HOW2POWER TODAY
Your Power Design Newsletter

Focus on Magnetics
Sponsored by Payton Planar

ISSUE: May 2023

EV Traction Inverters And EMC: Keeping Car Radios Working

by Paul L. Schimel, Microchip Technology, Chicago, Ill.

There were a couple of equipment labels that drew me into electronics at an early age. The first was, "no user-serviceable parts inside." I took that as a challenge, and made good with it somewhere in grammar school. The second came from FCC rule 47 CFR part 15: 1. This device may not cause harmful interference and 2. This device must accept any interference received including interference that may cause undesired operation. These were bold statements and I've explored and challenged both points in depth over the last four decades.

These efforts leave me puzzled by modern headlines along the lines of "EVs have no AM radio option due to interference from the inverter" and "state, local and/or national safety agencies furious that EVs will not be able to receive emergency broadcasts via AM radio." These headlines surely aren't new concepts in the world of electromagnetic compliance and electromagnetic compatibility (EMC is an abbreviation used for both terms). However, from this engineer's perspective; I believe our duty is to improve traction inverter emissions in EVs.

To me, eliminating the AM radio is no more of a solution to the EMC problem than the ostrich sticking its head in the sand. But to dig into the problem, we have to understand a couple of things we don't normally look at and tie them together as a system.

In this article we'll look at the problem from both radio frequency (RF) and power design perspectives and I'll propose possible paths to solving the electromagnetic incompatibility between the radio and the traction inverter. These suggestions for achieving EMC mostly concern altering the operation of the inverter to reduce its emissions. However, I also share some thoughts on possible changes to the AM receiver and the motor design that could help.

"What Is This Radio Stuff?" Exclaimed The Expert Power Designer

An AM receiver is a simple apparatus. AM of course stands for amplitude modulation. The AM band in the U.S. spans 540 kHz to 1700 kHz in 10-kHz steps. But to call this the AM band is improper. Amplitude modulation can be used at most any frequency we choose. Air traffic is controlled around 120 MHz with AM communication, yet we don't call that the AM band.

The term AM broadcast band lies in the MF or medium frequency band (also referred to as medium wave or MW) as per ITU (International Telecommunication Union) nomenclature. A broadcast signal in this band is allowed ±5 kHz from center frequency. If we think about this in terms of linear modulation, the fidelity of an AM signal isn't great. Talk radio, news radio, religious broadcasts, and sports talk broadcasts must dominate the band. High-fidelity music will be bandlimited.

But why is this band still alive? If we can watch the latest streaming videos, while checking social media, multitasking a video conference and fielding endless calls from robo dialers, the AM band couldn't have been the apogee of telecommunications technologies. We are clearly doing so much better now that we turn our brains completely off and mindlessly stare at our smart phones.

So why do we need this silly antiquated beast of a broadcast band? The answer is fairly simple—propagation. The wavelength of an MF broadcast station in the U.S. is from 556 meters (at 540 kHz) to 176 meters (at 1700 kHz). But why does this matter?

The best answer to this lies in the purpose. A single AM transmitter can cover a lot of ground. Most AM broadcast transmitters run higher power during the day. They do this because propagation is usually limited to groundwave. The lowest layer in the ionosphere (called the D layer) absorbs MF energy during the day and limits long propagation. Higher power in the daytime allows for uniform groundwave propagation over a few hundred miles with good signal reception in a modest receiver and antenna system.

But at night the D-layer cools off allowing signals to easily propagate through the upper layers of the ionosphere (known as the F-layers). At this time, signals travel much further, often in the range of thousands to tens of thousands of miles. Transmitter power output (TPO) can be reduced at this time to cover much more area than daytime operations and the "fun" begins for radio enthusiasts.

© 2023 How2Power. All rights reserved.

By comparison, a higher-frequency band like HF is much more susceptible to sunspots and other propagation conditions. Given the three choices of HF, MF and LF bands, MF was just right for broadcasting information to a large area with the simplest receivers and antenna structures.

