WBG Semiconductors Pose Safety And EMI Challenges In Motor Drive Applications

by Kevin Parmenter, Chair, PSMA Safety and Compliance Committee

For years we've been told that silicon (Si) power MOSFETs and IGBTs have largely reached their performance limits and that wide-bandgap (WBG) power semiconductors such as SiC and GaN MOSFETs will soon take over. One area where this is supposed to happen is in variable-speed motor drives, where SiC MOSFETs are competing with silicon IGBTs to be the power switch of choice for driving permanent magnet synchronous motors (PMSMs). GaN FETs are also being positioned for use in these applications. Despite the hype, there are serious obstacles to overcome in making the WBG power switches viable in *large* motor-drive applications.

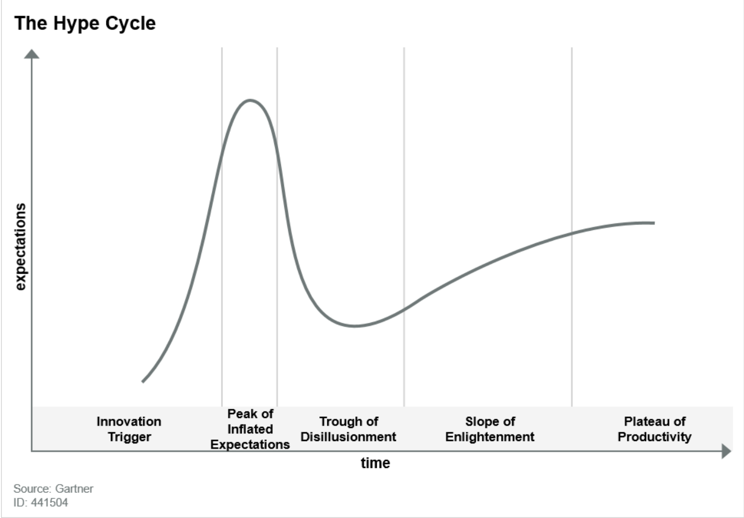
With their fast rise and fall times, WBG power switches generate serious EMI that not only threatens a product's electromagnetic compliance (EMC) but could also lead to power switch failures. While those types of problems might be somewhat expected, you may not be aware that the fast edge speeds of WBG devices also threaten the integrity of insulation materials. It turns out that the varnish used on transformer and motor windings becomes lossy at the fast edge rates produced by SiC and GaN devices, which can lead to heating that compromises winding insulation. Product failures due to partial discharge (PD), corona, inception and burning are possible.

There is a path to overcoming these problems and we can turn to the industry's experience with class D audio amplifiers for an enlightening history lesson. We'll review that experience before diving into the problems faced when designing WBG power switches into motor drives. This discussion is about the real problems and real solutions that are encountered in designing and building products—not the ideal world of simulations. But first, a few words about disparity between WBG marketing and reality.

WBG Marketing Hype Meets Design Reality

The untiring marketing campaigns told us "wide bandgap semiconductors will replace all silicon in all things by 2010…." Then it was 2012…2015… 2020, etc. While that's a fine strategy to pump and dump shares of semiconductor company stock and sell companies, the WBG replacement of silicon didn't actually happen. As it would turn out, the variable frequency drive (VFD) that hangs on the wall in the pumphouse really doesn't need to have a 15-ns commutation time. Nor is there a budget in that standard catalog product for the premium "WBG parts" that we are told have taken over the world.

And then the "experts" came along, having never really touched hardware, designed anything, debugged, taken the waveforms, done the work, built a system, or pushed a product through the safety agency and EMC directives. The experts of course took out the silly silicon and put in their WBG devices, perhaps wearing a cape to the meetings like batman or superman. "Go statements" included things like "it works great in simulation, thereby it works great" at power levels that senior folks knew wouldn't fly.



Source: Gartner
ID: 441504

The Gartner Hype Cycle chronicles the stages of product marketing experienced by many new technologies. Currently, WBG semiconductors such as SiC and GaN seem to fall somewhere on the curve between the trough of disillusionment and the plateau of productivity. (Source: Gartner).[1]

Learning From Class D Audio

But what went wrong? It's a secret, you can't tell anyone, but WBG devices in motor drives, particularly SiC MOSFETs, are in the same place class D audio was 25 years ago. The supported switching frequencies aren't high enough yet to build in the integrator economically or within a reasonable space, so the motor, the insulation system applied therein, the lineset, the gate driver, the dc-dc converter and the inverter output have to see the fast rise and fall times associated with the higher frequency switching.

Some of course have sidestepped this by slowing down the WBG devices to perform like the old Si devices. At that point, the price premium for the WBG devices is absolutely fruitless. One could get the same performance with a Si IGBT for much less cost.

