An Introduction to Permanent-Magnet Gearless Motors and Drive Control Systems

by Tony Heiser

Learning Objectives

After reading this article, you should have learned about:

- Benefits of PMs: efficiency and potential regen applications
- Difference between AC asynchronous induction and PM synchronous gearless motors.
- Similarity of commutation between DC and PM AC machines
- Importance of synchronism
- Encoder feedback; absolute position, resolution and technique
- Ride quality control: why more adjustment is needed

Permanent-magnet (PM) AC gearless machines have been an established technology in the European and Asian elevator industry for more than a decade. Within the last few years, PM installations and modernization applications have become increasingly prevalent in the North American market. A few reasons for their increased popularity include higher mechanical efficiency over a geared traction system, higher electrical efficiency compared with traction induction motors, DC with a motor-generated (MG) set or hydraulic systems, reduced physical size that allows for a smaller machine room or machine-room-less (MRL) installations and low overall maintenance. These efficiency and installation aspects provide a new solution to building architects in their desire to provide building owners with lower operating costs, while maximizing square footage.

As PM gearless applications continue to gain momentum, it is important to understand this technology in order to properly install, adjust and maintain these installations with the same quality and service.

Relating Synchronous PM Gearless Motors

A primary difference between a typical asynchronous induction motor of a geared traction machine and a synchronous PM gearless motor are the concepts of how the motor rotations are generated.

Asynchronous Motors

A geared traction machine typically uses an asynchronous induction motor. The term "induction" refers to how the rotor magnetic field is generated. The sinusoidal AC current applied to a stator winding and the geometric placing of the three-phase stator windings creates a rotating magnetic field. As the magnetic field moves past the rotor bars, the magnetic flux is cut, and a voltage is induced unto the rotor bars. The induced current creates an opposing electromagnetic field on the rotor, which follows the stator. The interaction between these two fields results in mechanical torque, which, in turn, causes rotation of the rotor. However, for an induced voltage to be present, the magnetic flux lines across the rotor windings must be moving relative to them. If the rotor were to move at the same speed as the stator field, there would be no change in magnetic flux across the rotor bars, and therefore no induced voltage on the rotor and no induced field. The result is no torque production. So, the rotor must be moving at a speed *asynchronous* to the stator, where this difference in speed is

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referred to as the slip speed. The slip speed is typically 2-5% of a motor's theoretical synchronous speed, n_1, defined by the applied frequency and number of motor poles:

$$n_1 \text{ synchronous speed (rpm)} = \frac{\text{motor operating frequency(Hz)X 120}}{\text{\# of poles}} \qquad \text{(Equation 1)}$$

and the actual motor speed, n, given the slip speed n_S:

$$n = n_1 - n_S \qquad \text{(Equation 2)}$$

Note that the frequency reference is not necessarily the line frequency, but rather the operating frequency. This takes into consideration the use of a variable-frequency drive, rather than a line start. The frequency applied by the inverter at rated speed in closed-loop operation will be the entered motor rated frequency, which may be different from the line frequency, (for example, European 50 Hz motors). A common misconception is that PM gearless machines are 60-Hz motors, since they run from a 60-Hz line. For induction motors, the most common are four-pole or six-pole designs, which, given a typical 60-Hz rating dictates the corresponding 1175-rpm or 1750-rpm asynchronous output speeds. But PM AC gearless machines will have a much higher number of poles, ranging from 16 to 66. Given the necessary rotational speed to generate the correct car speed, the rated frequency generally needs to be calculated using Equation 1.

Synchronous Motors

PM gearless motors are similar, but the rotor rotates at the same speed, synchronous to the stator-generated magnetic field. This is a function of the rotor design, which consists of outlying PM. So, a change in magnetic flux across the rotor is not needed to create an opposite magnetic field to follow the stator magnetic field. The rotor is already magnetized. Therefore, slip is not required. The rotor magnets will follow the rotating magnetic field of the stator.

