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Field Solvers: A Different Perspective On EMI In Power Electronics

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On a business trip to Manilla, I had a coworker lose some critical documents including his passport, ID, credit cards, wallet and some cash. The circumstances surrounding the event might not have been marketable by the bureau of tourism. My associate was a nervous wreck over the events.

I, on the other hand, was somewhat savvy and prepared. When I travel on a long haul, there are a few things that I carry: rations, tools, a flashlight, a pocket knife (checked of course in baggage), the U.S. embassy number, a can opener, local contacts, my PC, my phone, a DMM. OK, probably too much. Maybe I'm a hopeless geek, but I've never been burdened by carrying all this stuff and I've *never* been stuck or stranded anywhere I've roamed.

So, I found the U.S. embassy, made contact and started to take action with my coworker. We made it to the embassy, got his temporary ID documents and were cleared to travel home. But there was a fishing fleet in the harbor, and I had to see it. I convinced him that he'd be fine going back to the hotel on his own.

Begin The Adventure

I like to push the boundaries. Having been a field applications engineer (FAE) for a long time—and loving every minute of it—I've been tossed into some wild and wonderful situations involving power electronics, current and voltage levels, geography and applications. Again, I've welcomed and embraced every challenge.

In line with that Mark Twain call to adventure, I decided to go fishing. I walked out to the boats on the pier. One of the fishermen said hello and I started a discussion with him.

"Do you have a ship to shore radio? An HF? A VHF?" I asked.

"What's that? Got FM radio!" he replied.

"Hmmm, OK, how many engines on board?"

"Two," he answered. "This one here runs, and this one here is for spare parts."

Not exactly N+1 redundancy, but not without hope. I can swap a starter motor or fuel pump if I have to, I can even reroute the water pump intake if needed to fix a leak. Rusty tools were forthcoming, so I was comfortable with those answers.

"Do you have a flare gun?" I asked.

"Guns, sure, got a couple on board," he smiled. (Almost the right answer.)

"Do you have life jackets?" I pressed.

"Jackets? Why, are you cold? You won't need a jacket!" he said.

Love the local charm—Rock On Sir!! And then he got a little mad.

"This boat has been in my family for 50 years, and it's only sunk five or six times."

Now for most people, that would be enough to run the other way, but I handed him my money and climbed aboard his boat. From my lexicon, the math seemed solid: nothin' ventured, nothin' gained—so venture a little and temper it with common sense. I had a wonderful time fishing with him. We were out in pretty rough seas, but it was great. We caught species that I've never seen before. Great day, all because I chose a different perspective. The man had been fishing all his life.

The Old Science Of EMI

The time has come to do the same with our perspective on EMI. Most articles I've read on the subject of EMI are very well done. There is a large emphasis on filter design, finding hotspots and mitigating them. All are required and essential skills to pass and comply with a given EMI standard, whether MIL-461E, CFR 47 part 15B or IEC-61000 directives. I've given papers on EMI too. I'm a big advocate of the Bruce Carsten nearfield magnetic (sniffer) probe. We can't get to compliance without these things. I give the utmost credit and respect to my fellow EMI authors and practitioners.

But what if we viewed the subject from a different perspective? What if we roamed out a little further? Pushed the boundaries of our math a bit?

The Path Forward: The Notion Of Field Solvers

In the 90s, my buddies that designed RF circuitry were big into stacks of equipment. They would measure impedances, S parameters, gains for every circuit, and every pc board interaction, for what seemed like every node. Design was staccato lumped two ports, cascaded. And the designs worked well. This is why I paid attention to RF designers.

For me RF was a hobby (K5NJP, PG00017030), but I had the highest regard for those that went beyond. If I could design and implement a gamma match on a vertical antenna such that return loss was 15 dB or so, and then work a VK station (Australian call sign prefix) from my location near Chicago with 50-W transmitter power, it was a harbinger. My buddies were designing RFPAs with optimal gain and noise match. Wow!

