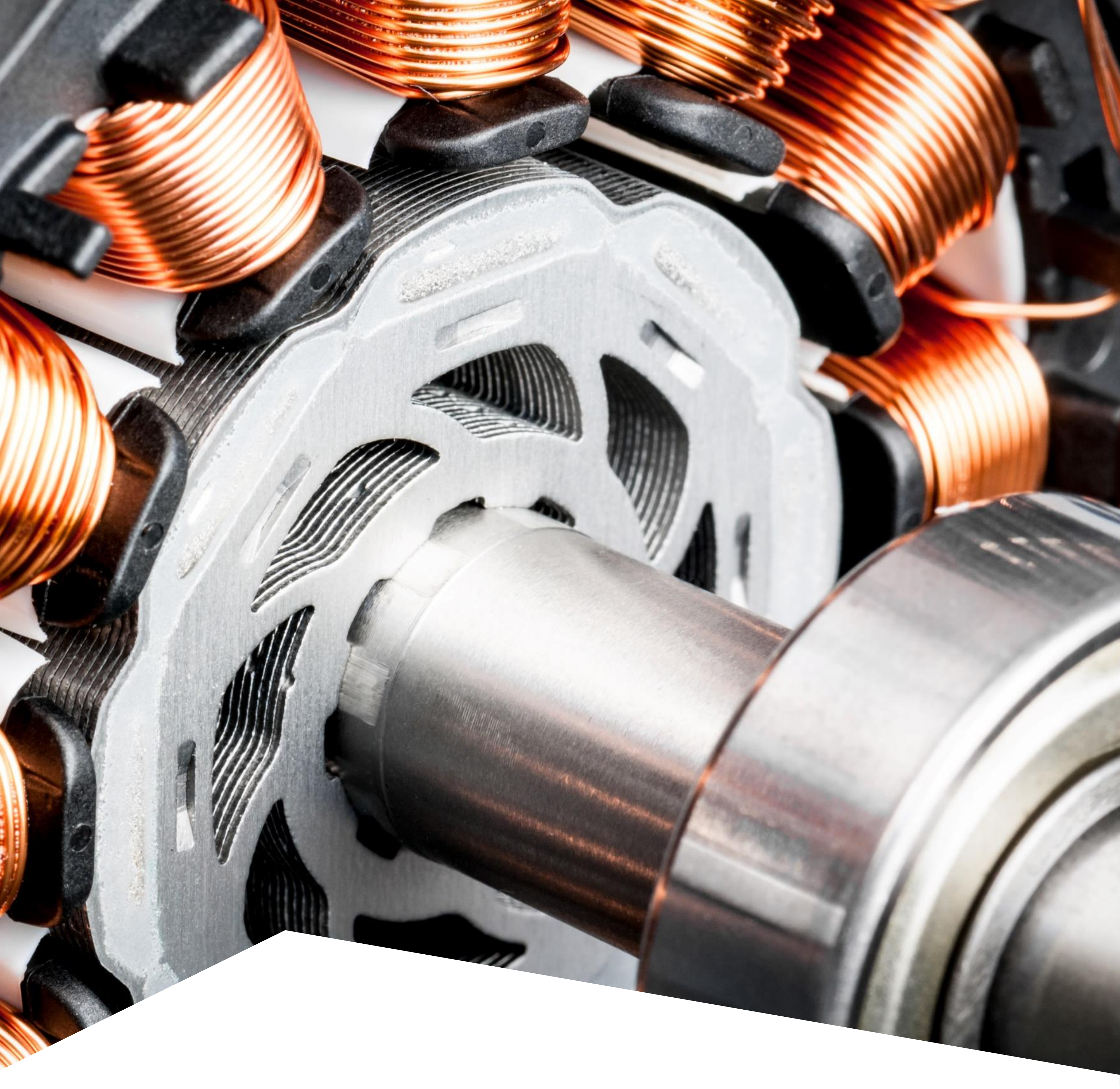

WHITEPAPER

WBG switches in motor drive systems

Investigating the impact of high-frequency switching wide bandgap-based inverters on motor drive losses

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Table of contents

Abstract

Motors drive systems that use pulse width modulation (PWM) switching control techniques experience high-frequency switching losses associated with a current ripple that negatively affect efficiency. Different studies have been developed to predict how these losses correlate with switching frequency. However, most of them only apply to the frequencies applicable when using Insulated Gate Bipolar Transistors (IGBT) – typically up to 20 kHz.

Infineon used a combination of simulations and experimental measurements on a practical motor system to investigate the potential impact of using wide bandgap devices (WBG) - silicon carbide (SiC) and gallium nitride (GaN) - wide bandgap (WBG) switches which can switch at higher switching frequencies (50KHz) on the efficiency of the motor drive inverter.

This white paper discusses emerging trends in electric motor applications, possibilities, opportunities, and challenges for using WBG devices in motor drive systems. It also details the approaches used and the results of simulated and experimental tests. In addition, we consider the significance of different WBG and silicon device parameters by comparing their most important figures of merit and their performance in a typical motor application. Finally, before discussing the calculated results, we present the experimental setup to estimate the impact of using WBG switches in a motor drive inverter.

1 Recent trends in electric motor applications

Motors used in industrial applications will soon be required to comply with new energy standards (IE4 and IE5) [1], and investigations are ongoing to determine which of the three most commonly used types – permanent magnet, synchronous reluctance, and induction – are best placed to meet these standards (Figure 1).