There is a measure of this known as the maximum useable frequency (MUF). It varies between 5 MHz and 30 MHz. Higher sunspot activity can drive it up, allowing longer communication ranges at higher frequencies. For example, now that we are at the peak of a solar cycle, higher frequency HF communication is more likely, much to the chagrin of the ham radio community. MF band isn't impacted by MUF at all, it's always well below, very consistent, minimally impacted by solar conditions.

Higher frequencies like VHF, UHF and microwave tend to be limited to line of sight or LOS. If you can't see the transmitter, you can't receive the signal. This is why cell towers decorate our buildings and landscapes at increasing densities.

In principle, if there is a large-scale emergency, MF radio broadcasts can get information out with unrivaled coverage and efficiency. The backbones are in place ranging from fiber optic studio and transmitter links for backup of LOS microwave links, to backup transmitters, antennas, and generators.

The broadcast equipment is simple and requires no extensive towers or transmitters like VHF and UHF broadcasting. It can operate in the absence of cellular infrastructure. The receivers are equally simple, whether superheterodyne or direct digital conversion (Fig. 1). In the old days a simple reflex receiver (Fig. 2) could be fashioned with a couple of tubes, a couple of batteries and a simple magnetic loop antenna. Fundamentally, the MF broadcast band remains unrivaled for communication.

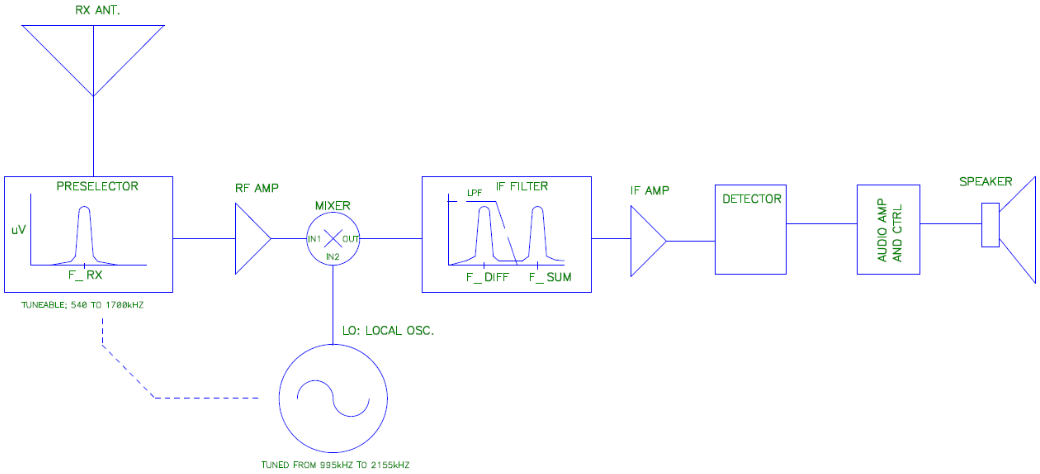

Fig. 1. Block diagram of a superheterodyne MW AM receiver.

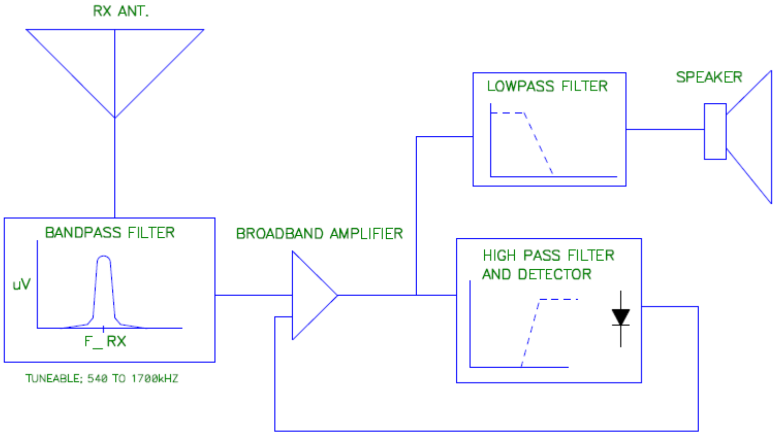

Fig. 2. An artform in application—a reflex receiver block diagram.

