

Understanding Permanent Magnet Motor Operation and Optimized Filter Solutions

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Todd Shudarek, Principal Engineer

MTE Corporation

N83 W13330 Leon Road
Menomonee Falls WI 53154

www.mtecorp.com

Abstract

Recent trends indicate the use of permanent magnet (PM) motors because of its energy savings over induction motors. PM motors offer energy savings, higher power densities, and improved control. The upfront cost of a PM motor may be higher than an induction motor, but the total cost of ownership may be lower. However, a PM motor system brings design challenges in terms of selecting the best variable frequency drive (VFD) as well as a filter to protect the motor.

A PM motor requires the use of a VFD to start and operate. The best VFDs will need to operate at higher switching frequencies to meet the higher fundamental frequencies of the PM motors. In turn, the PM motor will need to be protected from power distortion, harmonics, and overheating. While a traditional filter is de-rated to meet the higher frequencies, this paper will demonstrate that, by nature of the operation of a PM motor, an appropriately design filter that operates for higher switching and fundamental frequencies will reduce the size, weight, and cost of the system.

Introduction

Historically induction motors have been used in a variety of industrial applications. Recent trends indicate a shift toward permanent magnet (PM) motors which offer up to 20% energy savings, higher power densities, and improved control. The PM motors can have increased upfront costs but over the life of the system reduce the total cost of ownership through efficiencies and energy savings. Requirements to drive, filter, and protect PM motors can present unique challenges. The switching frequencies tend to be greater than 4 kHz with a required fundamental frequency of up to 300 Hz and higher. The readily available 2 kHz, 60 Hz “off the shelf” filters can be de-rated for the higher frequencies, but their does not meet the performance needs of the typical PM motor with variable frequency drive (VFD).

This paper explains the basic operation of a permanent magnet motor as compared to an induction motor. It also explains some of the

special considerations when specifying a filter for a PM motor system, specifically the use of higher switching frequencies and filters.

Induction Motor Operation

The operation of an induction motor involves using stationary stator coils placed in a circular pattern that through the use of three phase power, creates a rotating magnetic field about the center axis. Each pair of windings on the stator is referred to as poles that rotate in the direction as shown in figure 1. The orientation of one of the sets of poles is shown with the direction of rotation. Stator laminations, as included in figure 2, surround the stator coils to increase the magnetic field and decrease losses.

Figure 3 shows a squirrel cage rotor. Currents are induced into the loops of metal in the bars of the rotor by the magnetic field created by the stator. These loops of current create a rotor magnetic field. Rotor laminations, shown in

figure 4, surround the squirrel cage to increase the magnetic field strength and decrease losses. This magnetic field attracts the magnetic fields created by the stator and forces rotation. The speed of rotation (RPM) is based on the supply frequency and the number of poles, is calculated by equation [1].

$$\text{Speed (RPM)} \approx \frac{\text{frequency (Hz)} \times 120}{\text{Number of Poles}} \quad [1]$$

