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APEC 2021 Presented Novel Concepts For Energy Storage, Million-RPM Motor Transmitter

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One of the two main power-electronics conferences and expositions held annually in America is the Applied Power Electronics Conference (APEC), held this year in cyberspace on the Internet. APEC is vast, with a multitude of papers, both technical and industrial, with presenters from both academia and industry. *Power electronics* includes both electrical-electrical power conversion and electrical-mechanical conversion (electric machines), with attention focused on motor drives in the latter case. APEC mainly included papers in the former category.

This report selectively highlights talks from two of the sessions, the plenary and a session on motor drives and control. In one of these sessions, an expert in the magnetics field looked ahead to new options for energy storage in power electronics, using piezoelectric and LC resonators. Meanwhile in the other, a researcher discussed a novel high-speed motor that creates a powerful low-frequency wireless transmitter by supplying mechanical energy to a permanent magnet antenna.

Plenaries Spotlight EVs, Quantum Computing And Energy Storage Components

At APEC 2021, the emphasis on power electronics for electric vehicles was substantial, if not dominant, and the first plenary talk was an overview of it.[1] The last plenary talk was almost beyond power electronics, presenting what IBM is doing in building quantum computers.[2] The quantum chip is operated at a Josephson-junction superconducting temperature under 1 K, with circuit power dissipation in the microwatts, while in the same cryogenic chamber above it, at a few Kelvin is the very-low-power electronics for driving the quantum IC, dissipating a few watts.

The second-to-last plenary concerned efforts to reduce the size of the energy storage components, namely the magnetics and capacitors.[3] That presentation was one of two I found most interesting at the conference, and so I’ll discuss it at some length. But first, some context may be helpful.

The frontier being pushed for converters is mainly seeking higher power density. Magnetics suppliers have been reducing core loss at higher frequencies, and discussion of magnetics now operating in the 1- to 10-MHz frequency range is not uncommon. Yet it was noted by more than one speaker with a goal of shrinking converter components that the magnetic components are still the largest. This is to be expected because all converter power transfer goes through them.

The basic conversion equation for power transfer through magnetic components is

$$\overline{P} = \Delta W \cdot f_s = \Delta B \cdot \overline{H} \cdot f_s$$

where ΔB is magnetic flux density variation, $\overline{H}$ is average magnetic field intensity (or strength) and f_s is the switching frequency. Power transfer is thus proportional to f_s, and to increase power density, components of a given size must either have increased per-cycle energy transfer, ΔW or operate at higher frequency with an acceptable power loss. Consequently, f_s is pushed higher, by developing magnetic materials that have reduced loss at higher frequencies. Although recent developments have yielded improvements, more dramatic gains for the future are being sought.

High-Performance Reactive Components

In his plenary talk,[3] Dartmouth College engineering professor, Charles Sullivan gave a far-sighted and insightful overview on alternative schemes for future converters. The question he addressed is what constrains the advancement of power conversion. With wide-bandgap switches of SiC or GaN and their low losses at high switching frequencies, passive reactive components—those that store energy—have become the main constraint.

After surveying both mechanical and electrical energy-storage mechanisms, he presented two categories of intermediate storage; one remains magnetic and the other is electric, in this case piezoelectric. Piezoelectric resonators are more than capacitors, which are essentially storage tanks that hold charge and store energy in an electric field across the dielectric material. Instead, they displace charge through a change (albeit small—in the micron (μm) range) of the dielectric material itself and are, in essence, electrostatic motors.