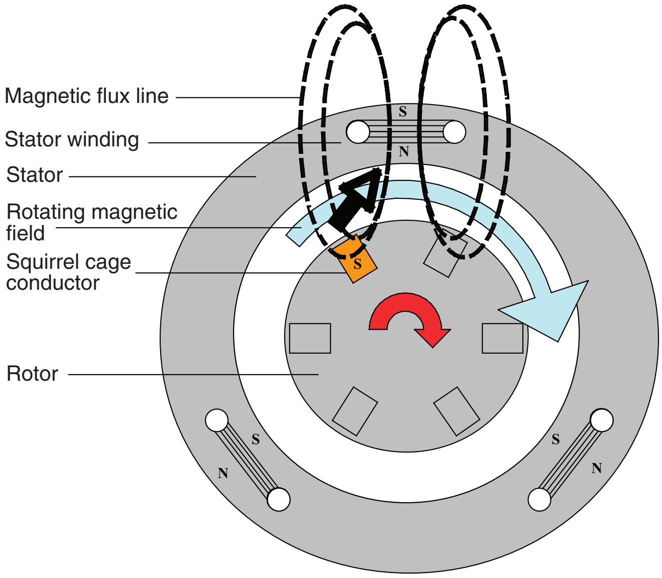

Figure 1: Asynchronous induction motor design: rotating magnetic field lines produced by the stator windings are cut by rotor bars, inducing voltage and creating an opposite electromagnetic field. The interaction of the two fields generates a resultant force (torque), which rotates the rotor.

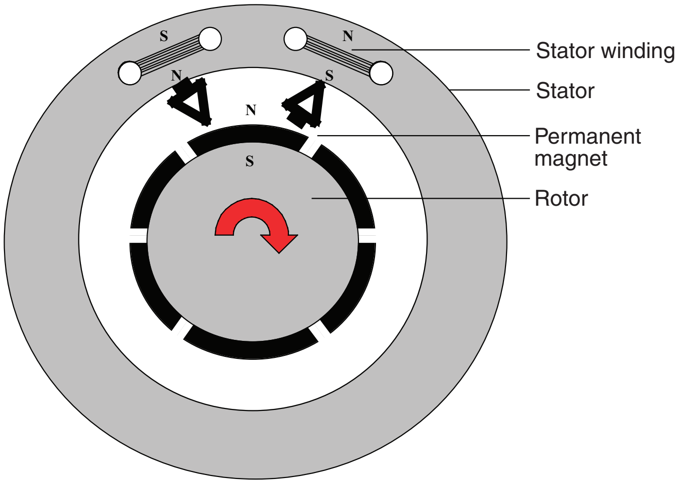

Figure 2: Synchronous PM motor design: the magnetic field of the fixed rotor magnets interacts with the rotating stator field, creating torque. The fields rotate synchronously, with the relative angle between them determining the resultant rotational torque.

Synchronous Motor Data

For variable-frequency drives, it is important to enter the correct rated motor speed of asynchronous induction motors rather than the synchronous speed. Conversely PM AC gearless machines are synchronous motors and require no slip, so it is important that the relationship between the motor speed and frequency, as determined by the number of motor poles, is correct. This is one of the most important concepts when programming a variable-frequency drive, but is generally not familiar with most mechanics prior to first installation. For example, a 97-rpm, 16-pole PM gearless motor will have a rated frequency of 12.93 Hz (97 rpm X 120/16 poles).

If the number of poles is not listed on the nameplate, this can be verified by the machine manufacturer based on model. Otherwise, if the rated speed and frequency are known, solving the equation for the number of poles should always give a whole, even number. If not, round to the nearest whole, even number and use it in the equation again to solve for either rated speed or rated frequency. It does not matter which one, as long as the relationship holds true. This quick exercise will ensure that the motor data entered in the drive is correct and precise. This also accounts for any rounding off of numbers on the motor nameplate.

Furthermore, it is common for machine manufacturers to de-rate a larger motor for a lower speed. If the machine is intended to operate slower than the motor rated speed, then the rated speed and rated frequency can be reduced linearly in proportion. But, regardless of the actual motor speed and frequency, the most important concept is that the relationship between the speed, frequency and number of motor poles holds true. Otherwise, the drive can provide the wrong frequency for a given rpm, resulting in higher current and uncontrolled rotation of the motor.

Another note regarding the motor ratings is in regards to the motor rated power. Depending on the nameplate data, the motor rated power may be listed as horsepower, kilowatts, torque Newton-meters or foot-pounds. Depending on the drive's units for motor power, the following conversions may be needed:

$$\frac{\text{Lb.-ft.} = \text{HP} \times 5259}{\text{Rated Speed}} \qquad \text{(Equation 3)}$$

$$\frac{\text{Lb.-ft.} = \text{kW} \times 7051}{\text{Rated Speed}} \qquad \text{(Equation 4)}$$

$$\frac{\text{Lb.-ft.} = \text{Nm}}{1.355} \qquad \text{(Equation 5)}$$

As previously mentioned, larger motors may be de-rated per the application specifications without changing the nameplate information. In terms of power for PM gearless machines, de-rating is linear, and the ratio of torque to current remains constant for a given speed.

