Application of Sine Wave Filters with High-Speed, High Power Motors

Corey Jones
Senior Applications Engineer
CTM Magnetics, Inc.
Tempe, Arizona 85282, USA
cjones@ctmmagnetics.com

***Abstract*—Decreases in permanent magnet synchronous motor (PMSM) costs are leading to increased utilization in high power applications due to benefits in energy efficiency, partial load efficiency, and decreased motor size. Typically, low pass sine wave filters are used to eliminate switching frequency harmonic content at the output of the variable frequency drive (VFD), minimizing excess heat and voltage stress in the motor. Traditional silicon steel sine wave filters exhibit excessive core losses at high fundamental and switching frequencies, leading to difficulties with overheating and negating the efficiency gains of the sine wave filter. These limitations have led to low adoption rates for sine wave filters in high-speed, high power motor applications. This paper will first discuss the evolution of AC motors, from induction machines to PMSMs. The paper will conclude with a discussion of how properly designed sine wave filters, with optimal materials and construction, can be used to realize substantial benefits in efficiency and reliability when installed in a high-speed, high power motor system.**

Keywords*— permanent magnet synchronous motors, sine wave filters, high-speed motors, variable frequency drive, variable speed drive, PWM drive

I. Introduction

Traditionally, induction motors have been utilized to drive a majority of high power, industrial applications. However, with recent improvements in material costs and efficiencies, permanent magnet synchronous motors (PMSM) are increasingly being applied in a variety of high power installations due to benefits in efficiency, partial load capabilities, and higher power density. These benefits are improving motor performance and decreasing total cost of ownership. [1]

However, PM motors have their own limitations. The current generation of PMAC motors use magnetic rotor materials that are sensitive to high temperatures, experiencing permanent demagnetization and decreases in torque and power when elevated thermal conditions are introduced. Accordingly, PMSMs are more susceptible to switching frequency harmonics, which create hysteresis and eddy current losses in the motor, increasing the motor temperature. In line frequency motor applications, sine wave filters are often applied to eliminate PWM switching harmonics. However, PM motors often operate under high fundamental frequencies, which causes overheating issues with traditional silicon steel sine wave filters. Since the PM motor is manufactured with laminated silicon steel (the same material in the sine wave filters), the filter experiences the same core losses as the motor and the addition of the filter does not improve efficiency.

Due to these restrictions, high frequency sine wave filters are often avoided or not considered in PM motor applications. Without a filter, motors need to be overdesigned, and longevity is often compromised. Through the use of low-loss core materials and optimal high frequency filter designs, CTM Magnetics is able to overcome these limitations and provide filtering solutions that are dependable, increase motor reliability, and boost system efficiency.

II. History of Electric Motor Systems

A. Electric Motors

In most industrial applications, high power motors come in the form of three-phase AC motors. Since utility-provided electricity is AC, there is nothing inherently prohibiting an AC motor from being directly connected to the grid; in fact, most machines were originally implemented in this manner (large motors sometimes needed starting help). However, there are some limitations in using an AC motor directly connected to the grid.

For starters, many motors require high start-up torque, necessitating current surges up to eight times the required full load current. While small motors can usually get away with this torque (i.e. current) demand, start-up torque requirements for large motors can be problematic. There is no option to slowly increase motor speed with a grid-connected motor. In addition to start-up and speed concerns, directly connecting a motor to the grid will subject the motor to all the voltage spikes and noise associated with the grid. However, one of the biggest limitations of an AC motor directly connected to the grid is complete lack of speed and torque control.

A grid-connected motor is subject to a single fixed frequency and fixed voltage. The fixed frequency results in a fixed motor speed, while the fixed voltage leads to limited motor torque. Voltage can be set for the motor/application with a transformer, but once set this represents a fixed voltage. Motor speed is directly dependent on the frequency provided by the grid and the motor's inherent design, which is again fixed.