© 2023 How2Power. All rights reserved.

"What Is This Power Stuff?" Exclaimed The Expert RF Designer

And then we built an electric car. The traction motor(s) in the electric car were designed for highest power density and efficiency. These polyphase machines require inverters (Fig. 3) to deliver energy from the dc battery to the motor stators to make both torque (current) and speed (voltage) in the rotor(s). Whether the rotor is moving synchronously to the rotating fields in the stator (like in a PMSM) or in slip (like an induction motor) is immaterial to this discussion.

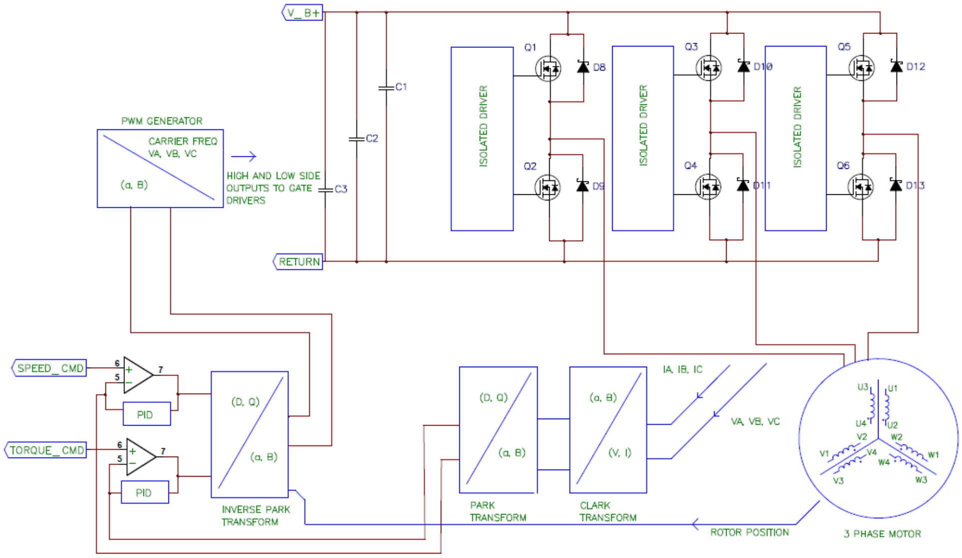

Fig. 3. Simplified block diagram of an automotive inverter.

Inverter performance is balanced against inverter cost. For a simple example, let's say that the motor in a sedan-type EV has to make 40 kW of tractive effort to maintain 60 MPH cruising speed on the highway. Said motor is 80% efficient from electrical input to mechanical output. The inverter then delivers 50 kW to the motor. The efficiency of the inverter is nonideal. Perhaps the efficiency of an inverter comprised of field stop (FS) trench IGBTs and soft-reverse-recovery FREDs (fast recovery epitaxial diodes) is 94%. The 50-kW inverter output then comes with 3192 W of loss requiring 53.192 kW from the battery.

Let's say the battery capacity is 200 kW*H for a modest EV and the cruising speed is 60 MPH. With this, the FS trench-based IGBT inverter will get about 225.6 miles on a complete charge. If we switch to a "nearly ideal" power switch technology in the inverter, the vehicle can go as far as 240 miles on the same complete charge. This comes with much faster switching speeds as the related power switch capacitances and switching losses dropped dramatically (to zero in this exaggeration).

In practicality, the commutation speeds in a wide bandgap (WBG) inverter are in the handful of nanoseconds range whereas the FS trench devices were in the hundreds of nanoseconds. The difference between the more-expensive ideal power switches and the standard FS trench IGBTs inverter is about 6% added distance for the premium inverter.