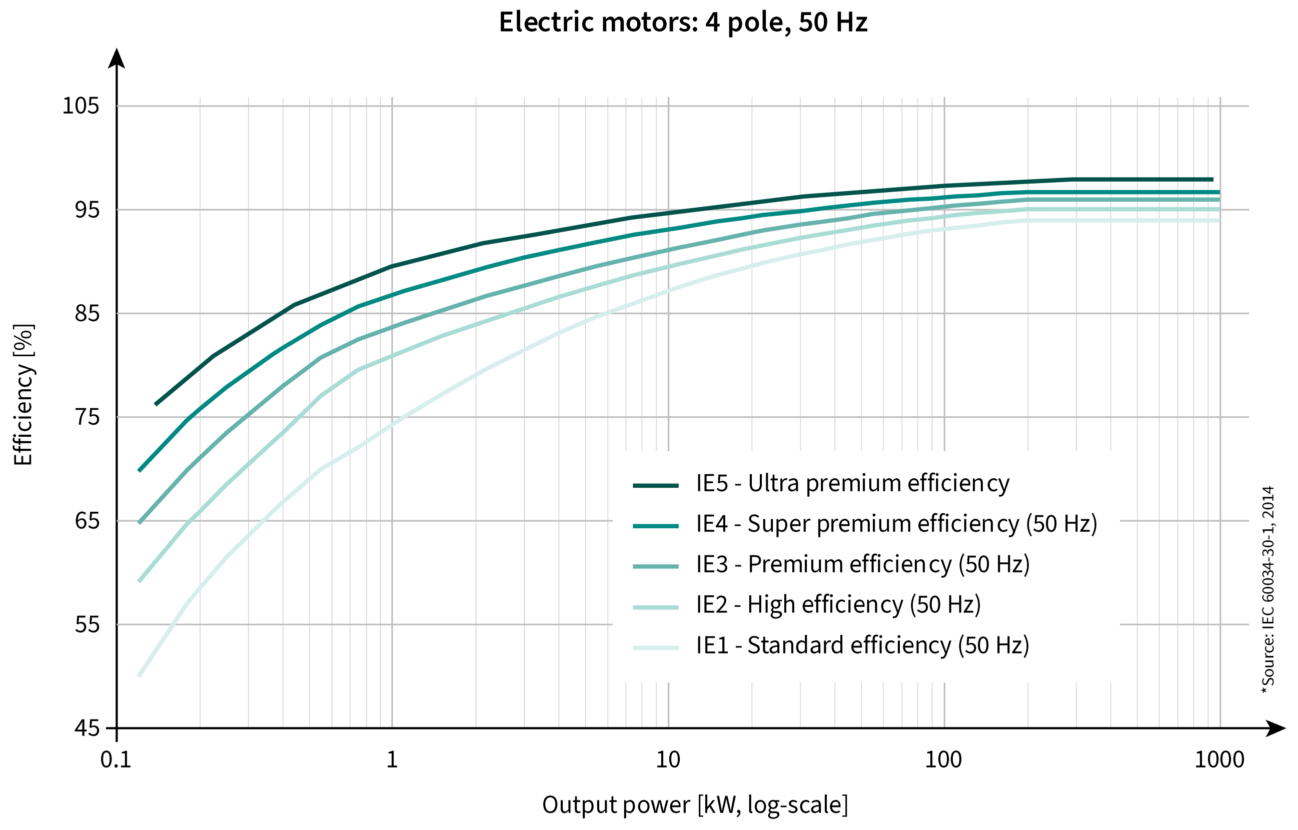

Figure 1 New motor efficiency standards

Permanent magnet motors provide high efficiency and torque density but are more challenging to drive than induction motors. While they are also higher cost (due to their higher earth metal magnets) and have speed limitations (due to back EMF), they are still widely used in traction applications. Synchronous reluctance motors have low production costs and provide high efficiency, but they are also difficult to drive and offer a low torque density which is not ideal. The induction motor, which is the most widely used in industry, is easy to drive and has low production costs. However, it has a low torque density and low efficiency.

An emerging trend is that inverters are becoming more widely used in industrial motor applications to achieve the required efficiency levels, and this opens up the possibility of using wide bandgap-based inverters to drive efficiency to even higher levels, even for induction motors (Figure 2).

Motor type	PMSM	SynRM	IM
Advantages	• High efficiency • High torque density	• Low production cost • High efficiency	• Easy-to-drive • Well-established on the market • Low-production cost
Disadvantages	• Difficult-to-drive • High cost (rare earth magnets) • High speed limited by magnets	• Difficult-to-drive • Low torque density	• Low torque density • Low efficiency

Figure 2 Summary of advantages and disadvantages of different motor types

2 Opportunities for using wide bandgap switches in motor drives

2.1 Low inductance motors

Low inductance motors have different applications, including large air gap, slotless and low leakage induction machines. They can also be used in a new motor type that uses a PCB stator instead of a winding stator. These motors require a high switching frequency (50 to 100 kHz) to maintain an acceptable ripple.

Still, these cannot be attained using a standard insulated gate bipolar transistor (IGBT), which only provides high-power switching at a maximum of 20 KHz. These frequencies are also beyond the upper limit achievable using silicon MOSFETs (50 KHz), opening new opportunities for WBG devices.

2.2 High-speed motors

Because of the high fundamental frequencies, these motors also require high switching frequencies. They are used in applications like high-power density electric vehicles, high pole-count, and high-speed motors with high torque density and megawatt (MW) level high-speed motors. Here again, the maximum switching frequencies of MOSFETs and IGBTs present limitations that could possibly be overcome using wide bandgap switches.

2.3 Harsh operating conditions

Two appealing features of wide bandgap devices for motor control inverters are that they generate less heat than silicon devices (meaning they are less likely to require heatsinks). They can withstand higher operating temperatures – 600°C for SiC and 300°C for GaN, compared to only 200°C for silicon devices.

While GaN devices currently have some packaging-related issues limiting their application to operating temperatures not exceeding 200°C, research is underway to overcome these. Still, wide bandgap devices are better suited for motor applications that may experience harsh operating conditions, like integrated motor drives in hybrid electric vehicles (HEV), sub-sea and downhole applications, and space applications (Figure 3).

	WBG in motor drives		
	Low inductance machines	**High-speed motors**	**Harsh environments (high temperatures)**
Applications	- Motors with large air-gap - Slot-less motors - Low-leakage induction machine (traction applications)	- High power density motors (EV) - High pole-count high-speed motors with high torque density - MW-level high speed motors	- Integrated motor drives HEV - Sub-sea and downhole applications - Space applications
Requirements	- PWM switching frequency of 50-100 kHz or higher to maintain an accept-able ripple	- Fundamental frequency of multiple kHz	- High junction temperature operation and low losses

Limitations of silicon devices	- MOSFETs:
	  - 50 kHz max switching frequency for few kW
	- IGBTs:
	  - 20 kHz max switching frequency in a high power range
			- Si devices:
			  - Junction temperature 200°C
			- SiC and GaN devices*:
			  - Theoretical limit 600°C and 300°C

*Still limited by packaging at 200°C

Figure 3 Summary of opportunities for using WBG devices in motor drives [2]

3 Challenges for wide bandgap devices in motor drives

While wide bandgap devices certainly appear to have many features which make them attractive for motor drive applications, there are still challenges to overcome when using them.

3.1 Winding insulation

The first risk relates to inter-turn short circuits, which can occur because wide bandgap devices switch at speeds that currently used motor winding insulation cannot withstand. There are two possible options to address this risk – the first is to limit dv/dt, but this means not fully exploiting the full capability of the wide bandgap devices and raising inverter losses. A second option is to research further the development of new types of insulation that can withstand these switching frequencies and dv/dt.