But then something happened. As computers and modeling improved, tools began to run Maxwell's equations for complete circuits and board layouts. These tools were called field solvers. The emergence of these tools converged with good component-level models and those stacks of bench equipment. The need to step through a design part by part, piece by piece migrated from stacks of gear into the computing space, models and field solvers. Running Maxwell's equations accounted for the parasitics, dielectrics, trace routing, plane layers, trace widths, thicknesses, etc. Once the distance steps for the integrals became fine enough, the results were *superb*.

RF And Power Supply Teams: "They" Don't Talk To "Us"

It's no secret that communication between RF design teams and power supply design teams has been fairly minimal. But times are changing and you can't build an envelope tracking supply without understanding the envelopes and the RFPA being throttled. The same can be said for a class E, switch-mode RFPA. RF designers don't always know about "power stuff" like loop bandwidth, peak current mode control and V/I compliance. Meanwhile power designers don't always embrace RF stuff like reflective filters and the impact of a third harmonic that is only 10 dB down (hang on! voltage is going to pop up!).

Fundamentally, most RF designers are concerned with a given bandwidth and sinusoidal signals. There's a lot of emphasis on spectral purity, noise figure, etc. and tons of regulations on the matter (FCC CFR47 part 95, narrowband initiatives, etc). The time varying function applied is generally understood to be sinusoidal, perhaps with linear modulation.

On the other hand, the power world often deals with fast edges. Certainly not sinusoidal, trapezoidal for most discussions. But I can express most any switch-mode power supply (SMPS) waveform in terms of sinusoids, no mystery there. Simple Fourier analysis. Our metrics deal with a limit line and radiated/conducted noise limits (and then of course, susceptibility matters).

So then, the difference between "them" and "us" is a harmonic distribution and some terminations. What I'm saying is that the very same field solvers that run Maxwell's equations on RF circuitry can and should operate on SMPS circuitry and waveforms.

If we can run big data updates every 5 nsec on the server, parse terabits of sales data and schedule an online training about bullying in 4K resolution, we surely have the time, MIPs, storage and capability to run a field solver on SMPS components, boards, actives, passives and entire assemblies in the power supply design domain.

This is a powerful statement and it's not to be underestimated. Yes, we still have to identify high dv/dt nodes, we still have to understand high di/dt loops, stray flux, coupling mechanisms, circuits, etc. However, for those cases when things become more complex than a simple one- or two-dimensional circuit-level interpretation, we will soon have field solvers. Tools to step from circuital understanding to that of lines and fields.

Can you imagine actually seeing the fields around the gapped center post EE core transformer, with the large gap and the humbucker, over frequency and three-dimensional space? Seeing the interaction in the windings and accounting for cross regulation directly? This should be the new plateau. The present tool is perhaps a local E field or B field probe and some means to show position over board and noise spectra. The tool of the future will get us to first pass success on EMI matters.

What Is This Field Solver?

But what does this field solver do? A brief review is in order. I'll apologize as my perspective is not that of a funded theoretician. My pursuit (and the funding derived therefrom) is to keep the electrons flowing efficiently so that the theoretician can wave his or her hands, offer conjecture and draw on the white board with the lights on. I do acknowledge the need for the theoretician, we couldn't grapple new concepts without them. With this as a disclaimer and a coarse agreement to coexist, let's have a go at it.

Divergence And Gauss' Law For Charges

If I had some like charges in a confined space they would repel. The vector field associated with this repulsion is divergent. Charges moving away from charges, without prejudice. If we apply this to an electric field or specifically the flux therefrom, the divergence of the electric flux from a volume is equal to the initial charge contained.

Equation 1. Gauss' Law for charges

$$\nabla \cdot D = \rho_{\mathrm{V}}$$

That's not terribly difficult to envision. To me, it always looks like a sea urchin or a spiny flower, the notion of repulsion happening in all directions.

