage diode-thyristor slip power recovery drives. The drives were installed on seven wastewater pumps installed about 40m below ground. The wound rotor motors were vertical units and still in excellent condition. The viability of the motors for future use and the cost of procuring and installing new motors in the subterranean pumping station motivated the end user to look for replacement slip power recovery drives.

The rating of the pump motors was 5500 HP and 3150 HP, with 4 kilo-Volt (kV) stator voltages. The voltage and current ratings of the wound rotor motors fitted well for a PWM-SPR drive solution.

The end user's goal included; updating the drives to current technology, improving operation, and minimizing changes to the existing building. The original drives had served for over 20 years and had performed acceptably, but spares had become scarce and service was difficult to obtain. The PWM-SPR drives offered an improvement in harmonics and improved in the net power factor at the motor terminals. Figure 10 shows a picture of the motor.



Figure 10. Wastewater treatment vertical mounted motor (Courtesy of TMEIC)

The PWM-SPR drive had a modular design that could be modified to meet the end user's installation requirements. This wastewater pumping application was deep below ground with

limited access for moving equipment. The requirement to install the new drive in the space of the old one led to a design with two lineups back-to-back. This design allowed moving the drive equipment into the pump hall possible.

Due to the age of the existing drive system, the end user chose to replace the starting rheostat and the slip power recovery system. A new liquid rheostat with stationary electrodes and adjustable electrolyte level was supplied. This liquid starter was rated for starting duty only. The startup sequencing of the rheostat and the PWM-SPR (Figure 11) drive was controlled by a programmable logic controller (PLC), integrated into the system. The existing power recovery transformers were reused.



Figure 11. Front view of the PWM-SPR drive (Courtesy of TMEIC)

This first drive system was installed and operated in July 2006. Subsequent units were installed over the next (24) months, including an eighth unit that was installed on a motor that was operating on a liquid rheostat. Presently, all the units are installed and operating.

The new PWM-SPR drives have several advantages over the drives that were replaced. The most important advantage is up-to-date electronics with available spare parts and service support. In addition, the new PWM-SPR drives operate at unity power factor at the source converter connected to the power system. While operating at high loads, the overall power factor of the motor and PWM-SPR drive increased from (0.65) to (0.9). The harmonic current from the new drives is also lower than the old drives, with a decrease from 8.4% to 3.5% for a single drive. The new PWM-SPR drives also can operate the motors at higher speeds and smoothly transfers the motors to full speed with the slip rings shorted.

VII. CONCLUSIONS

This paper outlined how PWM-SPR drives can be used on wound rotor motor for smooth torque control and higher system efficiency. A detailed description was presented on the different methodologies of starting a WRIM and the difference between PWM and resistor based rotor current control strategies. It was concluded that using PWM-SPR drives can lead to significant

energy savings in the long term. Also, the PWM-SPR can be a very cost effective & efficient option in retrofitting only wound rotor induction motors that would still have significant life remaining.

VIII. REFERENCES

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IX. BIBLIOGRAPHY

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Bill Horvath (William.Horvath@tmeic.com) has been with GE and TMEIC in applying DC and AC Motors and Adjustable Speed Drives for over 38 years. His experience includes five years in GE Transportation Systems applying DC & AC transit propulsion drives, and over 20 years selecting and applying DC MG set and Static drives, PLCs, and computer monitors to surface mining excavators. After five years of broad-based drive and power systems applications engineering in Arizona, Bill joined TMEIC as their General Industries Application Team Leader providing AC & DC drive and system application support. Bill is a registered professional engineer in Arizona, Pennsylvania, and Virginia.

X. ACKNOWLEDGEMENTS

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APPENDIX A

Calculating the energy savings obtained with the PWM-SPR drive follows the steps in Table 1. Note that the slip power varies with the slip speed (synchronous speed minus the actual motor speed).