3.2 Bearing lifetime

Faster switching increases partial discharge on motor bearings, potentially reducing their (and the motor's) lifetime, thereby negating the benefits achieved using wide bandgap devices. One possible way to overcome this is to use ceramic-coated bearings. Unfortunately, these are expensive and increase motor costs.

3.3 Cable length

Higher switching frequencies create the problem of signal reflections over long cable lengths. Filtering is one option to address these, but it introduces filter losses to the system. Research is currently taking place into increasing levels of integration by placing the inverter closer to the motor to reduce cable lengths and the reflection effects in the cable.

The benefits that wide bandgap switches can bring to motor drive systems can be summarized as follows:

- Energy efficiency
  - Reducing electricity consumption makes people's lives more environmentally friendly and sustainable.
- Exceptional performance
  - Enabling higher power density makes motor designs more economical by delivering the same performance using smaller devices.
- Simpler topologies
  - Enabling more compact and space-efficient designs with a lower bill of materials and less requirement for cooling.
- Higher quality
  - Wide bandgap-based inverters have longer lifetimes and are less prone to failure meaning manufacturers can offer longer warranties.
- Disruptive innovation

4 Figures of Merit for comparing switching technologies

The switching performance of devices constructed with different semiconductor technologies is compared using their respective figures of merit (FoM). Figures for the following device types from Infineon are presented:

- GaN (Infineon's CoolGaN™ HEMT technology)
- SiC (Infineon's CoolSiC™ technology)
- Standard silicon MOSFET (Infineon's CoolMOS™ MOSFET technology)
- Silicon MOSFET (Infineon's CoolMOS™ superjunction MOSFETs with a fast body diode)

Table 1 below compares device parameters.

Table 1 Figures of Merit for silicon and WBG switches

Technology	$V_{(BR)DSS}$ [V]	$R_{DS(on)}$ @ 100°C [$R_{DS(on)}$*K]	$R_{DS(on)}$*Q_{rr} [mΩ*µC]	$R_{DS(on)}$*Q_{rr} [mΩ*µC]	$R_{DS(on)}$*Q_g [mΩ*µC]	V_f @ rated current
CoolMOS™ 7	600	1.7	100%	100%	100%	100%
CoolMOS™ 7 – Fast diode	600	1.7	10%	104%	108%	100%
CoolSiC™ Gen. 1	650	1.2	2%	21%	41%	270%
CoolGaN™ Gen. 1	600	1.5	0%	13%	6%	330%

From this comparison, it can be seen that:

- Comparing $R_{DS(on)}$* Q_{rr} performance, SiC, and GaN devices have an advantage over the two silicon devices for applications with continuous hard commutation like motor drive applications and continuous conduction mode (CCM) totem pole and power factor correction (PFC).
- With respect to driving losses or how, the SiC device and, to an even greater extent, the GaN device make a big impact compared to using either of the silicon devices. This means that they can be used to reduce driving losses, especially in light load operations, i.e., applications that do not work continuously at the nominal point of operation of the motor.
- However, for reverse conduction losses, the wide bandgap devices are at a considerable disadvantage compared to the silicon MOSFETs and silicon super-junction devices. This is because their V_f value is much higher, increasing dead time, which can have a dramatic negative impact influence on system efficiency. Therefore, when considering using a wide bandgap device in an inverter for motor drives, dead time is a critical parameter to consider, and this figure must be maintained as low as possible.

5 Comparing actual switching performance

Infineon compared the performance of an IGBT with CoolSiC™ and CoolGaN™ devices over a double pulse test, and it can be seen that the switching losses for GaN (40 percent) and SiC (55 percent) are lower than those measured for the IGBT. At 100°C for the light load conditions, the losses on the wide band gap devices are lower than IGBT. However, the IGBT still has fewer production losses at full load than the wide-bandgap devices. However, it is important to remember that this benefit is offset by the fact that the maximum switching frequency of an IGBT is only 20 kHz, compared to 100 kHz for wide bandgap switches (Figure 4).

Technology	Device	Comparison based similar $R_{DS(on)}$	$V_{(BR)DSS}$	$Eon_{(10\ V/ns)}$	$Eoff_{(10\ V/ns)}$	V_{drop} forward conduction	V_{drop} reverse conduction
CoolSiC™ Gen 1	IMX65R048M1	48 mΩ	650 V	47 %	57 %	104 %	275 %
CoolGaN™ Gen 1	IGX60R070G1	55 mΩ	600 V	47 %	42 %	150 %	220 %
TRENCHSTOP™ IGBT 7	IKX40N048M1	1 V/20 A = 50 mΩ	650 V	100 %	100 %	100 %	100 %

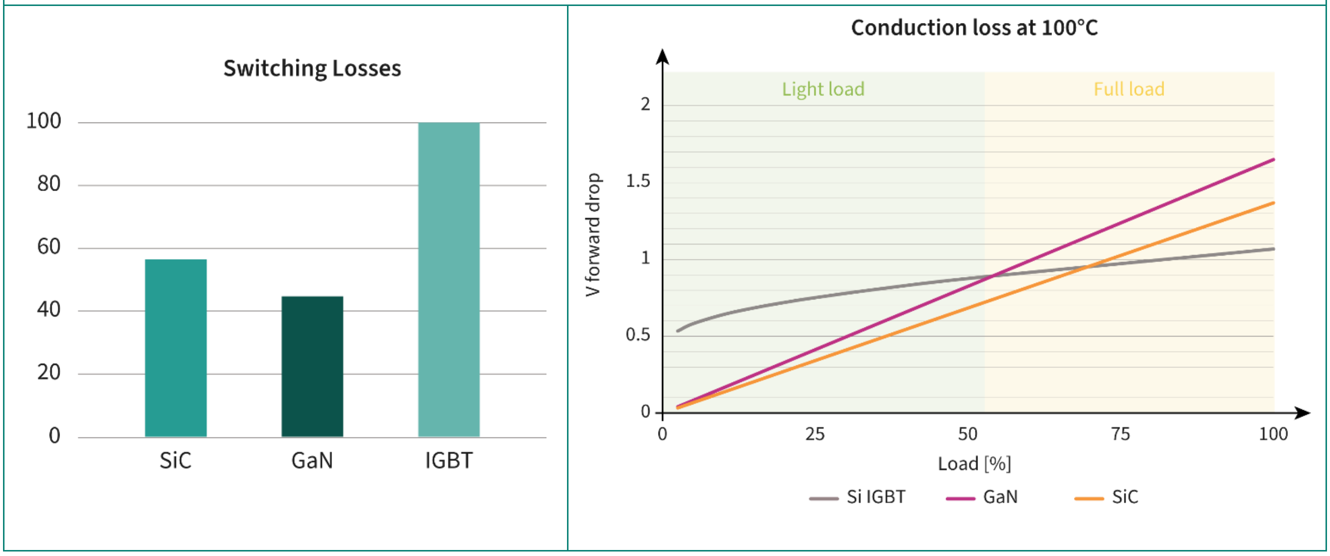

Figure 4 Comparing measured performance for Infineon's WBG and IGBT switches

6 Switching technology positioning

The present state of play in terms of how different switching technologies are positioned in industrial motor applications is as follows:

- Silicon MOSFETs remain the mainstream choice for applications operating between 25 V and 1000 V, with IGBTs dominating between 600 V and 6.5 kV.
- SiC complements silicon in many existing applications while also enabling new solutions. SiC devices are targeting high-power, fast-switching applications from 650 V to beyond 2 kV.
- GaN enables new horizons in high power density for medium power applications with the highest switching frequencies. It targets applications with operating voltages between 100 V and 600 V (Figure 5)

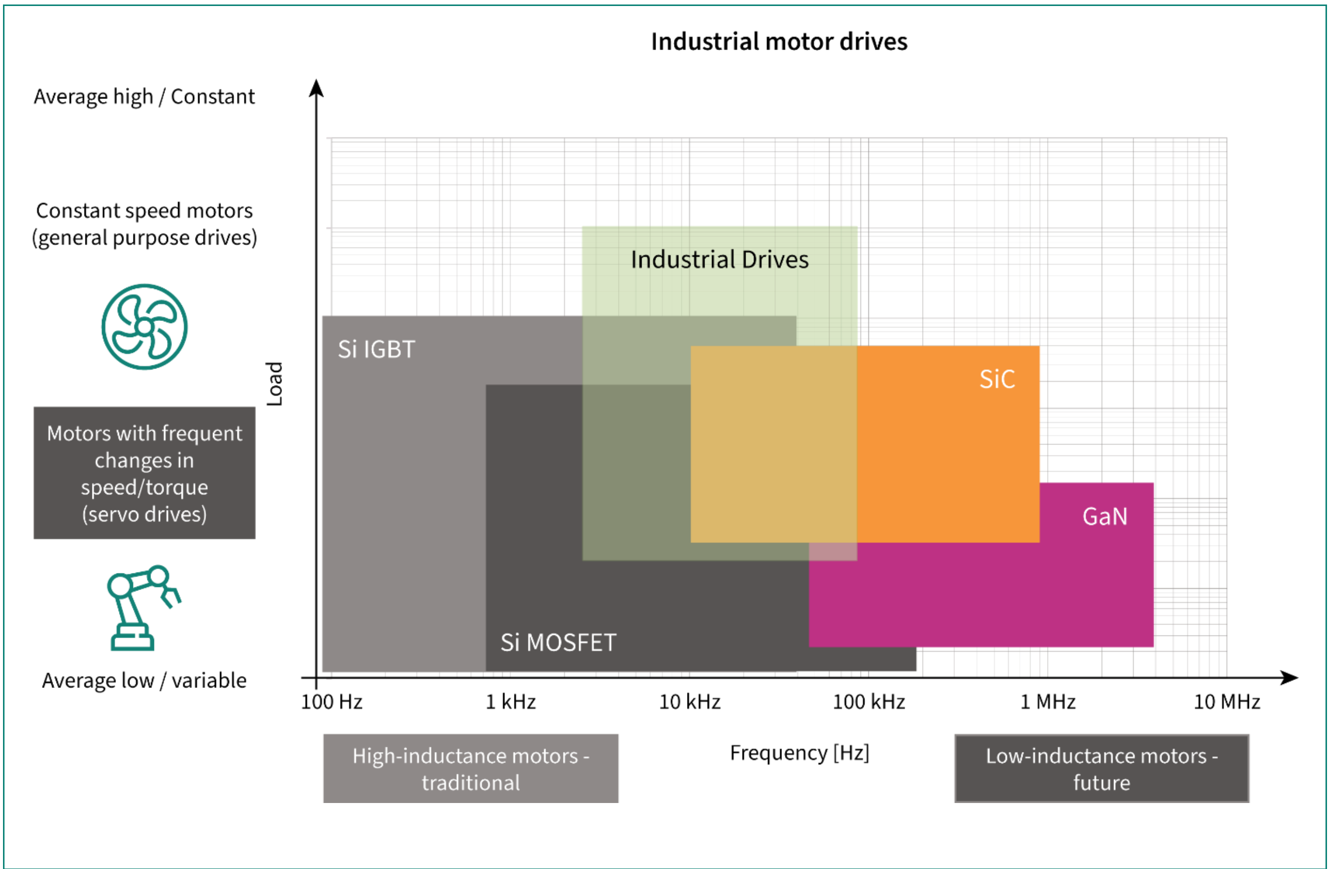

Figure 5 Switching technologies positioning in motor drive applications

7 System evaluation of wide bandgap technology in motor drive applications

The testbench (Figure 6) used to evaluate the impact of using wide bandgap devices on the performance of an inverter when driving an 'off-the shelf' motor drive consisted of the following:

- An induction motor that acts as a brake by imposing a load on the shaft of the test motor,
- A torque meter,
- The test motor – a three-hp permanent magnet motor,
- An encoder to measure motor speed and position that is used in field-oriented control (FOC),
- An XMC™ XMC4400 controller where the FOC is implemented and pulse-width modulation (PWM) signals are generated,
- An oscilloscope that is used to measure the inverter voltage, current, torque, and position,
- A thermal camera for monitoring the operating temperature of switching devices.

Table 2 Design specifications

Parameters	BSM33C-6177MHQ
Voltage	320 V
Current	12.5 A
Power	3 hp
Speed	1800 rpm
Inductance	5.2 mH
Resistance	1 Ω