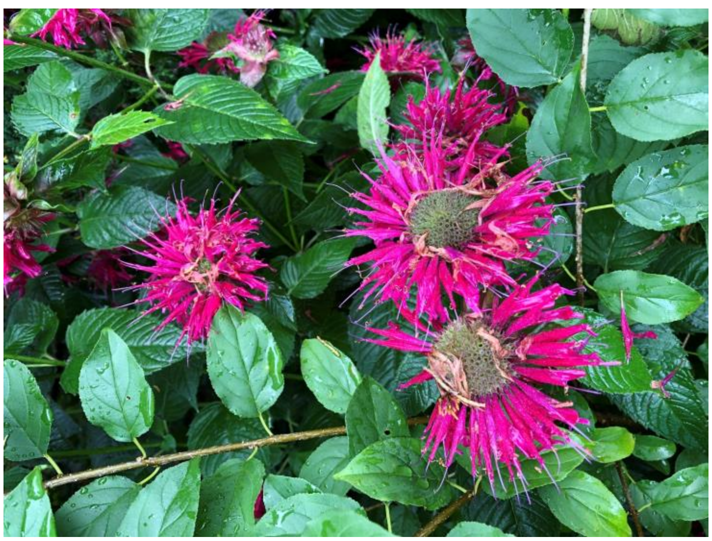


Fig. 1. The Gauss' Law concept of electric flux diverging from a volume with flux lines being repulsed in all directions has its analogies in nature such as the spiny flower, whose seed pods project in all directions.

The notion of divergence is simple when you look at it. As it relates to Gauss' law, the volume of the charge, call it ρ_v, is equal to the electric flux measured over the area of the volume. Back to the flower visual—if the spikes were the result of something inside repelling, this makes sense. Don't dare apply units to the flower, but the visual might be of assistance. If we started with a volume of things that repel, and the things repelled, we could then calculate the volume by looking at the surface around the volume and not the volume itself.

Gauss' Law For Magnetism

This one was tricky. I recall the theoretician writing it down as though we should just accept it and copy, and at the time we did. But it's a strange notion. That the divergence of "magnetic charge" is nonexistent; zero.

Equation 2. Gauss' Law for Magnetism

$$\nabla \cdot B = 0$$

If you remember playing with magnets as a kid, there were always two strong ends, two poles. Further, if two magnets were in play, one pole would attract one of the other ends, and repel its opposite. In that space, there was always a north and a south pole. When multiple units were played, each always had a north and south pole with which we could affect attraction and repulsion.

To boil that into divergence, if every north "charge" has a nearby mating south "charge", then the net divergence of those charges is zero. Envision a big bag of randomly arranged magnets (a biodegradable bag of course, with permittivity of unity). What is the resultant magnetic field well outside of the bag? Gauss' law for magnetism tells us that it is zero.

Curl And Faraday's Law

But then, what of passing current through a conductor? We've all done the experiment with a compass in the nearfield. The compass needle always aligns perpendicular to the wire direction. This gives the notion of the second upside down triangle operator, that of curl. If divergence vectors out like the seed pods of a prairie flower, then curl tends to surround at right angles. The magnetic field may have zero divergence, but the compass needle tells us that it surely has curl, as does the Lorentz force motor where the curl produces torque directly. An online video explains Lorentz force and offers a good example (see the reference).

If Maxwell was the accountant who put it all together, Faraday was the experimentalist who made the observations. The experiment is unforgettable. A few turns of wire were excited with a positive voltage edge applied via a switch. A nearby, magnetically coupled secondary then showed a current kick as a result of this excitation, both when the switch was closed (positive kick) and then again when it was opened (negative kick).

Most any cub scout pack or girl scout troop should have reproduced this, and most any grammar school level book of electricity should speak of it. Sometime later, Hertz did a more sensational job showing that the very same construct could transmit an impulse from a primary through the ether to a distant secondary as a spark. Surely not the most spectral friendly form of communication, but another fun experiment to reproduce…once in a while…far from an airport and pacemaker, perhaps with some limits on energy.