Electrical Commutation Using High-Resolution, Absolute Encoders

From an operational and control aspect, a PM gearless motor is very similar to a DC motor. On a DC motor, the field winding is stationary: therefore, to maintain the angle between the field and the armature, the armature windings are commutated by way of a mechanical commutator. Conversely, with a PM gearless motor, the fixed field is rotating on the rotor, and therefore the stator field must rotate synchronously with the rotor to maintain the angle. To accomplish this, an absolute position encoder relays the position of the rotor magnets to the drive. This way the drive uses the position from the encoder to electrically commutate the PM motor.

With this arrangement, the operation of a PM motor parallels a DC motor in that torque and current are directly proportional. This means that under conditions of no load (zero torque), the current in the motor is zero. Additionally, the voltage applied to the stator is a function of speed and current.

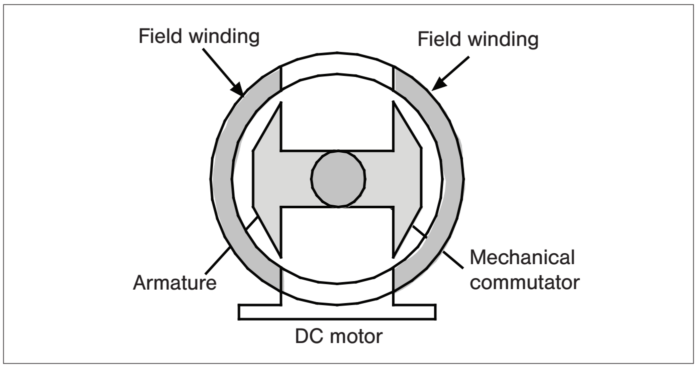

Figure 3: DC motor with stationary field and rotating mechanical commutator

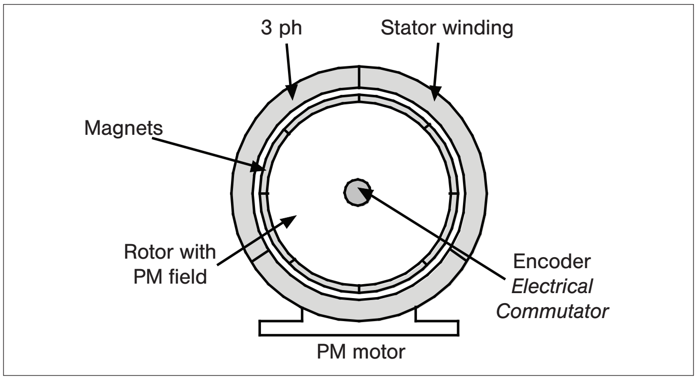

Figure 4: PM AC motor with stationary electrical commutator and rotating field

Encoder Absolute Position

The difference between an absolute encoder and a standard encoder is that it contains additional tracks for position, as well as speed. Typical formats for commercial

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applications serially transmit the position. Other formats send a set of single-turn sine-cosine waveforms or U,V,W phase pulses, from which the rotor position can be interpolated by the drive, but are less common and more susceptible to electrical noise due to the increased number of analog tracks.

Encoders that serially transmit the position data generate the position from a barcoded disc with a unique value within 360° of rotation. Multi-turn formats are also available, which may be used for absolute hoistway positioning. Before this information may be useful to the drive, a reference point must be established. This is commonly referred to as learning the encoder position, learning the motor pole position or phasing the encoder. The procedure generally determines an encoder position that is offset relative to one of the motor pole pairs. If not performed, the results would be similar to not having the correct motor speed or frequency pole relationship; the machine would jerk violently or stall and draw high current.

Establishing the encoder position is an important step in starting a PM gearless installation, but frequently not familiar to first-time installers. The motor generally must be free to move relatively unloaded, by either performing the procedure with an unroped sheave or balancing the car. Fortunately, these hassles will become a thing of the past as new technology allows the motor pole position to be identified statically by the drive without any sheave movement while the brake is set.