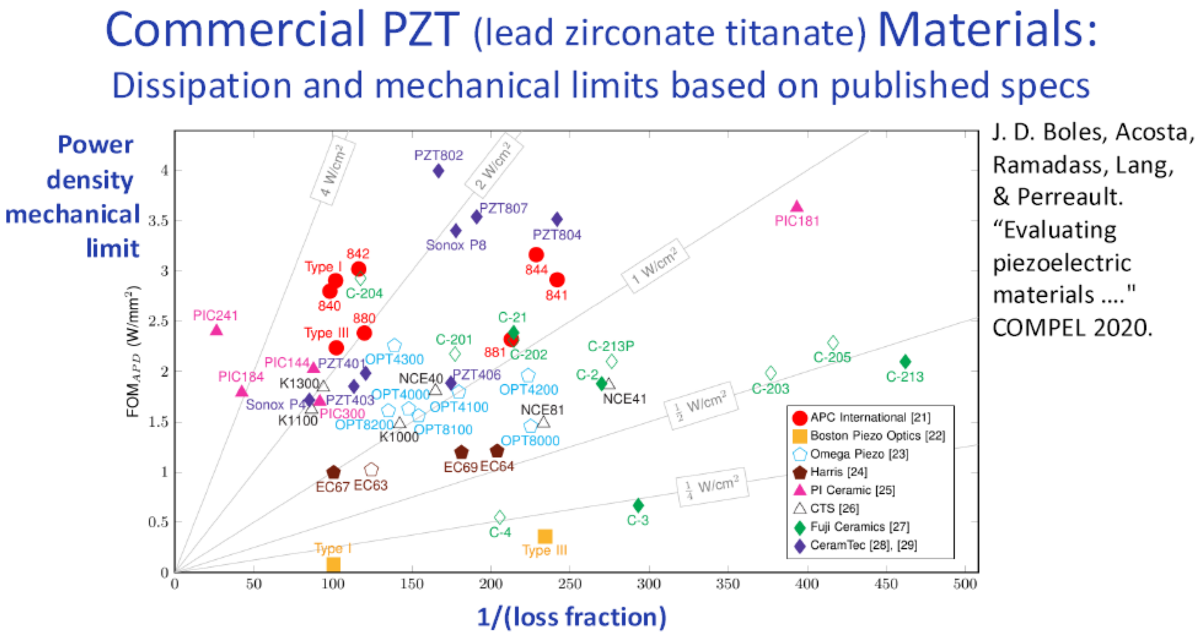
Similarly, LC resonators store energy in both inductive and capacitive reactances, and although they do not have the energy density capability of piezoelectric storage, their energy density can also be increased. Sullivan's slide 15, shown in Fig. 1, summarizes the possibilities for a common piezoelectric material, PbZrTi, or PZT, used as the transducer in medical phaco-machine probes, used for eye cataract surgery.

The predicted power density achievable with commercial PZT is 100 W/cm^3 at 93% to 99% efficiency. Lithium niobate is a better material. It has been used for decades for delay and filtering functions in electronic components. A prototype operated at 6.8 MHz had a component efficiency of 98% efficiency with a power density of 148 W/cm^3. In terms of energy storage capability, PZT is in a range comparable with the very best ferrite magnetic cores, operated at 1 MHz or higher.

Piezoelectric components are basically capacitors with a dielectric that can expand and contract with voltage. This makes them the dual of the dominant electrical-mechanical power converters that have come to be called *electric machines*, or motor-generators.

Like magnetic components in converter power-transfer circuits, electric machines also have two electromagnetic components: electric windings and magnetic core. The primary winding is on the stationary core of the stator, and secondary winding is on the rotor, though in permanent-magnet synchronous (PMS) machines, the magnets are modeled as a current source driving a fictitious winding to generate the rotor magnetic field. They are essentially transformers with a secondary or rotor winding that moves and hence is also mechanical.

The dual of these magnetic machines, based on electric-field energy transfer, are piezoelectric motors. They move translationally instead of rotationally in most cases, and have corresponding parameters to characterize them, though they have been expressed quite differently by manufacturers.



Commercial PZT (lead zirconate titanate) Materials:

Dissipation and mechanical limits based on published specs

Power density mechanical limit

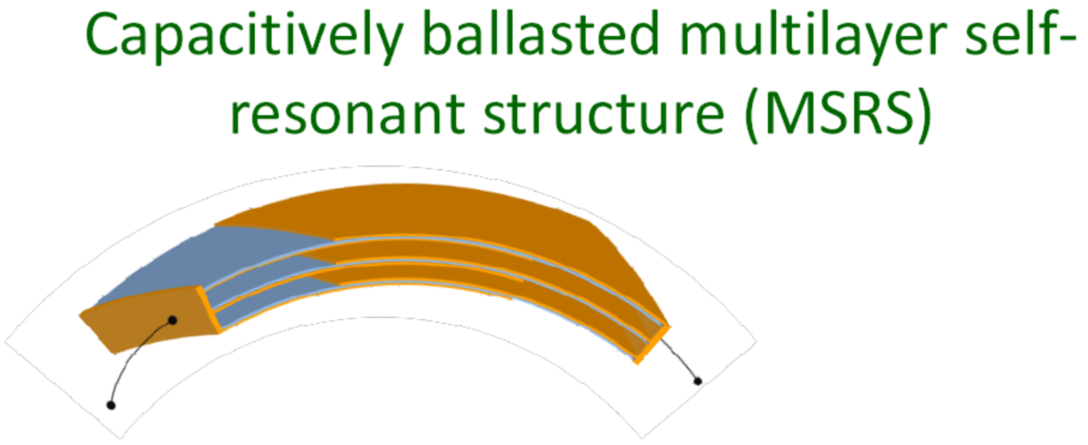
J. D. Boles, Acosta, Ramadass, Lang, & Perreault. "Evaluating piezoelectric materials ...." COMPEL 2020.

1/(loss fraction)

Fig. 1. Slide 15 from Charles Sullivan's plenary talk showing possible PZT material variations for future high-density energy storage.

For improvement of magnetic components, Sullivan noted winding frequency limitations, and turned to thin foil, less than 20 μm in thickness, noting that a cheap source is aluminum foil found in grocery stores. In taking a similar liking to kitchen foil, I bought a couple of rolls a few years ago at the grocery store and measured their thicknesses. Thin Al foil measures 15 μm, with an ampacity of 0.413 A/cm of width (though the consumer-oriented foil box states neither the thickness nor the ampacity); the thick foil is 22.5 μm with 0.619 A/cm.

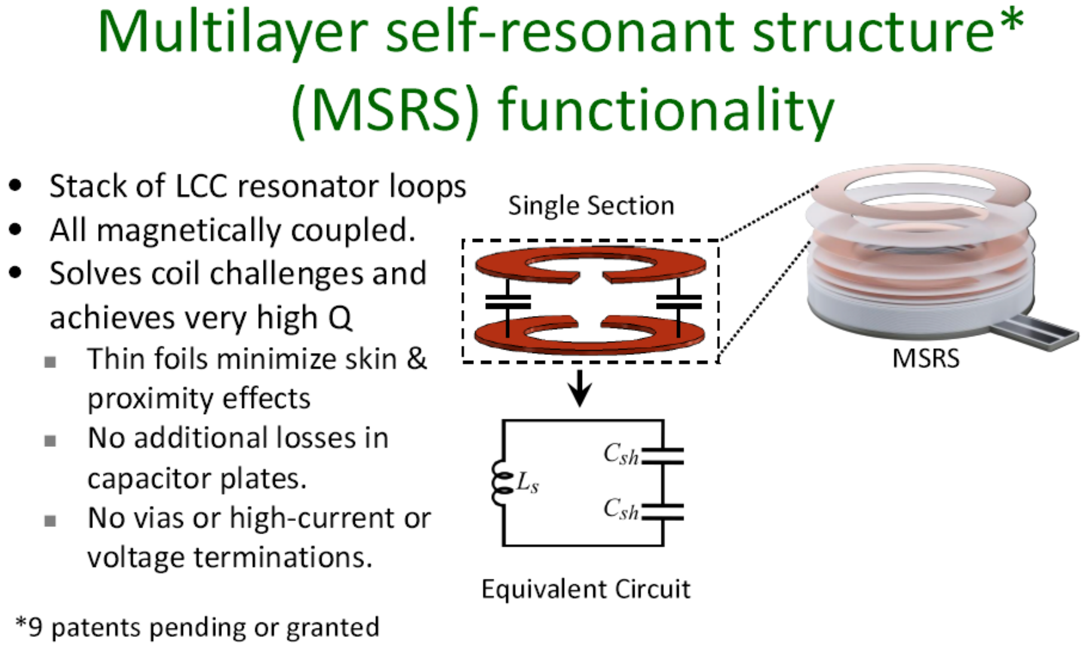
A thinner foil is used in foil-plate capacitors. The limited current density in these foils requires that they be paralleled, with a bundle (multilayer) skin effect. Stacked foil layers are paired, one stack per terminal, partially overlapped, and then bent. As shown in slide 26 of Fig. 2, the stack becomes an LC resonant structure.