If we go further, making the motor ideal, the vehicle will get as much as 300 miles on a similar complete charge. This brings the economics of the tradeoff into play. What is the value of switching to lower-loss power switches in the inverter for a few extra miles? If we bundled that at a dealership with a transverse flux, multi-layer motor with nearly ideal flux coupling and intensive 3d flux optimization whose efficiencies were near the ideal, how much extra would a consumer pay for this solution?

This is, of course, grossly oversimplified. The simple work includes no hills, start, stop, accel, decel, hysteresis loss in the tires, drivetrain loss, or regen efforts. Further there is no consideration for the cooling system reductions or weight reductions from the near-ideal inverter and machine example. It's a rough sanity check. If someone told me a new inverter quadruples the range of an EV, I would make these same calculations on the back of an envelope and counter, no, that doesn't sound right.

But what is the impact of this on the system? If the improved voltage-source inverter delivers these commutation speeds to the motor, the insulation system in the motor will see an increased dielectric loss. Remember those old lectures on permittivity tensor where we learned that not all dielectric materials are

© 2023 How2Power. All rights reserved.

created equal at ac? The tensor contained a frequency-dependent loss component. A 90-degree phase shift from capacitance is loss, resistance, heat.

If we look at samples of typical resin insulation systems found in motor windings, we see that the permittivity tensors go lossy in the 2- to 10-MHz range. The leading-edge SiC power switches are commutating in the 10- to 20-ns range. The dominant pole in this spectrum is then 30 MHz or so ($1/\pi * t_r$). The fast edges then cause excessive loss in the dielectric insulation system in the motor, and possible hotspotting, corona, arc inception and failure.

But that's not all. The electromagnetic noise from this fast commutation is 30-MHz wide—well within the received, IF, and LO portions of the MW AM receiver. It will create interference to the signal, images, birdies and false scan lockups in the receiver. And for this we rip out the AM receiver?

I must admit, I've never had the luxury of taking out parts of a design or system that I didn't like or that were too susceptible to noise. Further, this faster switching will excite standing-wave and quarter-wave effects in any motor lineset over 2.5-meters long with resultant voltage spikes at either end of the lineset adding additional stress to the inverter or motor.

As a good motor engineer attests, if it ain't fundamental, then it's heat. It is a brash and correct statement. If the rotor is rotating at the fundamental rotation frequency of the stator, high-frequency components from the PWM carrier contribute absolutely nothing to the machine output. In fact, it's worse. The low reluctance flux path will see added eddy current losses from the high-frequency components. The dielectric will see increased loss, especially at the sharp bends in the conductors where the E-field is maximal.

The motor conductors will see increased temperature rise from the skin and proximity effects in these high-frequency components raising Rac/Rdc. The eddy currents in the back iron or stator can cause secondary currents to flow in the back iron, the motor frame, and the bearing assembly. These secondary currents often cause pitting and galling in the bearing races and lead to premature failure.

We learned this 30 years ago when open-frame VFDs were taking off in the running of induction motors in industrial equipment. I recall "inverter grade" motors being heavier, running hotter, and being less reliable than standard motors at the onset of that marketing effort. This was touted as an efficiency improvement—it wasn't.

EMC: Making It All Work Together

The electromagnetic noise from the inverter couples into the rest of the electronics either by nearfield radiation in the electrostatic or magnetic fields. While the windshield wiper motor may be ok with this, the 0.1-µV MDS (minimum discernible signal) MF radio receiver will likely be in blanking. The IF strip and the front end will be overloaded and shoved well into compression. Even with the finest direct conversion or highest up-conversion mixing, receiving a 0.5-µV AM broadcast radio signal in 5 V of in-band noise is impossible.

Can this be fixed? Yes, we do this by controlling emissions. But how? I stipulate that a 50-kW traction inverter load will make perhaps 24 dB more nearfield magnetic and electrostatic noise than a 200-W audio output from a DIN chassis head unit to a speaker on a radiated and/or conducted EMC sweep. But mitigating this is not impossible.