Motor Output Phasing

An item to note in regard to learning the encoder position is that the motor must be phased properly with the absolute position increments. That is, the U,V,W phases of the motor must match the U,V,W output phases of the drive. If the direction of rotation is incorrect after the encoder position learning process has been completed, it can be inverted by a drive setting. Unlike induction motors, two output phases cannot be swapped to invert the direction, as this would invert the rotation opposite to the absolute position values of the encoder.

When Should the Encoder Position Be Relearned?

Once the encoder position is determined on an absolute encoder, the only time the position would need to be relearned is if the orientation of the encoder to the rotor were physically changed. (That is, anytime the encoder is removed or if any slippage of the encoder mounting has occurred over time). It does not need to be learned after a power cycle, even if the sheave is moved while power is off. The exception to this is when an incremental pulse encoder is used. In this case, the position would need to be learned after each power cycle, since the incremental pulses do not contain any information for deciphering position. This is one reason why absolute encoders are used, as opposed to incremental encoders. Yet, new drive features are available that can automatically determine the encoder offset position after a power up when an incremental encoder is used.

High-Resolution Encoders

In addition to retaining position values, most absolute encoders offer much higher resolution than incremental pulse encoders. An effective pulse count of more than 500,000 per revolution is not uncommon. The high resolution is needed for control of a gearless application with a much slower shaft speed, especially during takeoff and landing when the speed commands are zero during the release and setting of the brake. Additionally, high-resolution encoders also enable drive synthetic pre-torque to eliminate rollback without the use of a load-weighing device.

As an example of encoder resolution, consider a 500-fpm geared application with a 2048 incremental encoder. At a leveling speed of 5 fpm, the actual motor shaft speed may be 11.75 rpm. Now, consider the system as a gearless motor, where 5 fpm would correspond to 0.73 rpm. So, for the same encoder resolution, the incremental encoder line count would need to be at least 32,000 pulses per revolution.

The higher resolution is accomplished by sampling sine or cosine incremental tracks since a sine/cosine pair will have a unique sample at any point within one electrical cycle. These samples can also be used as a redundant position reference, as well. Such high resolution cannot be accomplished with incremental pulse encoders, since only two unique samples can be determined per cycle – during the rising and falling pulse edge. One aspect of the sinusoidal waveforms that must be considered is their susceptibility to electrical noise. Noise on these waveforms can cause a false speed reference signal and manifest itself as vibration on the motor or can be felt in ride quality. This is why mitigation of electrical noise from proper installation, grounding and shielding are important.

Continuous double-shielded, twisted pair cables are optimal. However, it is important that the encoder cables be separate from high voltage and switching supply sources, preferably in their own conduit. Additionally, installation of *dv/dt* filters on the output phases of the drive will decrease drive-emitted noise on the encoder cabling. Also, *dv/dt* filters protect motor windings from harmful rapid change in voltage, prolonging the life of the motor. These are recommended for any application with more than 40 feet of motor cable between the motor and the drive. Pure serial formats which eliminate problems with noise on the analog tracks can be used with less costly cabling and are currently available, but have yet to become common in the market.

Inverter Ride Quality Adjustment

The most common adjustments needed for PM gearless applications on the drive side are usually around the speed controller and encoder settings. Additional inertia and pre-torque settings will further fine tune the ride quality once final adjustments are ready to be made.

Motor Data

The first items to check before drive adjustment and troubleshooting should be the motor data parameters. As stressed previously, the synchronous relationship between the rated motor frequency, rated motor speed and number of motor poles is very important on PM AC gearless applications and quite often overlooked. Additionally, motor phase-to-phase resistance and inductance are commonly needed but generally not listed on the motor nameplate data and may not be available on motor data sheets. In this case, motor auto-tune and pole alignment procedures should be performed with the drive. Before performing these, be aware that the requirements may vary according to drive manufacturer. The motor auto-tune and pole alignment feature of some drives may be completed while stationary, whereas it may require movement with balanced or no load with another. In either case, a motor auto-tune procedure will ensure the most accurate values, as seen by the drive and yield the best performance results.

Speed Controller

The drive's speed controller plays an integral role in achieving good performance from a PM motor. Some of the challenges of controlling these motors range from non- linear torque ripple produced by the motor to large load inertia ratios as compared to gearless DC or induction AC and large operating speed ranges (40 fpm to > 1,000 fpm). Therefore, the speed controller must be of a high-bandwidth design and able to compensate for nonlinearities while being stable throughout the overall speed range. Independently adjustable levels of control during starting, acceleration, deceleration, low speed and high speed aid in being able to provide the correct level of control during each phase of the run profile.