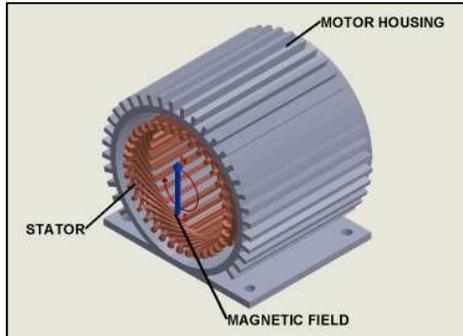


Figure 1 Stator windings and motor housing

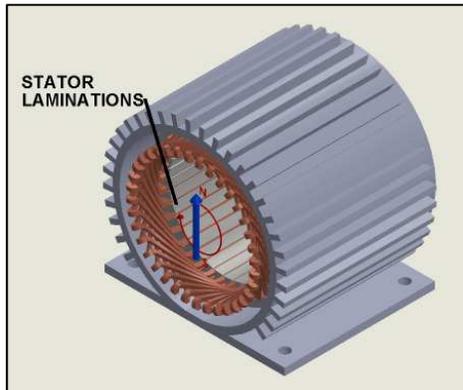


Figure. 2 Stator windings, motor housing and stator laminations

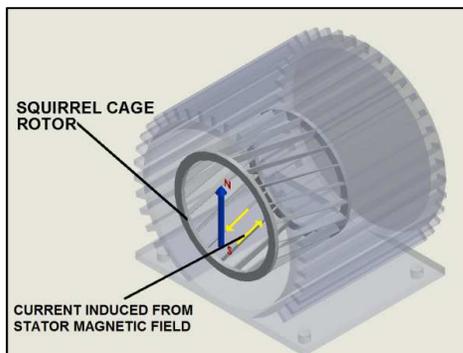


Figure. 3 Squirrel cage rotor and induced currents from stator

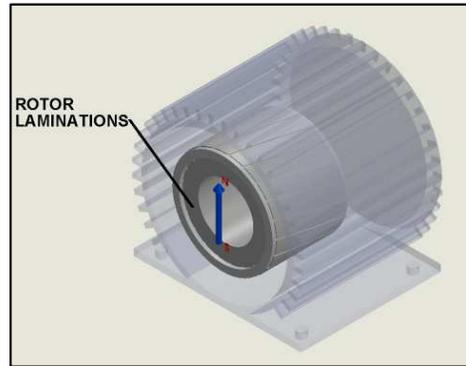


Fig. 4 Rotor laminations

Permanent Magnet Motor Operation

The stator windings on a permanent magnet motor are similar to those shown in figure 1. The difference in motor operation, as the name suggests, is the existence of permanent magnets. These permanent magnets are included in the rotor assembly. A single representative rotor assembly with permanent magnets is illustrated in figure 5. The magnets can vary in shapes and locations on the rotor assembly. The rotating magnetic field created by the three phase power to the stator repels the magnetic fields of the permanent magnets, forcing the rotation of the rotor. Much of the efficiency increase of a PM motor is due to the lack of a need for currents to be induced in the rotor, as needed in an induction motor, to create a magnetic field within the rotor. The rotation speed calculation, based on frequency and number of poles, is the same as for an induction motor (1). A PM motor also requires a closed control loop to establish and stabilize the desired speed.

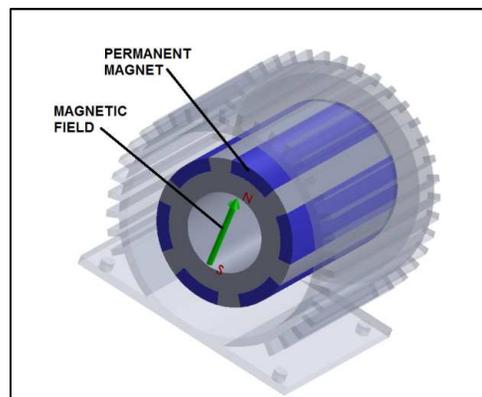


Figure. 5 PM motor rotor illustration

PM motors typically have more poles than a similarly rated induction motor. Therefore the drive will be required to provide higher fundamental frequency to achieve the same rotation speeds. The increased number of poles is a means to reduce motor cogging, an undesirable non-uniform motor torque that can sometimes cause audible noise and vibration.

PM motors typically require compatible drives and filters. They are not designed for across the line starting. A system integrator will work through selection of a drive, filter, and motor combination that will meet the applications needs. The drive control system is uniquely determined for a filter and motor combination.

PM motors are more sensitive to elevated thermal conditions for even a short period of time. Induction motors are very tolerant of infrequent, short duration elevated temperatures during overload conditions. The insulation system is “stressed” and the motor life is shortened an insignificant amount. In the case of a PM motor, the permanent magnets, that really are not permanent in some situations, gradually demagnetize if excessive temperatures occur. The temperature at which complete, irreversible demagnetization in a magnet occurs is called the Curie temperature. After significant demagnetization occurs the motor will cease to function. At any temperature, whenever the magnetic field strength exceeds the coercive force of the magnets, the magnets will fail. Elevated temperatures make the motor increasing more sensitive to demagnetization and eventual failure.