I've designed 1.1-MA, -48-V central office power supplies that delivered noise figures so low that they couldn't be heard in the C message band on transducers with near-ideal sensitivities. These were all uncorrelated switching supplies running in massive parallel, with frequency programming no more precise than the RC on the relaxation oscillator of the PWM controllers.

This was a tremendous EMC effort in that most adjacent switching supplies had frequency differences that were in the C message band. Keeping that energy from mixing and radiating was a tremendous challenge, well beyond an EN-61000-3-x, MIL-461 or 47-CFR part 15B limit line.

When the automotive radio head units went to class D audio to get more power out of a single DIN space claim, the class D amplifier was switching at about 500 kHz, inside of a superheterodyne receiver with a 455-kHz IF strip and 60 dB of gain ¼" away from the amplifier. These were difficult problems that were tackled by brilliant minds like Andy Adrian and Mark Purol. I've had the pleasure of working with both Andy and Mark and I can't say enough good things about them.

© 2023 How2Power. All rights reserved.

The switching frequency of the class D audio amplifier was made selective based on inputs from the radio on the tuned frequency. The amplifier switching frequency then landed at points of minimal interference to the received signal, the local oscillators and the IF strip.

They then added multiphase technologies to sum multiple phases and offer a higher ripple frequency to the transducer and wiring. This noise spectrum was then further from the received band and more attenuated in the preselector stage in the front end of the receiver.

Finally, they optimized the LC integrators in the audio amp for both minimal phase aberration at 20-kHz audio band and maximal RF attenuation on the speaker cabling. This solution has been in use for a long time, and both of these brilliant, visionary folks are well worthy of a solid handshake and mad respect.

How Do We Fix This?

Inverter Improvements

This problem is not as simple as getting to “pass” in the anechoic EMC test chamber on the EMC receiver with conducted or radiated fixturing and limit lines.

- We can’t slow down switching because this will increase switching loss and impact efficiency and range, the very impetus for using SiC switches in the traction inverter.
- The budget for added common- and/or normal-mode filtering combined with the space claim and weight of these solutions makes them prohibitive at present switching frequencies.
- The fast voltage ripple components from the voltage source inverter (VSI) will cause problems in the motor and the lineset. They will also couple into nearby circuitry by both conduction and radiation. There are better insulation systems that are cost effective that will handle the faster ripple voltage.
- Nearfield analysis is a great tool for finding and mitigating nearfield magnetic and electrostatic noise sources. It is far better than an electrostatic or magnetic probe looking over a prototype, but even finding and mitigating hotspots on best practice won’t bring the emissions down far enough.
- It’s not possible (or likely to become possible in the near future) to build the inverter into the traction motor and eliminate some or most of the coupling or radiating mechanisms.
- Taking out the overloaded receiver is a silly overreach that may leave the drivers or passengers in a void of critical information, for example, a tornado warning in a spot of bad to no cellular coverage.

With these constraints, the fundamental approach must be changed. If we could reduce voltage and current ripple from the inverter, the radiated and conducted noise would drop dramatically. We know that a voltage source inverter isn’t the only means of getting energy to the motor. Why not consider something different?

Solution 1: Switch Much Faster And Use LC Integrators

This solution would deliver fundamental waveforms to the motor, but is limited by the present state of the art. To switch much *faster,* we’d have to fall back to smaller power switches in smaller stages running in parallel. We could certainly interleave these stages like the class D audio solutions to raise the frequency of the small ripple currents on the output lines to the motor.

Then, to keep the LC integrator (see Fig. 4) space claim and cost to a minimum, we would likely have to be switching in the 500-kHz carrier range. This is a distant possibility given the present state of the art and tendency to switch slower with larger modules.

But if it were to be implemented, this solution would take the form of discrete switches and look more like an RF PA (power amp) where the gate-drive signals meet each power switch at the same time to guarantee turn-on, turn-off current sharing conditions. Microchip offers a full lineup of discrete SiC MOSFETs and Schottky diodes for this application. We further offer the four-pin TO-247 to accommodate our largest die. This provides a kelvin source connection for the gate driver to eliminate common source inductance and separate the power and gate-drive current paths.