A common speed control scenario is to use proportional and integral speed gains, where the proportional term corresponds to how hard the system responds, and the integral term corresponds to how fast the system responds. One common approach to this is independent speed control settings. Independent speed control levels allow for a high gain, tight response, catching and accelerating the load, a variable response at high speed to prevent vibration or oscillation, and a moderate response for a comfortable deceleration and controlled leveling. The best approach to gain adjustment is to break the profile into segments and adjust the gains for each segment independently. Start with the proportional gain, as this will typically be required to achieve stability over the entire speed range. Then focus on the integral gains at low speed during the acceleration and deceleration phases (independent values may be required for each). Change the gains by doubling or having the values to achieve the desired response. Cars with similar mechanical characteristics should require similar settings.

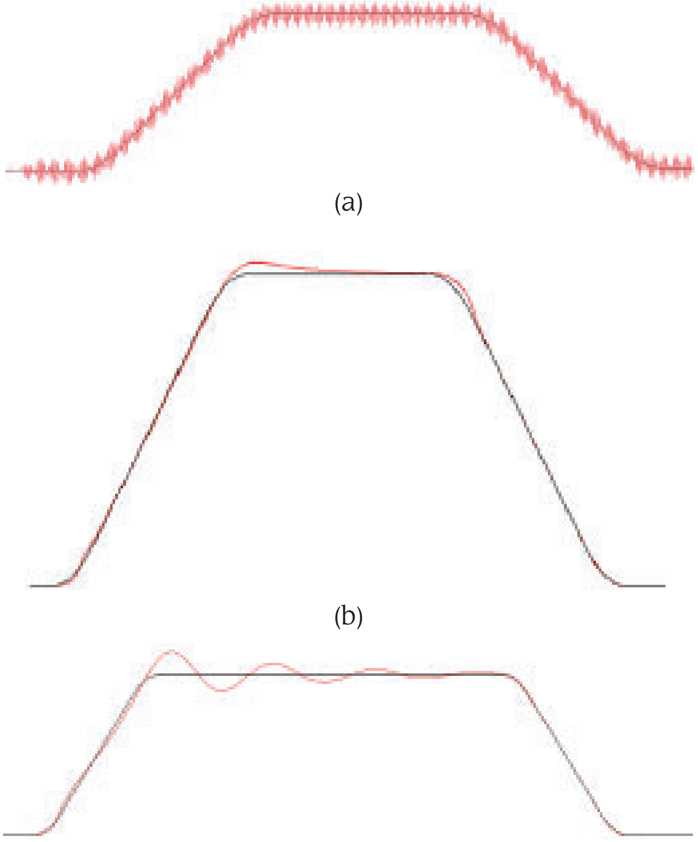

Figure 5: Speed control responses: (a) Proportional gain too high, inducing vibration; (b) proportional gain too low, causing overshoot; (c) proportional gain too low and integral gain to high, resulting in ringing

Encoder Settings

For encoder adjustments, the drive default settings should be fine for the majority of applications. Unresolved vibration after speed control adjustment may be caused by noise picked up on the encoder cable and can typically be filtered out by decreasing the encoder sample rate. However, if the sample rate is decreased too much, this will provide too much delay in the speed feedback causing speed oscillation or torque pulsation from the machine. As mentioned earlier, pure serial encoder formats can reduce encoder noise issues, allowing for faster sample rates and increased speed control bandwidth.

System Inertia

A third, but not always necessary, area of adjustment is determining system inertia. Providing the drive with the system inertia allows it to estimate how the system will respond. This estimate is used to determine the required motor torque at a given point in operation, which is then fed forward in the speed control loop, increasing stability

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and reducing dependence on the speed reference back from the encoder. The result is smoother torque output and less speed over- or undershoot. Generally, determining the system inertia is a final step in the tuning process. The system inertia can typically be determined by the drive, but should be done after final cab, compensation and counterweight adjustments have been made, and will require a balanced load to perform.