PM motors are also sensitive to the switching harmonics created from a PWM drive. These harmonics create eddy currents in the stator which increases the temperature of the entire motor.

PM Motor Protection Considerations

Filtering is required for a PM motors to extend motor life. Filtering reduces the motor temperatures by decreasing the amount of heat created in the stator windings and laminations. Attempts have been made to use a 60 Hz de-rated 2 kHz sinewave filters that are readily available in the marketplace. However, a de-rated 60 Hz, 2 kHz sinewave filter will be much

larger, have higher power loss, and higher voltage drop than an optimally designed higher frequency filter. Furthermore, with de-rating a 60 Hz filter, only 120 Hz fundamental frequency operation can be achieved. A typical PM motor requires 150 Hz operation or higher.

Figures 6 and 7 show pictures of the MTE de-rated 2 kHz filter and the new MTE 5 kHz filter offering, respectively. Table 1 shows a performance comparison between a 300 HP typical 60 Hz de-rated 2 kHz filter and a 300 Hz rated 5 kHz filters. The weight and power loss in the 5 kHz filter are almost half. The total volume of the 5 kHz filter is 40% less than the 2 kHz filter. The de-rated 2 kHz filter is still limited to 120 Hz operation whereas the optimized 5 kHz filter can operate up to 300 Hz.

When drives are operated at higher carrier frequencies, they need to be de-rated to account for the higher switching losses. However, an optimally designed drive and filter combination can have a lower total cost. The decreased filter losses and size need to be considered with respect to the enclosure size and cost to thermally manage the entire system.



Fig. 6 300hp 2kHz filter



Fig. 7 300hp 5kHz filter – 40% smaller than a 2kHz filter

Table 1 480 V 350 HP Filter option comparison

	2 kHz, 480 V, 600 A,60 Hz De-rated to 415 A	5 kHz, 480 V, 415 A
MTE Part Number	SWGM0600D	SWGM0415D-HF05300
Reactor Size HxWxD (in.)	18.3 x 24.0 x 14.7	12.1 x 15.3 x 14.3
Reactor Weight (lbs.)	471	237
Power Loss (W)	2,225	1,144
Capacitor Size HxWxD (in.)	7.9 x 16.3 x 7.6	6.7 x 16.3 x 7.6 (2)
Total Volume (in³)	7,417	4,307
Switching Frequency (Hz)	2,000-8,000	4,800-8,000
Maximum Fundamental Frequency (Hz)	120	300
THVD	<5%	<5%

Universal Filter Considerations

The idea, on its surface, of a universal filter is very desirable to drive manufacturers. The end users can operate at 2 kHz for induction motor applications at the full drive rating and de-rated 5 kHz PM motor applications with that same drive. The electrical engineering concept of frequency scaling can aid in understanding why optimally designed 5 kHz filters are better than attempting to use a 2 kHz topology for PM motor application. Figure 8 shows the frequency response of an optimally designed 2 kHz low pass LC filter (60 Hz fundamental). It will have a cut-off frequency near 700 Hz to provide 17 dB attenuation at 2 kHz required to ensure less than 5% THVD. The attenuation of a low pass filter designed for 2 kHz switching will have 34 dB attenuation at 5 kHz, more than what is needed to protect the motor. The concept of frequency scaling teaches that the component values of a filter can be

scaled to achieve identical performance at alternate frequency ranges. The procedure to scale a 2 kHz filter to 5 kHz is to multiply all of the impedances by 2 kHz/5 kHz (40%). This scaled 5 kHz filter, with the frequency response shown in figure 9, will have identical performance at frequencies scaled higher by 5 kHz/2 kHz (2.5). The new filter now has 17 dB of attenuation at 5 kHz to ensure less than 5% THVD. The 60% smaller inductance and capacitance result in lower cost and higher performance. The reactor voltage and capacitor current that the 2 kHz filter had at 60 Hz operation will now be at 5 kHz, 150 Hz operation. Rather than continuing to rise with higher frequencies which is the case of a 2 kHz filter at higher motor frequencies. The 5 kHz filter, with all of its benefits at 5 kHz operation, is not suitable for 2 kHz operation since the 2 kHz is close to the resonance point at 1750 Hz.