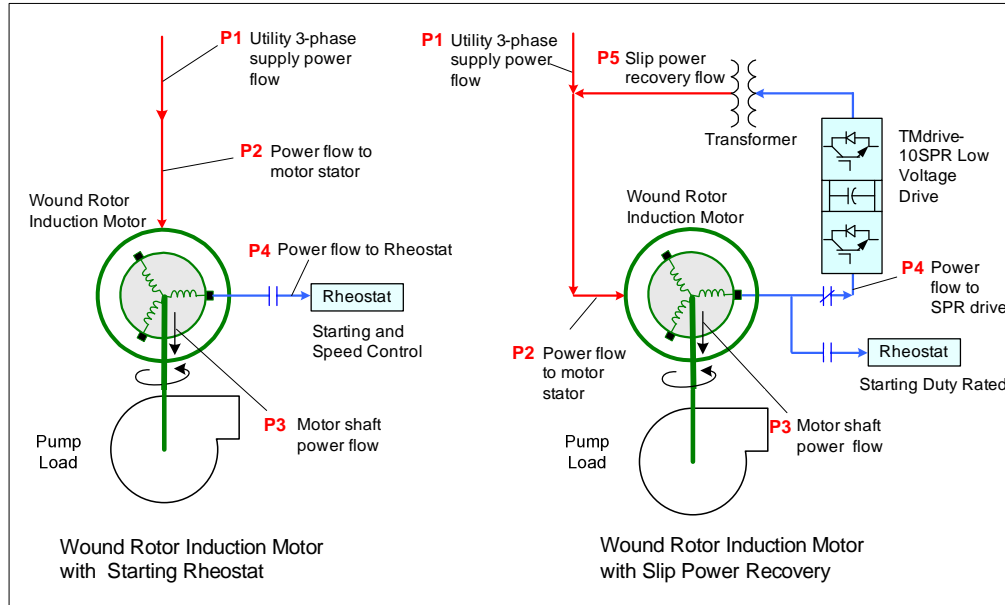


Table 1. Calculation of Savings with Slip Power Recovery Drive

| Energy Efficiency | Basic Equations | | | | |
|---|---|--|-----------------|--|----------------|
| <p>Energy efficiency of the components are estimated as follows:</p> <ul style="list-style-type: none"> • SPR drive efficiency = 0.97 • Transformer efficiency = 0.99 • Motor efficiency = 0.95 • Slip power from the rotor (est.), P4: Full Load x Slip % = 373 kW | <p>For the slip power recovery case in Figure 7, the basic energy flow equations are:</p> <ul style="list-style-type: none"> • $P1 = \text{Motor Power} - \text{Recovered Power} = P2 - P5$ WHERE • $P2 = P3 + \text{Motor Losses} + \text{Rotor Power} = P3 / (\text{Motor Efficiency}) + P4$ • $P5 = P4 \times \text{Drive Efficiency} \times \text{Transformer Efficiency}$ | | | | |
| Description | Power flow | Wound Rotor Motor (WRIM) with Rheostat | | WRM with Slip Power Recovery (PWM-SPR) Drive | |
| Mill Load at Full Speed, shaft kW | - | 3730 kW | (5,000 hp) | 3730 kW | (5,000 hp) |
| Mill Load at 90% Speed, shaft kW | P3 | 3357 kW | (assume linear) | 3357 kW | |
| Power flow from Slip Rings, estimated | P4 | 373 kW | (to rheostat) | 373 kW | (to SPR drive) |
| Power flow to motor (95% efficient) | P2 | 3906 kW | | 3906 kW | |
| Slip power recovery after transformer | P5 | 0 kW | | 358 kW | |
| Utility supply power flow | P1 | 3906 kW | | 3548 kW | |
| Difference in utility power used | P1(WRIM) - P1(PWM-SPR) | 358 kW | | | |
| SPR System Annual Savings with 7¢/kWh electrical power | | \$200,480 per year (8000 Hrs) | | | |

The results for a WRIM with a rheostat, running at 90% speed, show that adding the PWM-SPR drive saves energy worth \$200,480 a year. Over a 30 year life cycle this amounts to \$6 million which can be significant savings.