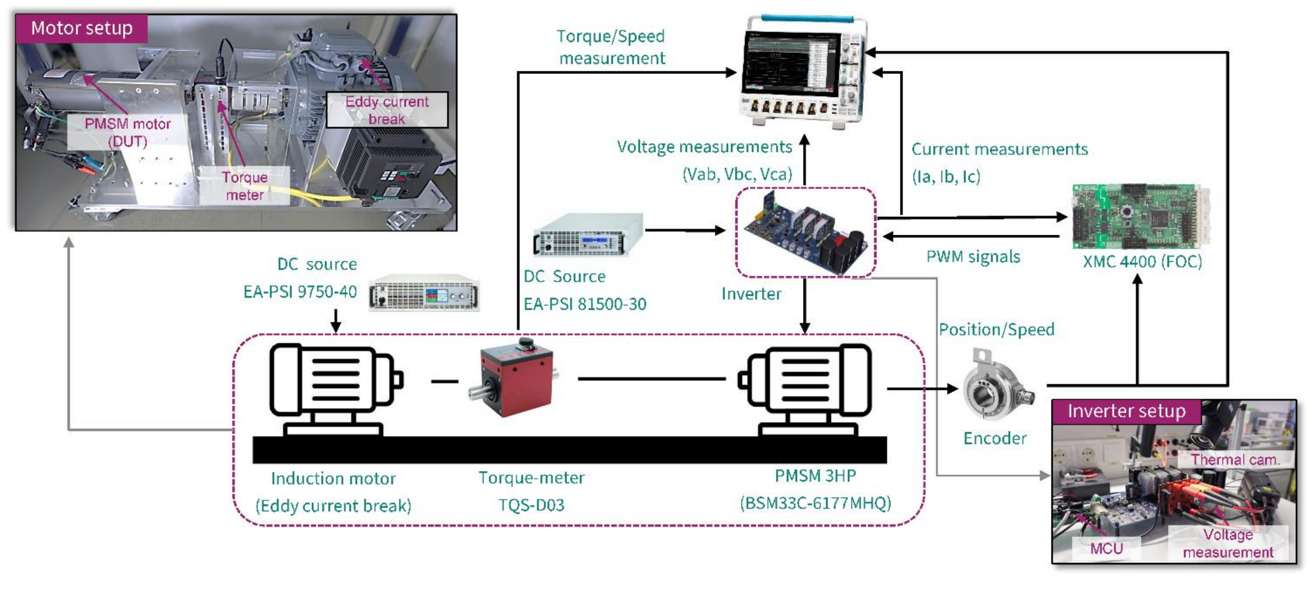

Figure 6 Testbench used for investigations.

7.1 Flexible inverter design

The inverter design used a motherboard on which the current sensing, the motor connection, the DAC, and the driver's power were located. It featured a scalable system with six 55 mΩ power devices, including GaN and SiC options (CoolGaN™ 600 V enhancement-mode power transistor (IGT60R070D1) and CoolSiC™ 650 V in TOLL package (IMT65R048M1H)).

The three legs of the inverter were located on a small daughter card that could be swapped easily from one wide bandgap technology to another (GaN or SiC) while using the same inverter. The gate drivers (EiceDRIVER™ 2EDF7175F) were dual channel devices with an isolated CT coreless transformer, and the main board provides an adjustable isolated bias supply for the different wide bandgap technologies – 18 V for the SiC daughter board and 10 V for GaN. Finally, the phase currents were measured using an XENSIV™ TLI14971 Hall effect sensor.

7.2 Acquisition procedure

The test conditions were defined, including a set of different switching frequencies, currents, and speeds to be applied for the motor under test. Measurements were then performed on the test bench, followed by PLECS simulations to estimate inverter losses. Once the data was obtained, post-processing was done in MATLAB. Losses were divided between motor and inverter losses, with motor losses further divided between high-frequency (HF) and low-frequency (LF) losses and inverter losses divided between conduction and switching losses.

7.3 Inverter losses

Energy is lost in a motor inverter when DC power is converted to AC. This is due to a combination of resistive losses in the inverter's components, switching losses in the power electronic devices, and electromagnetic losses in the passive devices. The amount of energy lost depends on the inverter design and specifications and is directly related to the switching frequency of the inverter at which the inverter operates. Higher switching frequencies increase the switching losses due to more switching events taking place.

Therefore, selecting an appropriate inverter switching frequency is important to optimize the overall efficiency of the motor drive system. Ultimately, compromises are necessary to determine the optimal switching frequency for a specific motor-inverter setup. The power semiconductor device technology chosen to help reduce power loss in an inverter depends on numerous factors, including voltage, current, switching frequency, duty cycle, rate of change of voltage (dv/dt), and gate resistance (R_g).

Figure 7 shows simulated power losses (using PLECS) for 600-650 V rated GaN and SiC power switching devices operating at 320 V and 8 A from the lowest to the highest switching frequencies. SiC switches have a slight advantage over GaN at lower frequencies (5-10 kHz). However, from 20-50 kHz, GaN devices exhibit significantly lower power losses when compared to SiC. Optimizing the performance and efficiency of the motor drive system requires power technology and device characteristics also to be considered.

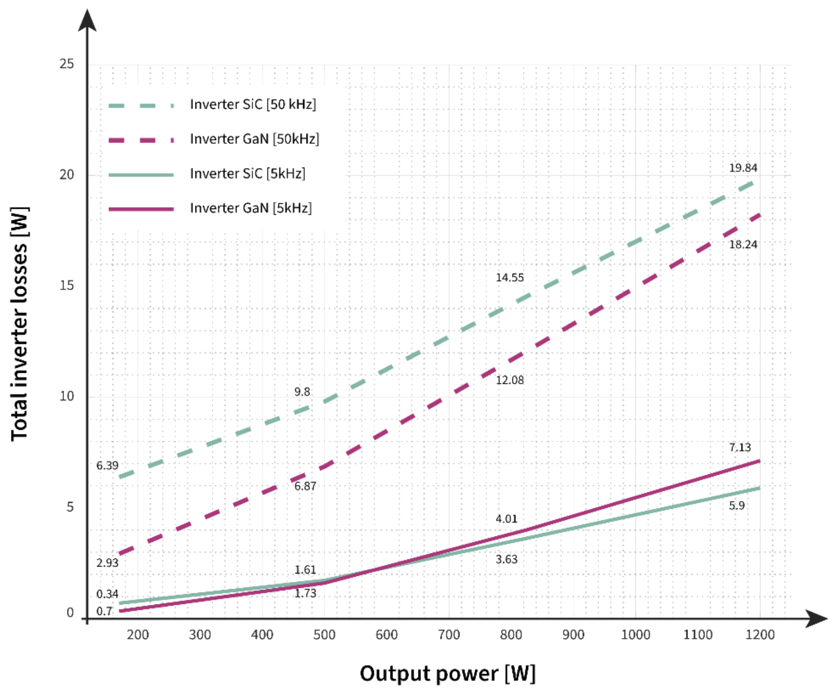

Figure 7 Inverter losses for different switching technologies

7.4 Motor losses

Motor losses can be divided into three main components - iron losses, mechanical losses, and copper losses. Iron losses include hysteresis and eddy current losses directly influenced by the switching frequency. Mechanical losses include friction and wide-range losses on the rotor. Copper losses include the skin effect of the copper, which contributes to high-frequency motor losses. In this study, only high-frequency losses were considered.