While some applications can make due with a fixed frequency and voltage, having the ability to control both frequency and voltage comes with advantages in process control and energy conservation. For example, whereas a fixed speed motor would demand high starting torque and current surges (not to mention mechanical stress), frequency and voltage control can be utilized to gradually ramp up to operating speed, lessening system stresses and current surge requirements, leading to smoother acceleration and deceleration. Energy savings represents an even greater potential market for variable speed motors. Fixed speed, grid-connected AC motors must run in "on-off" modes to meet partial demand (which is most of the time, since the motor is likely designed for peak demand requirements). Furthermore, for fan, compressor, and pump applications, true variable flow operation is only achievable by use of a damper or control valve, which takes a significant pressure drop to lower the flow rate. By operating under variable load/variable torque conditions, according to fan affinity laws, 50% of the airflow can be achieved with 12.5% of the input power by directly regulating the fan's motor speed. [2]

B. *Variable Frequency Drives (VFDs)*

Variable frequency drives (VFDs) are electronic converters that control AC motor speed and torque by adjusting motor supply frequency and voltage. Compared to mechanical and hydraulic adjustable speed drives, VFDs are now becoming the preferred method of speed and torque control of electric motors, mainly due to decreases in VFD size and cost. This trend is especially true in high power applications where energy efficiency is deemed critical.

VFDs come in a number of different topologies, however, by far the most common are voltage-source inverter (VSI) drives. In this topology, the AC line input is converted to DC link through a rectifier, filtering is provided by a DC link capacitor, and an inverter converts the DC link voltage to an AC signal through pulse-width modulation (PWM) techniques. The topology described is an AC-AC drive that takes the AC grid signal and converts it to AC inverter output. The benefit here is that the PWM inverter output can be adjusted to vary both the frequency and voltage. Unfortunately, the use of PWM techniques introduces higher frequency harmonic content (at multiples of the PWM switching frequency), as well as introducing voltage spikes due to switching elements. Motors are not designed to operate with high frequency noise. The high frequency harmonics lead to excessive motor heat, while voltage spikes can stress the insulation system. Optional equipment can be added to systems with VFDs and motor systems to limit these concerns.

C. *Sine Wave Filters (<90 Hz)*

Sine wave filters are low pass harmonic filters that consist of a series inductor followed by a shunt capacitor. Sine wave filters allow the fundamental frequency to pass while filtering all higher frequency harmonics (associated with the switching frequency). The bode plot in Fig. 1 shows the frequency-dependent filtering characteristics of a sine wave filter. Sine wave filters remove the PWM output noise, providing near pure sinusoidal voltage and current waveforms.

Sine wave filters offer one of the most robust solutions for motor protection. Voltage harmonics, voltage spikes and reflected wave issues (with cable runs up to 15,000 feet) are

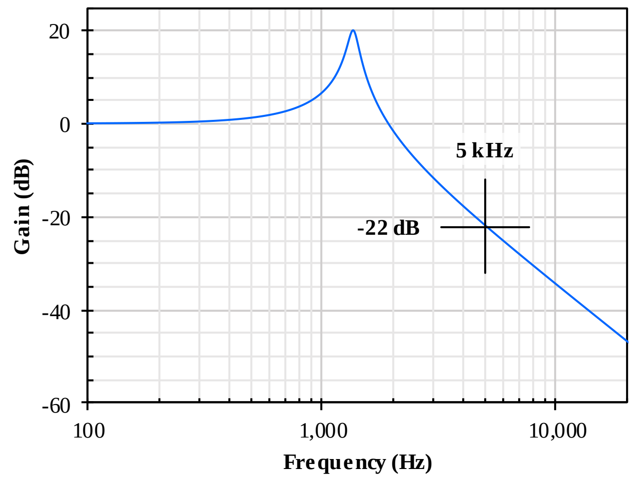

Fig. 1. Bode plot of CTM high frequency sine wave filter

virtually eliminated. These enhancements increase motor reliability and longevity by decreasing voltage stress on motor windings. Furthermore, sine wave filters remove switching frequency harmonic current distortions before they enter the motor, eliminating them as an additional source of motor heat. Less heat leads to cooler motors, which in turn lead to longer life and worry-free operation.