© 2023 How2Power. All rights reserved.

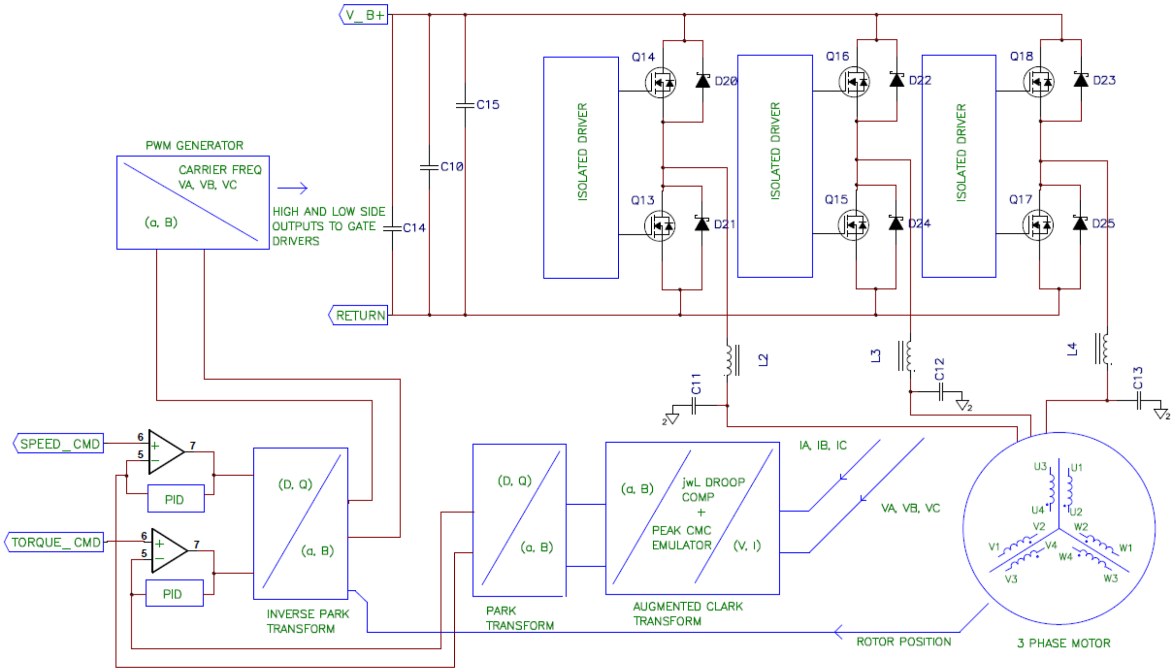

Fig. 4. Block diagram of LC integrators in VSI inverter output, like class D audio.

Solution 2: Use A Current Source Inverter And Integrate The Voltage Ripple

This integration can be done with a small output capacitor and would deliver fundamental waveforms to the motor. This solution (see Fig. 5) will require an inductor in series with the inverter poles. To keep the inductor space claim and cost to a minimum will require switching faster. Again, this may lead to an interleaved approach, falling back to paralleling of smaller output stages instead of using one large module.