Measurements showed that the cable length was too long, resulting in ringing on the current measurement. Therefore, this ringing was removed from the measured results to estimate the actual motor losses. – Figure 8 shows the measured current in one phase (I_{total} trace – Figure 8); the low-frequency current in this waveform is removed, leaving the high-frequency current (I_{HF}). The same method is also applied to voltage to calculate HF power losses. It can be seen that the high-frequency envelope reduces with increasing switching frequency meaning losses also reduce since they are directly related to the current ripple (Figure 9).

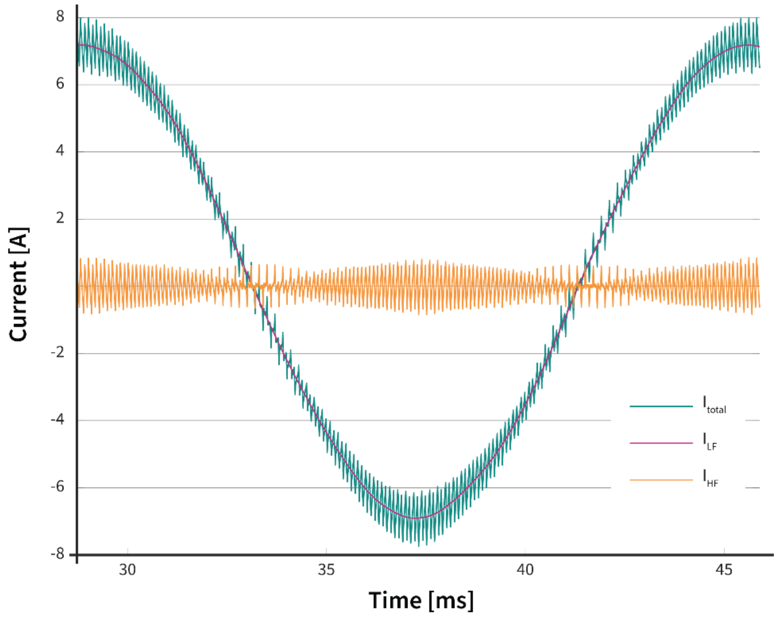

Figure 8 Separating high- and low-frequency currents

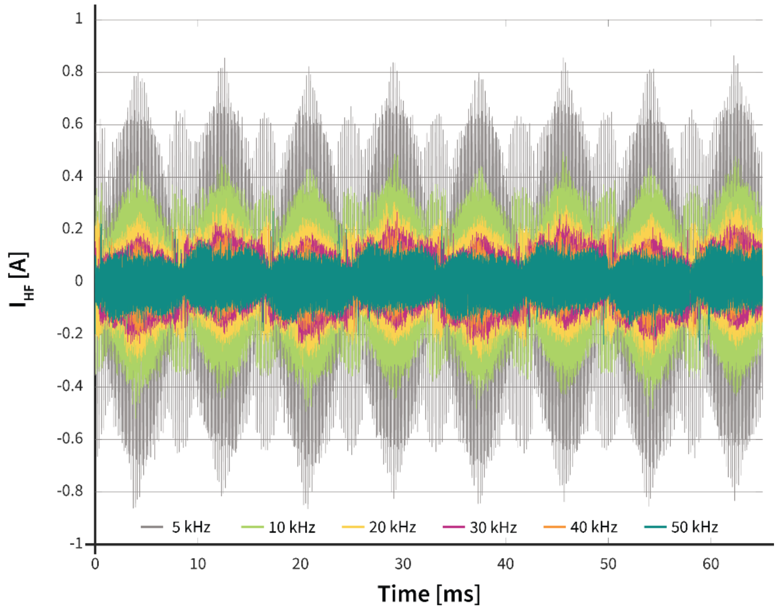

Figure 9 High-frequency current component

High-frequency power losses when a motor drives a shaft at high frequency can be calculated using the following equation:

$$Losses_{HF} = \frac{\left(V_{ab_{HF}}I_{a_{HF}} + V_{bc_{HF}}I_{b_{HF}} + V_{ca_{HF}}I_{c_{HF}} - V_{ab_{HF}}I_{b_{HF}} - V_{bc_{HF}}I_{c_{HF}} - V_{ca_{HF}}I_{a_{HF}}\right)}{3}$$

High-frequency power losses at different switching frequencies for various motor rotational speeds are shown in Figure 10, Figure 11, and Figure 12, where:

$$|I| = \sqrt{I_d^2 + I_q^2}$$

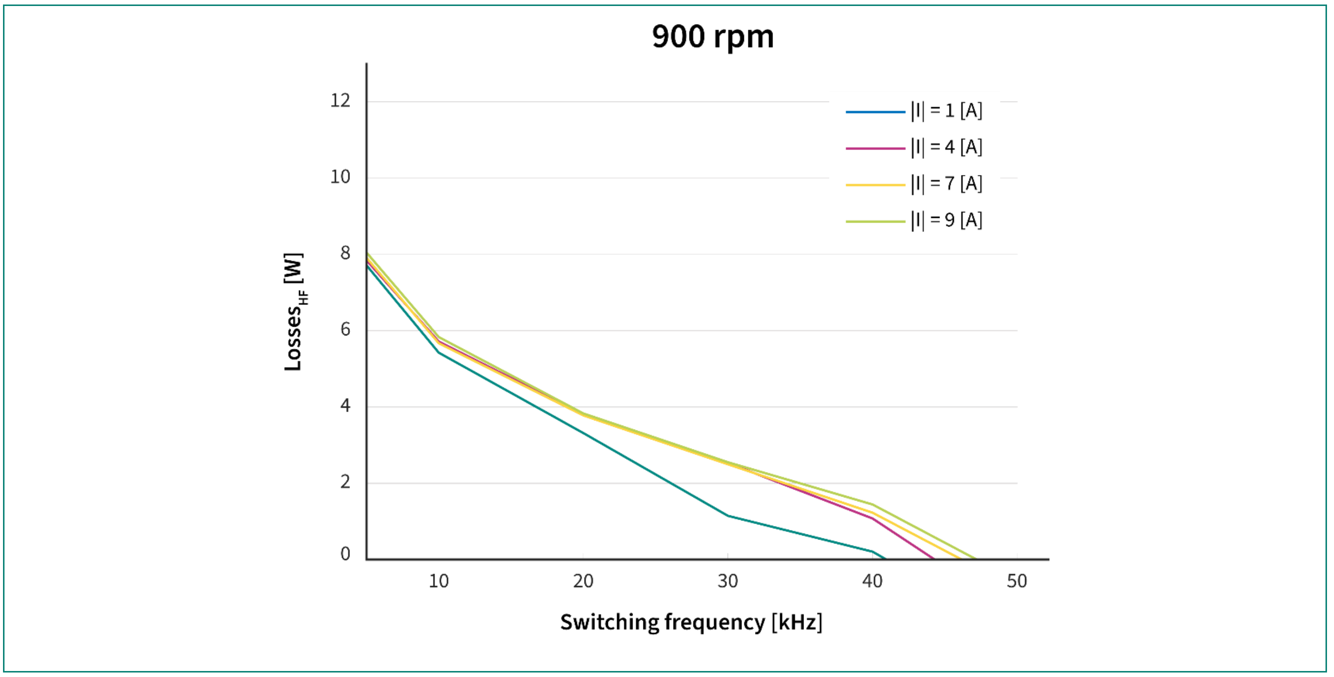

Figure 10 High-frequency losses at 900 rpm rotational speed

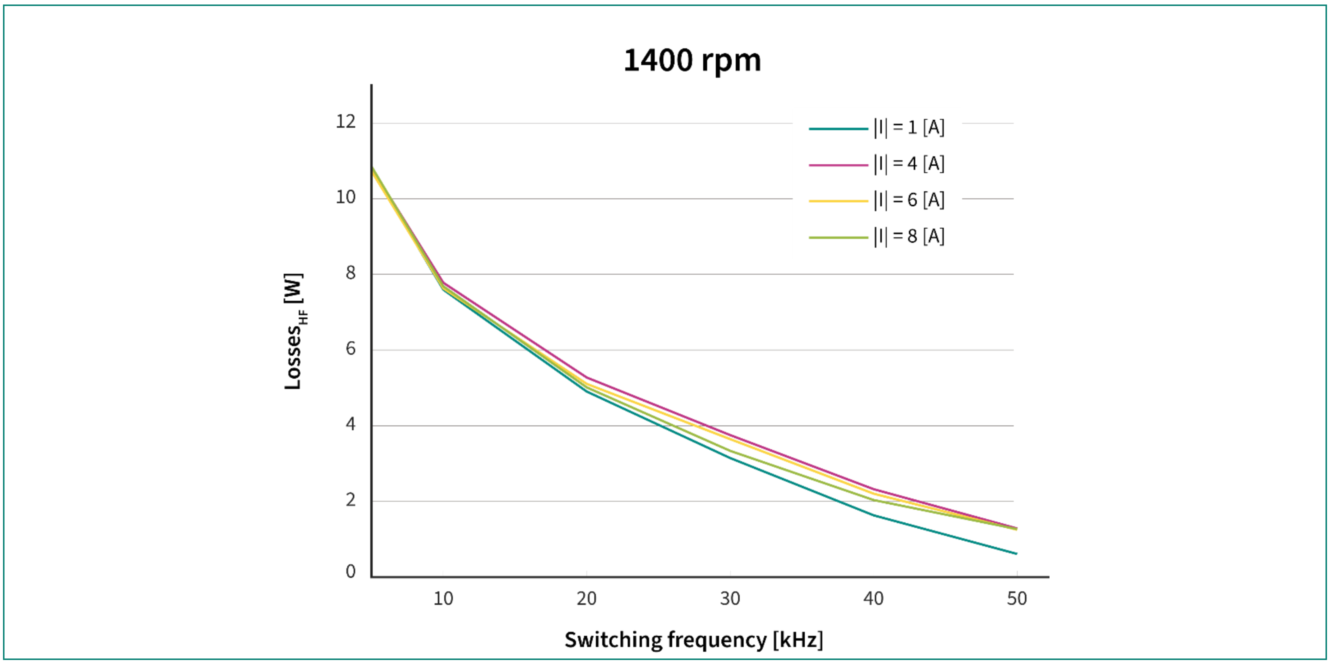

Figure 11 High-frequency losses at 1400 rpm rotational speed

Note that the high-frequency losses at 900 rpm and 50 kHz are too small to be displayed.

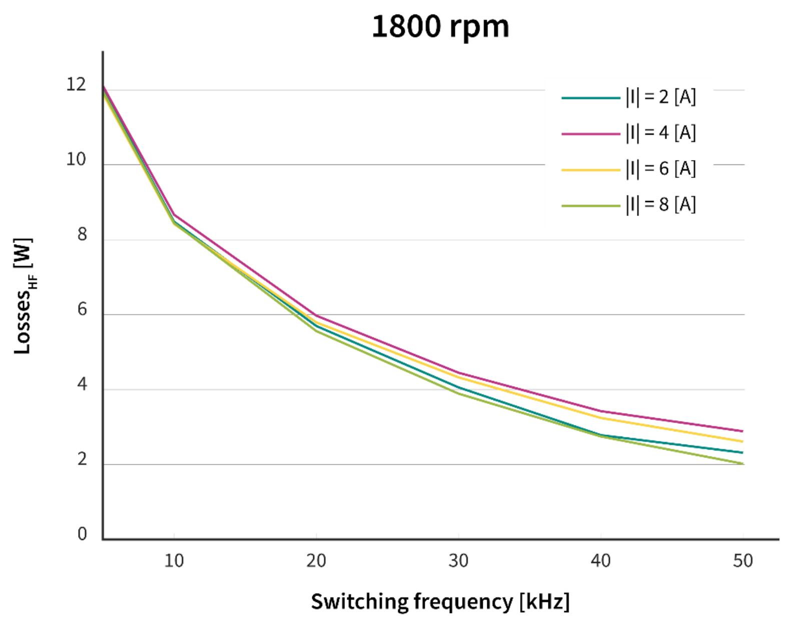

Figure 12 High-frequency losses at 1800 rpm rotational speed

The results demonstrate the clear impact of the switching frequency on the high-frequency motor losses, with high-frequency power losses being considerably reduced. The highest losses occur at 1800 rpm and 5 kHz. For this operating point, losses are approximately 12 W, while for the same speed and 50 kHz switching frequency, losses are only 2 W, representing a 10 W power saving.

Another key result is that the high-frequency losses depend on the motor's rotational speed, possibly due to increased eddy currents in the magnets at faster speeds. Iron losses are another feature that varies with speed, with hysteresis rising in line with motor speed, also impacting the amount of power lost in the motor.

7.5 Overall system losses

Parameters, including load, speed, and temperature, influence the efficiency of a motor drive system. Reducing energy losses relative to the output power delivers optimum motor operating efficiency.

An analysis of the combination of high-frequency motor and inverter losses revealed that the optimum operating point (where the motor drive system exhibits the lowest losses relative to its output power) was achieved at a switching frequency of 20 kHz when running at a nominal speed of 1800 rpm and 50 percent rated load (1.1 kW) (Figure 13).