CTM sine wave filters also provide the additional benefit of increased efficiency. Whereas high frequency harmonic distortion creates additional heat in the AC motor, sine wave filters remove these harmonics before they enter the motor, reducing motor heating. Unlike silicon steel inductors, CTM sine wave filters process these harmonics with a low core loss material, decreasing the overall power losses.

III. Permanent Magnet Synchronous Motors

Permanent magnet synchronous motors (PMSM), also known as permanent magnet AC (PMAC) motors, differ from typical induction motors in that the rotor magnetic field is provided by permanent magnets, instead of being induced by the stator in the rotor bars. Whereas induction motors require slip to induce the rotor magnetic field, PM motors have an "always on" rotor magnetic field and run at synchronous speeds.

PMAC motors have many advantages over typical induction motors. First and foremost, PM motors are more efficient, as they do not rely on a field excitation system to produce the rotor magnetic field. This means no excitation losses (rotor copper losses are eliminated), yielding higher efficiencies. Efficiency improvements for PM synchronous motors become even more pronounced when partial load is considered, as efficiency remains high over a much wider speed range (see Fig. 2 from [3]). Additionally, PM motors are capable of higher power densities than their induction counterparts and operate with higher power factors. [4]

PM synchronous motors are typically more expensive than induction motors due to the use of rare earth magnetic materials. However, recent trends have seen increased utilization of lower cost rare earth materials, leading to a much higher value proposition for PMSMs [4]. Furthermore, when energy

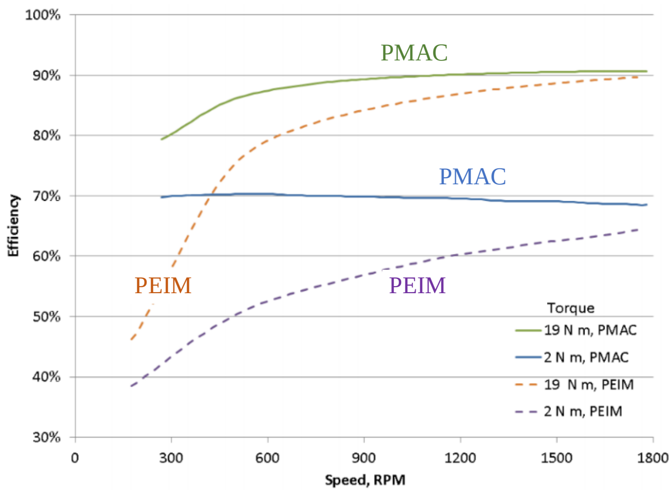

Fig. 2. Efficiency at various loads of permanent magnet (PMAC) and premium efficiency induction motors (PEIM)

efficiency is also considered, PM motors have significantly lower total cost of ownership in most applications. For many users, this lower ownership cost is worth the initial investment.

PM motors do not have line start capabilities, so VFDs are required for starting (unless other features are included, such as an asynchronous cage winding damper). However, for most applications this is not a concern, as VFDs are already in use with induction motors. [5]

PM motors, while considered very robust due to their simple design, are susceptible to demagnetization when exposed to high temperatures [4]. While induction motors can recover when overstressed, the demagnetization of PM motors is a permanent condition. Therefore, managing cooling and power loss in PM motor designs is critical for long term reliability.

A. *High-Speed PMSM*

There is an increasing trend in the industry towards high speed motors. Since power is directly proportional to motor speed, high speed motors have a power density advantage compared to low speed motors. For PM motors, high speed operation is extremely beneficial as it can reduce the overall rotor volume, thereby reducing the motor cost [4]. Additionally, with high power fans and pumps requiring high rotational speeds, high speed motors can operate without a gearbox, thereby eliminating this system power loss and increasing efficiency. The highest efficiency and highest power density is achieved with high speed permanent magnet motors. It is therefore not surprising to see more and more markets switching to high speed PM motors.