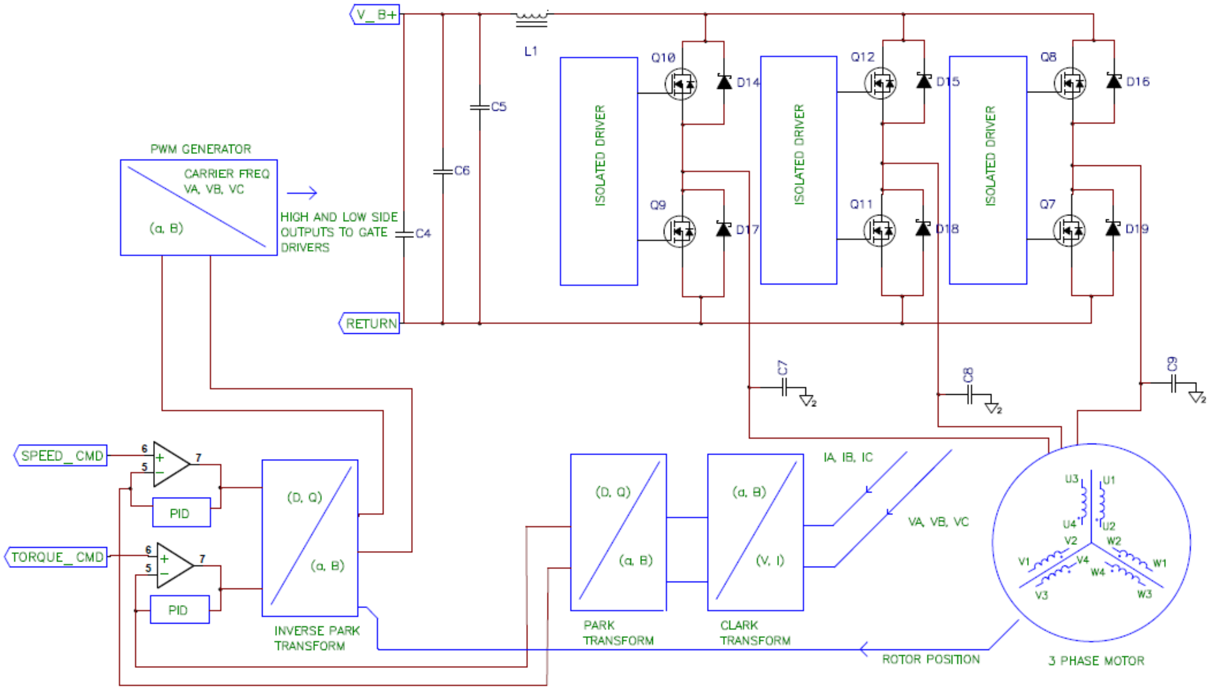

Fig. 5. Block diagram of a current source inverter.

© 2023 How2Power. All rights reserved.

Solution 3: Use A Pilot Switch To Soft Switch The Main Inverter Switches

This solution was done in the late 90s with the Unitrode UC3855. It was an extension of an ARCPI or auxiliary resonant commutated pole inverter. The idea was that a pilot switch is used on the edge(s) of the main switch to assist the commutation of the switch and provide unconditional zero voltage or zero current switching.

Many will extend the topology to include a small pilot inverter pole that runs in parallel to the larger main inverter pole. An impedance is inserted between the main pole and the aux inverter pole with the intention of storing and pumping energy to the main switch to facilitate zero voltage switching.

I've also heard of topologies that actively look for resonant transitions and switch at voltage minima, but the line and load profile of an EV will have this varying wildly. Should this solution be chosen, Microchip's discrete SiC MOSFETs and Schottky diodes, for example, can be used in conjunction with the larger modules such as the SP6LI to provide the ARCPI functionality.

Solution 4: Incorporate The Inverter Into A System With Improved Control

We could implement fast current sensing akin to peak-current-mode control and its integral feedforward in the transforms that get into and out of the DQ0 reference frame. We could also compensate for the LC integrator droop in these same transforms.

It is then conceivable that the controller could have similar stability advantages and improved performance into, out of and at stall torque conditions just like peak-current-mode control survives a dead short by terminating the PWM cycle as fast as the propagation time of the comparator and driver will allow. Microchip's FPGA and dsPIC microcontrollers can accommodate this with support provided by the company's software experts.

Solution 5: Best Design Practices Applied To All Solutions

My belief is that an equally large part of the solution to this problem lies in best practice.

- Build the dc bus cap into the module and mitigate the dc bus ringing and overshoot.
- Use field solvers to optimize the modules and circuit layout. Improve gate drive distribution among parallel devices and output structures.
- Understand the sources of the noise, the coupling and the applicable mitigation techniques.