Maintaining operation as close to this point as possible is vital to minimize power dissipation. However, the operating switching frequency requires evaluation at a system level. This choice involves consideration of the device technology used in the inverter and the motor. Using different switching technologies can alter the optimal operational switching frequency and the power losses experienced in the system.

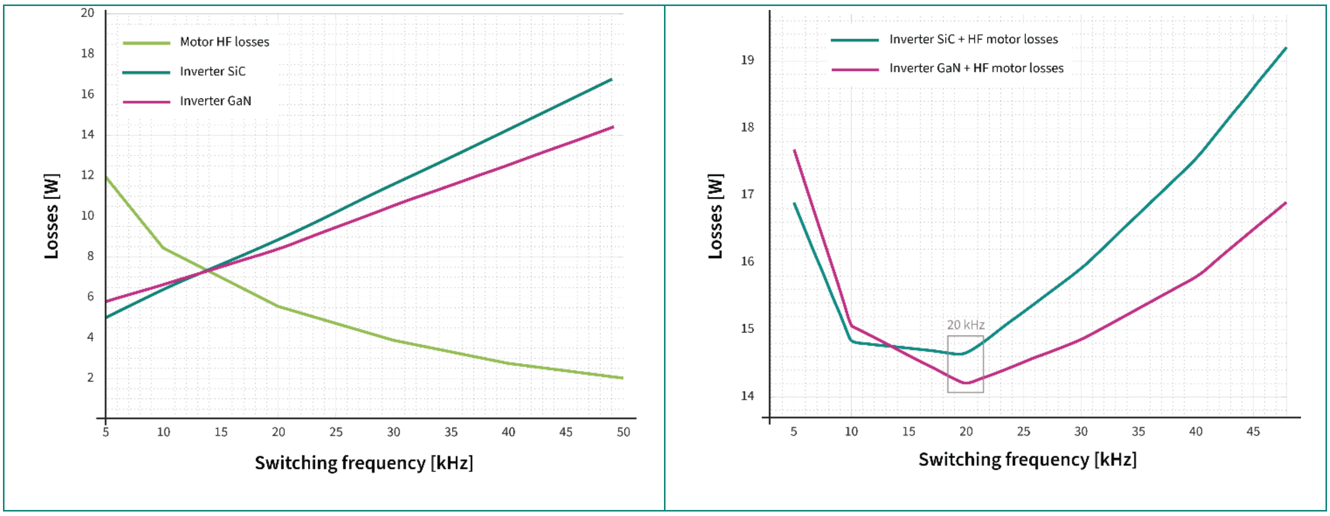

Figure 13 **Determining overall system losses and optimum operating switching frequency.**

8 Conclusion

Wide bandgap switching devices allow motor drive systems to operate at higher switching frequencies than those constructed using silicon devices to deliver higher overall system efficiency. However, the right switching frequency should be carefully selected because of the resulting trade-off between the inverter and the motor losses.

Experimental results presented in this white paper illustrated that motor power losses are reduced at higher switching frequencies, and the trade-off switching frequency was estimated to be around 20 kHz. However, further analysis is required on the impact on the lifetime of motor bearings and windings at high switching frequencies and faster transitions (dv/dt).

Furthermore, the effect of faster switching on low-frequency losses, mechanical losses, and dead-time compensation also requires investigation. Apart from enabling performance improvements for existing designs, WBG devices have the potential to open up opportunities for new motor driver topologies to meet future efficiency demands. Furthermore, future motor designs using WBG switches may also help address problems associated with higher switching frequency (e.g., wear and tear in bearings and windings, etc.).

References

[1] F. Oliveira and A. Ukil, “Comparative Performance Analysis of Induction and Synchronous Reluctance Motors in Chiller Systems for Energy Efficient Buildings,” in IEEE Transactions on Industrial Informatics, vol. 15, no. 8, pp. 4384-4393, Aug. 2019, doi: 10.1109/TII.2018.2890270.

[2] A. K. Morya et al., “Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges,” in IEEE Transactions on Transportation Electrification, vol. 5, no. 1, pp. 3-20, March 2019, DOI: 10.1109/TTE.2019.2892807.

[3] L. Chang, M. Alvi, W. Lee, J. Kim, and T. M. Jahns, “Efficiency Optimization of PWM-Induced Power Losses in Traction Drive Systems with IPM Machines Using Wide Bandgap-Based Inverters,” in IEEE Transactions on Industry Applications, vol. 58, no. 5, pp. 5635-5649, Sept.-Oct. 2022, DOI: 10.1109/TIA.2022.3178979.

[4] L. Chang, W. Lee, T. M. Jahns, and K. Rah-man, “Investigation and Prediction of High-Frequency Iron Loss in Lamination Steels Driven by Voltage-Source Inverters Using Wide-Bandgap Switches,” in IEEE Transactions on Industry Applications, vol. 57, no. 4, pp. 3607-3618, July-Aug. 2021, DOI: 10.1109/TIA.2021.3075647.

[5] K. Yamazaki and A. Abe, “Loss Investigation of Interior Permanent-Magnet Motors Considering Carrier Harmonics and Magnet Eddy Currents,” in IEEE Transactions on Industry Applications, vol. 45, no. 2, pp. 659-665, March/April 2009, doi: 10.1109/TIA.2009.2013550.

[6] N. Voyer, G. Bueno Mariani, A. Besri, V. Quemener, Y. Okamoto and A. Satake, “High-Frequency Modelling of Permanent Magnet Synchronous Machine,” 2018 8th International Electric Drives Production Conference (EDPC), 2018, pp. 1-6, DOI: 10.1109/EDPC.2018.8658271.

[7] Dahaman Ishak, Z. Q. Zhu, and David Howe“Eddy-Current Loss in the Rotor Mag-nets of Permanent-Magnet Brushless Ma-chines Having a Fractional Number of Slots Per Pole,” IEEE Transactions on Magnetics, Vol. 41, No. 9, September 2005.

[8] F. Z. Zhou, J. X. Shen, and W. Z. Fei, “Influence on Rotor Eddy-Current Loss in High-Speed PM BLDC Motors,” Proceedings of the 41st International Universities Power Engineering Conference, Newcastle upon Tyne, UK, 2006, pp. 734-738, DOI: 10.1109/UPEC.2006.367576.

[9] Pfingsten, G. & Steentjes, Simon & Thul, A & Herold, Thomas & Hameyer, K. (2014). “Soft magnetic material degradation due to manufacturing process: A comparison of measurements and numerical simulations.” 2014 17th International Conference on Electrical Machines and Systems, ICEMS 2014. 2018-2024. 10.1109/ICEMS.2014.7013817, Oct. 22-25, 2014, Hang-zhou, China

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