Faraday's law states that the curl of the electric field is equal to the rate of change of the magnetic field. If we read it backwards it makes more sense: if a time-varying magnetic field is applied, it will give rise to an electric field.

Equation 3. Faraday's Law

$$\nabla \times E = \frac{-\partial B}{\partial t}$$

Ampere's Law

For me this was a tough one on paper, and yet perhaps one of the handiest. Ampere stated that the curl of the magnetic field around a conductor was caused by two things. The current flow through the conductor and the time varying electric field around the conductor. Note that there is both a dc and ac component.

Equation 4. Ampere's Law

$$\nabla \times B = \frac{\partial D}{\partial t} + J$$

Ampere's law and Faraday's law describe the basis of wave propagation. The idea that a time-varying electric field gives rise to a magnetic field and vice versa. Ampere then completed the law with the addition of the dc term that describes the compass needle observation in a dc field.

To the old salt of power electronics professionals, this is baseline jibber jabber. I am guilty of drawing the same conclusion, however I believe it's time to take another look. If simply looking at the fast dv/dt nodes and fast di/dt loops was enough, everyone would pass EMI the first time around. Given the number of consultants in the field and the wait lists for test chamber time, I might infer that this is not happening.

What then if we expanded the models? Rather than just strictly circuital analysis, what if we looked beyond, in terms of fields? What if we looked at the results of Maxwell's equations directly over distance and frequency in a switching power supply circuit?

The Transmission Line And Energy Delivery

The transmission line discussion is limited. And perhaps I was my own limiting factor, but when I first learned about 50-Ω transmission lines, they were RG58, LMR400…and in a crazy application perhaps Andrews 7/8-in. line. But is the impedance always 50 Ω? Can I use RG58 to run the stinger on my arc welder? Probably not, but is it because of the 50-Ω characteristic impedance?

No. It's because of the DCR (ohms per foot), excessive current density and the fusing point of the cable. At welding frequencies, the transmission line looks like a few hundred nanohenries with a few hundred picofarads in shunt. It's not 50 Ω at all. This is often not clarified in transmission line discussions. Lower cutoff frequency is seldom discussed. Ampacity and current density are seldom considered, they are often lost in discussions on skin effect, depth of penetration and proximity effect.

What is the Thevenin output impedance of the source? What is the characteristic impedance of the transmission line connecting? What is the impedance of the load? In a power circuit, the answers are probably not as rosy as in the dedicated RF circuit. Perhaps you have to get 150 A across a PCB in 6 ounce/square foot copper to a bobbin flange of inductor pins.

The theoretician would worry about the transmission line impedance (the more funding, the more worry). I will not. I know that that circuit will be loss limited and I'll have to interleave as much copper as I can on as many layers to get the trace resistance down and manage the current flow. But in "not worrying" about the transmission line impedance, I have created a transmission line. The impedance of this transmission line is very small. Wide layers, minimal inductance, short distance, decent dielectric and layers close together.

Equation 5: Impedance of a transmission Line

$$Z = \sqrt{\frac{L}{C}}$$

Thinking through high-current routing on the PCB, Z would be a small number. Certainly, much smaller than 450-Ω ladder line. Ideally, I'd like the L to approach zero and the C to be large, the transmission line heads toward 0-Ω impedance. But again, this is not without limitation. We then might have a large surface moving at a fast dv/dt. This gives us an electric field radiator in the near field. While the ampacity was great, the area of the planes might require a little tweaking.

And this is where power electronics gets its strong tie to circuital models. We have to deliver current to a load with minimal losses to satisfy a mission, usually some sort of regulated voltage. The load can be modeled as an impedance, the circuit is comprised of voltage sources, current sources, conductors and Thevenin/Norton impedances. These are circuital models. Would anyone reading this hookup a 3-hp air compressor in the shop with 28-AWG phone wire? I should hope not. I don't think the wire would even properly clamp under the terminals of the 30-A or 50-A thermomagnetic breaker or the service disconnect.