Your power semiconductor supplier can provide assistance with addressing these design challenges. For example, our Microchip team has the experience, both in the hands-on and theoretical, along with the SiC power modules, drivers and design experience to help you through this design process.

Receiver Improvements

Going further, we can change the receiver architecture a bit. If the class D audio amplifiers' switching frequencies were agile and placed at points of minimum interference to the receiver chain, we should then be able to modify the receiver chain to stay away from the inverter. For example, if we are tuned to AM 1000 and the inverter or some harmonic therefrom were switching at or near an image frequency, why not raise the local oscillator frequencies and put the IF band somewhere higher, where inverter switching frequencies can't interfere?

Clearly this is moot if the interference from the inverter is at the tuned frequency of reception, but if it is not, we can shift the LOs and IF stage appropriately and dodge the images, birdies and noise. There are products on the market such as Microchip's processors and frequency products, which can help with this work.

Motor Improvements

At the system level, there are many companies that are taking power-to-weight ratio to exciting new levels. The good engineers at H3X are doing a superb job with this. To bring up the power-to-weight ratio requires challenging conventional stator structures and optimizing flux in three dimensions. These geometries often give rise to near-ideal flux utilization, high saliency and very high flux in the gap of the machine.

These designs often give rise to simpler winding techniques like transverse flux. These windings will experience much lower E-field gradients than conventional winding techniques, reducing the E-fields in the insulation

© 2023 How2Power. All rights reserved.

system as well as omitting the secondary eddy currents and related current/flux paths through the frame and/or bearings.

Conclusions

While this article combines a discussion on EMC, traction inverter systems and broadcast MF radio band, I don't believe the central motivation should be to make automotive traction systems compliant with MF radio receivers. RF and power are no longer separate skillsets. With commutation speed RF envelopes in the 10- to 30-MHz range, no power engineer can claim RF ignorance nor can the RF engineer treat power as nonexistent.

With the fast commutation speeds and switching frequencies that WBG devices enable, RF and power engineering resources must be one and the same. The band-aid EMC measures of yesteryear have to be traded up for root cause analysis, field solvers and precise system-based mitigation. The problem involves fundamentally reducing RF emissions from an electric vehicle traction inverter system and maintaining highest vehicle performance.

The skeptics will argue that the noise from an inverter is simply too much for an MF receiver to handle. I disagree entirely. I've designed very large systems that worked in environments with extremely sensitive broadband RF receivers and audio chains, and I found ways to bring emissions down to the lowest levels while maintaining cost and performance targets.

Sticking my head in the sand was never an option. I never got to remove or ignore parts of a design that were too difficult. The solution to this may involve emissions dipping well below standard limit lines like EN61000-3-x and 47 CFR part 15B. They will also involve frequency-agile receiver design. Yes, this is a tough problem to solve, but that's what we do, isn't it?

About The Author

Paul Schimel currently serves as the technical staff engineer for Microchip Technology's discrete products group. He has over 24 years of theoretical and hands-on experience in power electronics, spanning military, aerospace, automotive and industrial markets. Paul's work regularly includes module design, dc-dc converter design, device-level analysis, root cause analysis, failure analysis, EMI mitigation, PCB layout, control loop compensation, inverter design, transformer design, rotating machine design, bench-level measurement and validation techniques and system-level analysis/comprehension.

He has designed dc-dc converters from milliwatts to megavolt-amps, inverters to 5,000 HP. He is a licensed professional engineer (PE) and holds two FCC licenses (First Class Radiotelephone and extra class amateur). In addition, Paul holds three patents on power electronics matters. He can be reached at Paul.schimel@microchip.com.

For more on EMI and EMC issues in power electronics, see How2Power's Power Supply EMI Anthology. For more on inverter design, see the How2Power Design Guide, locate the Power Supply Function category and select "DC-AC inverters".

© 2023 How2Power. All rights reserved.