Pre-Torque

With gearless machines, there is no reliance on the gear to help reduce rollback during the transfer of the load from brake to motor, and there is no gear breakaway torque. In addition to speed-dependent gains, drives may also need pre-torque adjustment settings to eliminate rollback. Because high-resolution encoders are available, one particular drive feature that may be available is internal synthesized pre-torque. That is, the drive generates a pre-torque response between the load transfer period when the brake opens, and the rollback occurs when the profile begins. This means, no need for an external load-weighing device, which will fall out of calibration over time. However, drive-synthesized pre-torque is dependent on the physical brake opening time sequence, so this should always be adjusted after the brake has been calibrated, and spring tension and air gap are set.

Line Regeneration Potential

PM motors are the highest-efficiency ones available for elevator applications. Therefore, this high efficiency makes many PM gearless applications well suited for installation together with a line regeneration system. Such a system will provide the building owner further return on investment over time by returning energy generated during empty-car-up/full-load-down operation back to the main line to be consumed internally within the building by other loads. Typically, this energy is wasted by being dissipated in a bank of braking resistors. Additionally, the elimination of heat from the braking resistors will further reduce the overall system operation costs by reducing machine-room cooling costs. Finally, installation of a line regeneration system may provide the building owner with incentives from utilities or local governments and municipalities.

The additional positive aspect of a line regeneration system includes better power quality surrounding the elevator system. This can reduce harmonic distortion on the line and effectively increase the drive's DC bus lifetime by a factor of two through reduction of DC bus current ripple and protecting input against transient voltage spikes. Finally, it is considered a "green" solution and becoming more welcome among many building owners and architects.

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Learning-Reinforcement Questions

Use the below learning-reinforcement questions to study for the Continuing Education Assessment Exam available online at www.elevatorbooks.com or on page 111 of this issue.

- How are PM motors similar to and different from induction motors?
- How is the motor data of a PM motor different from that of an induction motor with respect to the relationship between motor rated speed, frequency and number of motor poles?
- What is the importance of knowing the rotor position with respect to the encoder, and when does this relationship change?
- What are important installation techniques when utilizing high-resolution encoders with analog tracks?
- In a PI speed control loop, how does each term affect ride quality?

ELEVATOR WORLD Continuing Education Assessment Examination Questions

Instructions:

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1. When does the motor pole position need to be learned on a PM AC motor with absolute encoder?
   a. This is done at the factory and never needed in the field.
   b. Only when it is new.
   c. After each power cycle.
   d. When the encoder mounting has physically changed.

2. Which of the following should be used when entering the motor data for a PM AC motor?
   a. Actual line frequency.
   b. Inverter rated line frequency.
   c. Inverter rated frequency at rated speed.
   d. Output frequency at rated speed.

3. Which of the following PM AC motor data would be incorrect?
   a. Rated motor speed = 97 rpm, rated motor frequency = 12.93 Hz
   b. Rated motor speed = 146.9 rpm, rated motor frequency = 53.86 Hz
   c. Rated motor speed = 125 rpm, rated motor frequency = 21.87 Hz
   d. Rated motor speed = 250, rated motor frequency = 58.33 Hz

4. If a motor stalls and draws high current, which could be the problem?
   a. Incorrect endcoder position.
   b. Incorrecy rated motor speed or frequency.
   c. Torque limit set too low.
   d. All of the above.

5. What is the typical rated slip on a PM AC motor?
   a. 2–5%
   b. None.
   c. 25–90 rpm
   d. 2–5 Hz

6. Which of the following installation technique is not recommended?
   a. Run the encoder cable with incoming power.
   b. Run the encoder cable with the brake wires.
   c. Run the encoder cable with the motor wires.
   d. All of the above.

7. If the motor runs in the opposite direction, the solution is to swap two motor phases.
   a. True
   b. False.

8. If the drive has a difficult time picking full load, but the current is not excessive, which could be the problem?
   a. Not enough magnetizing current generated.
   b. Speed control set too low.
   c. Flux buildup too slow.
   d. All of the above.

9. The ride quality is smooth coming out of the floor and into leveling, but vibrates during high speed. What would likely eliminate this?
   a. Reduced high-speed control response.
   b. Increased high speed control response.
   c. Reduced low-speed control response.
   d. Increased low-speed control response.

10. Which would be a good method to start adjusting speed controller?
    a. Make adjustments in large steps to clearly see the difference.
    b. Make adjustments in small steps to make sure optimal value is obtained.
    c. Make all adjustments for inspection speed first.
    d. None of the above.

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