But the characteristic impedance of the twisted pair is about the same, whether it's 28 AWG or 8 AWG. One solution is severely loss limited and will fuse open, the other will be just fine, even under locked-rotor conditions for the motor. What then is the lumped capacitance and inductance of that transmission line at line frequencies? (It's negligible). To deliver power, power designers are often constrained by matters of ampacity and not characteristic impedance.

A Bit On Ampacity

When it comes to ampacity, I've seen a lot of wrong answers. I had the luxury of having very aggressive management early on and some "in your face" moments where I learned ampacity well. I fell back on common sense.

For example, a 10-AWG conductor with a THWN jacket in a conduit in my house can handle 30 A in most cases as per NEC article 310 in NFPA70. If it's on the rooftop with appropriate terminations it derates a little due to the high temperatures on the roof. The cross section of a 10-AWG wire is 10240 circular mils. The current density for this conductor, operating safely in my home is then 341 CM/A (circular mils/ampere). What then is a bad current density?

If I examine a 3AG or 1.25-in. x 0.25-in. fuse rated for 3 A, I see that the fusing element is 5 mil x 5 mil square and approximately 1.25-in. long. It fuses at 3 A. In this particular case, the cross section of the fuse conductor is 31.8 circular mils and it is rated for 3 A. The fusing current density is then somewhere around 10.6 CM/A for this glass fuse. This is for a long conducting element in a sealed glass tube with very little heat removal (sparse radiation and end conduction to the end caps).

For perspective, bondwires in semiconductors are often designed to handle current densities of 10 to 20 CM/A, but these are *very* short runs, often surrounded by a molded encapsulant or gel. On the other asymptote, a small transformer with absolutely no airflow in a closed enclosure may be designed for 1000 to 500 CM/A current densities.

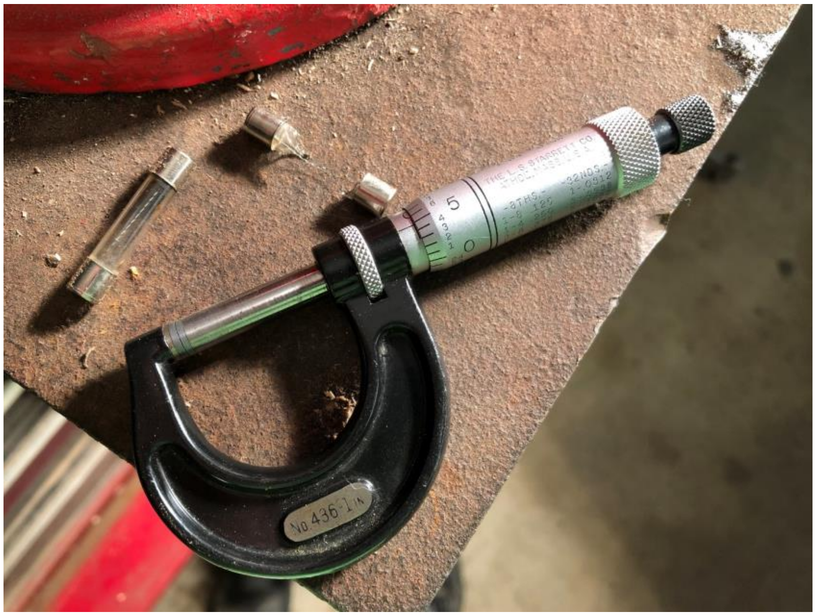


Fig. 2. Picture of fuse, mic'd on a Vernier scale!

The Present State Of Field Solvers In EMI

The push is clear. Most in the business of field solvers have begun adapting RF field solvers to EMI problems. Near field modeling and analysis is presently happening on smaller sections of power electronic circuits. I've seen no aggregate model that ties each component together and captures all of the interactions, but it is surely coming as fast as the computing bandwidth will allow. Some of the software is going the last mile and getting good correlation to test chamber spectrum analyzer data.