High speed operation requires a high frequency signal. With the possibility of permanent magnet demagnetization, and the increased significance of efficiency, minimization or elimination of harmonic currents from the PWM output from the VFD is highly valuable. Traditionally, sine wave filters have been avoided in all but the most necessary circumstances, as the high frequency fundamental operation leads to excess power loss and overheating in traditional silicon steel designs. CTM Magnetics, through use of proprietary low core loss materials, advanced cooling technologies, and unique geometries, has managed to overcome these obstacles.

IV. High Frequency Sine Wave Filters (>120 Hz)

Sine wave filters designed for high frequency operations serve essentially the same purpose as their line frequency counterparts: take a PWM inverter output and remove switching frequency related harmonics, outputting a near perfect sinusoidal voltage and current waveform. However, the effects of sine wave filter installation in high-speed, high power motor applications can be more pronounced than with traditional line frequency induction motors. Benefits of installation of a sine wave filter typically fall into two categories: reliability and efficiency.

A. *Reliability*

The two greatest stressors on an electric motor system that affect reliability and longevity are typically voltage spikes and heat. Voltage spikes are completely removed by the sine wave filter, eliminating a potential source of early fatigue and electrical failure. Heat is also reduced by eliminating the effects of high frequency harmonic currents running through the motor. High frequency currents create both DCR resistance losses and (more drastically) core losses, as PWM related currents induce magnetic fields in the ferromagnetic motor materials. At the fundamental frequency, these magnetic fields are absolutely critical, as they are directly related to torque and power developed by the motor. However, the high frequency magnetic fields (created by switching noise) do not develop useful torque or power and instead cause undue heat due to hysteresis and eddy current losses.

A unique characteristic to modern PM motors based on low-cost neodymium materials (NdFeB) is that high temperatures can lead to demagnetization of the permanent magnets, resulting in permanent loss of magnetic properties and premature failure of the motor. [4]

Additionally, high speed motors have high fundamental frequencies, which necessitates higher inverter switching frequencies in order to keep the frequency modulation (m_f) at acceptable levels. For example, a 60 Hz waveform generated with a 2 kHz switching frequency has a frequency modulation of 33.3, (1). However, when the fundamental frequency is increased to 400 Hz, the modulation ratio decreases to 5. Increasing the switching frequency to 5 kHz still leaves a frequency modulation ratio of 12.5.

$$m_f = f_{switch} \,/\, f_{fund} \tag{1}$$

Due to limitations on high power switching devices, frequency modulation is most often lower in high frequency applications than in line frequency applications, leading to more harmonic content (as shown in Fig. 3). When combined, all these factors lead to higher harmonic-related power losses, especially considering most motor stator materials (silicon steel) typically display high losses at high frequencies. Eliminating these losses from the motor therefore has a significantly more pronounced

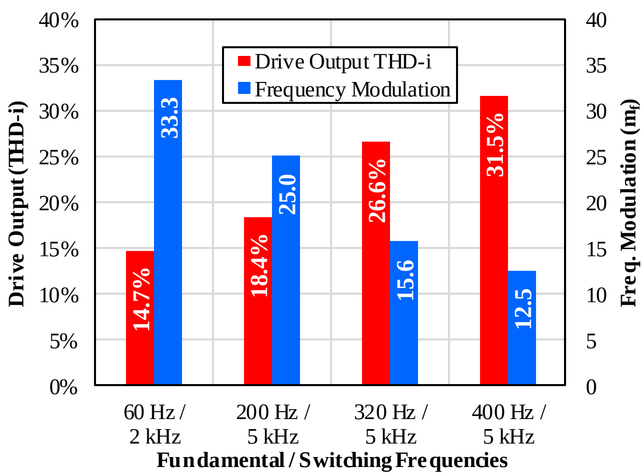

Fig. 3. Drive output current harmonics as a function of frequency modulation

effect in a high-speed motor application than in a line frequency motor application.

B. System Efficiency

The second primary benefit of a CTM sine wave filter installed with a high speed, high power motor is improved system efficiency. System efficiency improvements come through two primary means: filtering high frequency harmonics before they enter the motor (processing with low core loss material), and power factor improvements through capacitive reactance.