What then happened with class D audio? You may recall, the early amplifiers relied on the voicecoil inductance to integrate the current waveform. The same voicecoil was wound with wire that had significant skin effect losses at the switching frequencies in play. Then the wire was often wound in layers, which took us into the Dowell curves where Rac/Rdc became exponentially worse. So by having the voicecoil integrate the current waveform, the ripple current simply caused heating.

Now if you are running perhaps classic audiofile stock, like a tangerine phase plug Altec Lansing transducer, with only one or two replacement diaphragms left on earth, the notion of having your voicecoils “cook” was disheartening, expensive and ultimately full of distortion as the wire/varnish/glue loosened up from the heat and started to rub in the gap.

After a little suffering, the class D audio designers discovered that it was smart to add the integrator to the output. They upped the switching frequency a bit to make the L and C small while also minimizing phase distortion and added lag. The LC then integrated the high-frequency ripple and delivered fundamental program material to the voicecoils (with careful consideration of Q). Problem solved. On behalf of the audiofiles: WHEW!

Why then would this matter to the WBG inverter? The secret is one the experts never knew. The high frequency energy in that WBG device’s fast switching excites problems that the slower Si speeds did not. Let’s consider a system: motor, drive, lineset, control, gate driver and dc-dc converter.

At the inverter output, the switching frequency may have gone up a bit. Perhaps the Si IGBT-based drive switched at 5 to 10 kHz. The WBG inverter may switch at 20 to 40 kHz in a practical design. The rise and fall times of the midpoint of the inverter in a Si IGBT design may have been in the 200-ns to 600-ns range while the rise and fall times of WBG power switches are in the 10- to 20-ns range. In terms of bandwidth, the best means I’ve found to quantify the spectral envelope of a given waveform is to have dominant poles at $1/\pi * t_r$ and then at $1/\pi * t_{on}$. This method is as antiquated as Ohm’s law and it still works just as well.

Why Is Edge Speed Important?

If we consider the lineset connecting the drive to the motor, the lineset has a characteristic impedance. Most linesets will be a twisted-pair type of cable, perhaps with a shield and an earthing conductor as well as U, V and W conductors of appropriate ampacity. The impedance of most any reasonable conductor insulation, from THHN to SOO cable, is usually on the order of 100 Ω. It’s easy enough to measure this with lumped parameters (inductance per unit length, capacitance per unit length) and then calculate $Z_0 = \sqrt{(L/C)}$.

But why would power electronics care about the characteristic impedance of this lineset? What if the lineset were relatively long? Relatively needs to be carefully considered.

Let’s say that $1/\pi * t_r$ of the output commutation was in the 30-MHz range. A quarter-wave stub of transmission line at this frequency range will be on the order of 2.5 meters in length. If the lineset is 2.5 meters in length or longer, there may then be a quarter wave effect or a standing wave. The fast pulse causes a standing wave in the lineset such that the whole lineset radiates common-mode noise at this wavelength.

The second problem is that of reflections. Neither end of this transmission line is terminated with the characteristic impedance. The impedances in play are much lower (this is why power electronics people often can’t “speak RF language”).

These impedance mismatches will then cause reflections at both the motor (read as voltage spikes on the edges) and then reflected back to the drive output (and possibly avalanche on those delicate WBG power switches!!). A proper design will have terminations at both the machine and the inverter output to offer a reasonable match and damping to the high-frequency reflections.

The Threat To Insulation

Then what happens at the motor? Old salt may remember that the large "inverter-grade motors" were actually larger and heavier than the older line-locked beasties. I always found that perplexing. I understood the added losses, the frame current, bearing race galling from circulating currents…..but high tech is supposed to be smaller and better, no?

WBG inverters are heading down the same path as silicon-based motor drives, only it will be tougher this time around. One may note that the permittivity tensor of common motor-winding insulators like varnish goes lossy well within the bandwidth of the WBG rise and fall times. Loss is heat. Heat makes varnish fail. Failure comes in the form of partial discharge (PD), corona, inception and burning. The insulation will fatigue around the points of maximum E-field, such as the sharp bends where the conductor channel loops from one slot to the next.

There's More! Transformer And Driver IC Stressors

With those considerations for the power path, most stop there. It's a big bite, and it's a lot to deal with at design. The motor, the lineset, and the drive didn't get cheaper by going to WBG. But that's not all.

The high-side driver connects to the high-side gate-source terminals. This means that the high-side driver's galvanic isolation boundaries have to deal with the very same fast dv/dt and the very same insulation stress seen by the motor windings. One might note that the dc-dc transformer is often comprised of similar insulation systems and allowable temp ranges as the motor. Varnish, tape, etc. are present in the transformer too.