Once these field solvers come into play and can handle more than a few parts at a time this will be a very powerful tool. It will be possible to import a layout, model the pc-board interactions, model components and visualize and mitigate hotspots without entering the RF anechoic chamber or screen room (depending on tests performed). I should hope that the applicable safety agencies never get to the point of solely accepting a simulation on a product as proof that it is meeting emissions standards. But on the design side, field solvers will become a great EMC tool. They will give rise to first-pass success.

One Last Note

In closing, I had a reminder of why these things need to move forward. I ran into an old manager at APEC, the Applied Power Electronics Conference. He told me that he had just attended the half-hour training seminar in his big giant corporate server on EMI and was an expert on all things related to the matter by virtue of a printed certificate and a grueling five-question multiple-choice exam that was psychometrically balanced such that three of the four answers were obviously wrong. I agreed with him and said that I planned on taking the courses on my big giant server on how to be a lawyer, how to be a brain surgeon and how to be an accountant. In that 90 minutes, I'd learn all there is to know on those matters and I'd be an expert on all.

My hope was that he was kidding too. In that jovial context, if big data can "deliver" us such intense omniscience in such time compression, it can surely handle running field solvers on some trapezoidal waveforms and component/board models. It can surely illustrate the EMI signatures of a pc-board with components, traces, actives, enclosures and cabling. From the server's viewpoint, solving some paltry Maxwell's equations between big data reports should be a trivial matter.

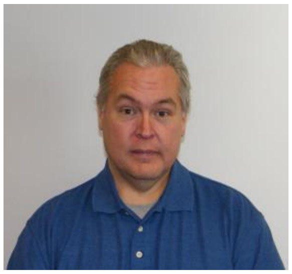
Reference

"Easiest way to make a homopolar motor - Lorentz force explanation," by JAES Company, YouTube video posted Dec 5, 2018.

Acknowledgement

Dan Beeker is conducting work with Ralph Morrison in the area of EMC. This movement is all about first pass success and visualizing the fields and energy propagation around the circuits, just as I've suggested herein. I am a member of Dan's army. We will change the face of EMC. The impetus for this work came from many spirited discussions with Dan on the matter.

About The Author



Paul Schimel is a lifelong innovator with an untiring commitment to engineering excellence in both the practical and theoretical aspects of power electronics and related mixed-signal, mixed-mode and mixed-domain design and control work. He is a principal applications engineer in the aerospace and defense group at Microchip Technology. Schimel is also a licensed PE bringing 24 years of formal experience to his A/D client base.

Prior to joining Microchip he spent the last 16 years in applications engineering, providing power management support and design work for Unitrode/TI, Fairchild and International Rectifier. Schimel has assisted successful designs from milliwatts to megavolt-amps and from IC/device design to prototype stages to finished end equipment. Applications ranged from industrial to automotive to full radiation-hardened designs. Before joining the power semiconductor industry, he spent eight years in successful power supply design engineering roles for consumer, industrial and hi-rel markets.

Schimel holds several patents on magnetic structures for power electronics and novel circuitry. He is familiar with most DOD, MIL, UL, NFPA70, 70E and IEC standards and how they are tested and passed. "When I find a design or problem to be impossible, I go see Paul, he figures it out," expounds one of his 20-year peers in the industry.

Schimel's informal training started at age six when he began following in his dad's footsteps: the Western Electric Hawthorne Works legacy of design excellence. Later, he attended the School of Electrical Engineering at the University of Illinois at Urbana Champaign, where he earned a BSEE degree while specializing in power electronics.

Paul moonlights in broadcasting, antique test equipment restoration, metal working, woodworking, TIG welding, loudspeaker building and amateur radio (K5NJP). He also holds a commercial radio telephone license (PG00017030), a refrigeration license and a PE license.

For more information on designing power electronics for low EMI and to meet EMC requirements, see How2Power's Power Supply EMI Anthology.