Thermal benefits from the elimination of PWM high frequency harmonics from the motor was previously discussed. Additionally, removal of high frequency harmonics carries a potential efficiency boost as well. Electric motors (even high-speed PM motors) are made with materials to produce and enhance a magnetic field to power the rotor. This material (silicon steel) was originally designed for line frequency applications; even thin, high frequency grades of silicon steel struggle to efficiently process high frequency harmonics. Adding a sine wave filter to the circuit removes the high frequency harmonics from the motor, but the filter must now process these harmonics. Traditionally, the inductive portion of the filter is made of the same material as the AC motor, resulting in equivalent high frequency power losses in the magnetic material. This has been a primary obstruction to prolific adoption of high frequency sine wave filters for high-speed, high power motors. However, CTM Magnetics filters utilize low core loss magnetic materials, which can process high frequency currents at a fraction the power losses of traditional sine wave filters.

Neglecting the capacitive portion of the filter (which will be discussed later), the inductive component of the filter adds impedance to the circuit. The additional impedance causes a voltage drop and reduces the current traveling through the circuit, thereby decreasing the power provided by the motor (actual applications will not see this power drop due to the capacitive reactance, which is discussed below). The power demanded by the drive (power in) also drops due to the inductive reactance. The CTM high frequency inductor removes the PWM harmonics from the motor and processes them with much lower core losses, which ultimately yields an efficiency boost (even with additional impedance). While adding a passive electrical component to increase efficiency might seem counterintuitive, when considered from a power in / power out perspective, it intuitively makes sense.

If the filter consisted solely of an inductor, it would be true that motor drive system would drop the power output of the motor (though not the efficiency, as discussed above). However, the sine wave filter also includes a capacitive element, which adds capacitive reactance to the circuit. The capacitive reactance partially negates the inductive reactance of both the filter inductor and the motor, lowering the impedance of the circuit and improving the overall power factor. The sine wave filter capacitance value is selected to provide the ideal power factor over the motor's operating range, leading to more shaft power delivered to the load using the existing motor, or the ability to design the system to use a smaller motor with the same shaft power. Consideration must also be taken when creating a leading power factor, as this can cause issues with feedback control loops and drive stability [5]. Bringing the voltage and current in phase with each other maximizes your real power (output power), maximizing effective energy usage.

V. Conclusion

In summary, the addition of a CTM high frequency sine wave filter between the drive and the high-speed, high power motor will minimally reduce the voltage delivered to the motor, though the improvement in the motor power factor will negate this voltage drop. The addition of this sine wave filter will improve the overall system efficiency by moving the switching losses from the higher loss motor material (silicon steel) over to the more efficient sine wave filter. Additional efficiency is gained by improvement of the motor power factor, as this will lower the motor current and remove heat, thereby lowering the DCR losses in the motor. Silicon steel sine wave filters only provide the benefit of improving motor reliability, while CTM sine wave filters have the added benefit of efficiency improvement.

References

[1] J. Murphy, "What's the Difference Between AC Induction, Permanent Magnet, and Servomotor Technologies?," Machine Design, 1 April 2012. [Online]. Available: https://www.machinedesign.com/motorsdrives/whats-difference-between-ac-induction-permanent-magnet-and-servomotor-technologies. [Accessed 6 July 2017].

[2] Y. A. Çengel and J. M. Cimbala, Fluid mechanics: fundamentals and applications, 1st ed., New York: McGraw-Hill, 2006.

[3] B. P. Dooher and J. Bersini, *Permanent magnet alternating current (PMAC) motor efficiency comparison - phase 1,* San Ramon, California: Pacific Gas and Electric Company, 2014.

[4] J. F. Gieras, Permanent magnet motor technology: design and applications, 3rd ed., Boca Raton, Floriza: CRC Press, 2010.

[5] J. Kang, *General purpose permanent magnet motor drive without speed and position sensor,* Yaskawa Electric America, 2009.