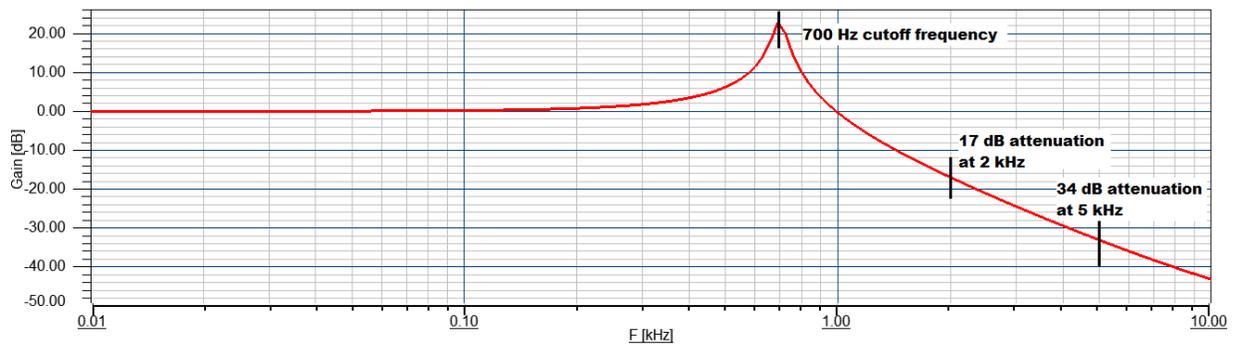


Figure 8 Typical 2 kHz LC filter frequency response

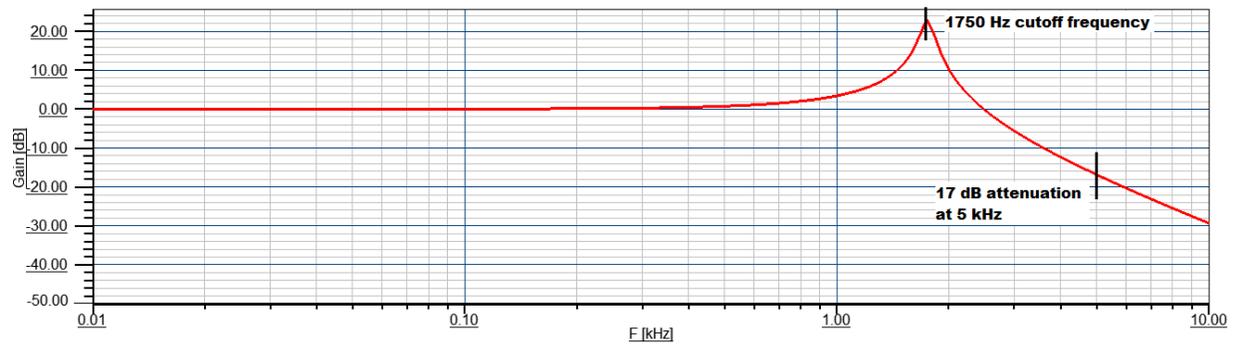


Figure 9 Typical 5 kHz LC filter frequency response

Conclusion

The basic operational differences between an induction motor and a permanent magnet motor have been disclosed. The unique filter requirements of the PM motor have been explained. As PM motors gain greater popularity, the need for an optimally

specified motor filter becomes even more critical for optimal system performance. The system integrator should not settle for a less than optimal filter system that is less costly, more efficient and can be operated at frequencies allowing the full speed of the motor.

References

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