So this transformer will see the same stressors in common mode from primary to secondary. The silicon on insulator (SOI) substrate in the isolated gate driver IC will see these stressors as well. For a practical consideration, if we consider perhaps an "older" IGBT type isolated dc-dc converter transformer, having perhaps 35 pF from primary to secondary, with an inverter commutating 700 V in 15 ns, we then have I =35 pF * 700 V/15 ns or 1.63 A of peak common-mode current flowing to ground on each and every switching edge. This *will be* an EMI problem.

Back To The Lab For Hi-Pot

If we take these concepts back into the lab, and block out the insipid experts spouting the right answers having never asked the right questions, we will discover some things quickly. A hi-pot test is most always performed with a sinusoid at 50 or 60 Hz. That dv/dt can *never* approach that of the WBG edge speeds. A 60-second hi-pot test that yielded transformers that never had PD, corona or arcing problems may fall on its face with WBG edge speeds and the aforementioned old school insulation systems.

Further, the partial discharge test does not capture the fast edge speeds. It does look for the RF signature of corona. (This was often detected on the production line with an AM radio receiver. If the receiver was tuned to a strong station and went into desense during a hi-pot or PD test, the next step was to turn off the lights and look for the purple glow, which meant that corona was happening!) But at these fast edge speeds, corona signatures are *in band*! How does one test for that? That dramatically changes the block diagram of the PD tester!

Field Solvers Are Our Friend!

While most austerity metrics and enforcing accountants will balk at the purchase, installation and use of a field solver, this software will become paramount in understanding the insulation system interactions and stackups with faster edge speeds and in predicting the EMI signatures of near-field magnetic loops and electrostatic surfaces.[2]

WBG takes power electronics into the RF domain, plain and simple. We have to adopt the RF tools if we are to build successful designs with WBG. While the old hyper-abrupt junction Si FREDS would ring at 6 MHz or so, the WBG parts are ringing up into VHF and UHF ranges in some cases.

Back To The Integrator

Shhhh! It's a deep secret, but the WBG inverters don't have much choice but to take the class D audio direction of yesteryear. If the motor is to stay cost effective, with a reasonable insulation system, then the high-frequency ripple must be integrated so that only the fundamental is presented to the motor. This will also mitigate standing waves, reflections, and high-frequency radiation from the lineset. However, the integrator needs a little more consideration than the 4-Ω or 8-Ω transducers.

A strong PMSM may have a stall current of 500 A and a run current of a few amperes. If the machine was designed for a stall current that high, we wouldn't want the impedance of the series inductor in the integrator to restrict that stall torque. Present switching frequencies won't allow for this as the integrator components are too large, too heavy and too costly. But if the switching frequency of a WBG inverter were to approach the switching frequencies in class D audio amplifiers, that would be the essential win/win.

Perhaps then the integrator could become a stripline to deliver fundamental waveforms to the machine while not detracting from stall torque performance. Further work may compensate out the added impedance of the LC integrator in the Park transform, like adding peak current mode control, only in glorious software. The benefit of this would be very useful in high-torque applications that do work into and out of stall conditions (like a wheel loader moving gravel).

Reference

1. "Understanding Gartner's Hype Cycles"
2. "Field Solvers: A Different Perspective On EMI In Power Electronics," How2Power Today, October 2019.

About the Author

Kevin Parmenter is an IEEE Senior Member and has over 20 years of experience in the electronics and semiconductor industry. Kevin is currently director of Field Applications Engineering North America for Taiwan Semiconductor. Previously he was vice president of applications engineering in the U.S.A. for Excelsys, an Advanced Energy company; director of Advanced Technical Marketing for Digital Power Products at Exar; and led global product applications engineering and new product definition for Freescale Semiconductors AMPD - Analog, Mixed Signal and Power Division.

Prior to that, Kevin worked for Fairchild Semiconductor in the Americas as senior director of field applications engineering and held various technical and management positions with increasing responsibility at ON Semiconductor and in the Motorola Semiconductor Products Sector. Kevin also led an applications engineering team for the start-up Primarion.

Kevin serves on the board of directors of the PSMA (Power Sources Manufacturers Association) and was the general chair of APEC 2009 (the IEEE Applied Power Electronics Conference.) Kevin has also had design engineering experience in the medical electronics and military electronics fields. He holds a BSEE and BS in Business Administration, is a member of the IEEE, and holds an Amateur Extra class FCC license (call sign KG5Q) as well as an FCC Commercial Radiotelephone License.

For further reading on power supply-related safety and compliance issues, see How2Power's special section on Power Supply Safety and Compliance.