Capacitively ballasted multilayer self-resonant structure (MSRS)

Fig. 2. Slide 26 from Sullivan's plenary: High-frequency foil windings with overlapping conductive-layer pairs between insulating dielectric, and with a bent structure.

With more bending, the windings become a circular structure, shown in Fig. 3 with its equivalent circuit.



Multilayer self-resonant structure* (MSRS) functionality

- Stack of LCC resonator loops
- All magnetically coupled.
- Solves coil challenges and achieves very high Q
  - Thin foils minimize skin & proximity effects
  - No additional losses in capacitor plates.
  - No vias or high-current or voltage terminations.

*9 patents pending or granted

Fig. 3. Sullivan's plenary talk, slide 30: The resulting combination of layer inductance from offsetting and capacitance through the dielectric separators of the foil layers.

This *multi-self-resonant structure* can be implemented with pot cores, and Sullivan showed several possible prototype implementations of this kind of LC resonator, with resonant current flowing across inductive layers and between capacitive layers. Monolithic integration possibilities have also been implemented on a 3-mm × 3-mm chip, operating at 48 MHz and 0.87 W with 86% peak efficiency (better than a low-dropout linear regulator), for a power density in the resonator area of 0.267 W/mm^2 = 26.7 W/cm^2. David Perreault and his team of researchers at MIT are collaborators on this effort.

One of the important conclusions from Sullivan's talk is that as size is reduced, piezo-resonators have an increasing advantage over LC resonators, though the refinement of LC resonators can be pushed further than the current state of the technology. On a discrete component macro-scale, capacitive power transfer has a much lower density than magnetic component transfer which is why capacitor-based converters are relegated to bias-voltage generation and similar functions requiring less than a watt. However, the roles reverse on the micro-scale of integrated circuits, where silicon material makes better capacitors as an energy storage medium than conductive traces make inductors.

Fast Motor With Unusual Application

In the motor-drives category, what caught my attention was a paper by Islam and Choi of Mississippi State U., of a 2-kW, two-pole permanent-magnet synchronous (PMS) motor that turns at a rated speed of a half-million* rpm.[4] The ball bearings have a lifetime at that speed of 15 hours of continuous operation. The abstract of the paper states that it is a "machine for a mechanical-based antenna … a mechanical transmitter for extremely/very low frequency (0.3 - 3 kHz) communication, which will immediately enable the bidirectional communication between the earth surface to underground or undersea facilities."

The antenna is the electromechanical load of the motor—a permanent-magnet pole-pair that is an antenna dipole, oscillating at the mechanical frequency of the motor. It requires no electrical power input because it is supplied mechanically in rotating the permanent-magnet antenna.

At 500,000 rpm—or 8.33 kHz mechanical—a conventional three-phase winding scheme is inadequate and the authors opted for a six-phase scheme. Although these kinds of motors operate at low shaft torque—typically 0.8 to 2 mN·m—at this high speed, the electrical winding frequency is also (for one pole-pair) 8.33 kHz, and the considerations that apply to switching converter magnetics begin to be relevant.

Consequently, the slotless stator material is not laminated silicon steel as found in 50- or 60-Hz machines, but is amorphous iron-based material (Metglas) with multi-strand Litz-wire windings. Core loss at maximum speed is 34 W and the winding loss is 48 W with 36 W of it being proximity-effect loss. Thermal 3D finite-element analysis (FEA) shows the maximum temperature of 127°C in the rotating magnets, from air friction; the winding is 102°C and the stator core a relatively cool 82°C.

Rotor air friction loss of 59 W was a major design consideration. The rotor magnets were chosen to be samarium-cobalt, SmCo over NdFeB because they have the highest energy density at the high temperature (> 80°C) that air friction produces at the rotor. The high centrifugal force on the magnets requires a nonmagnetic titanium retaining sleeve for magnet structural support.

With six phases, more windings cover a smaller arc angle with fewer turns per winding—40 turns each of 100-strand Litz wire. The reduced number of turns from that of a three-phase design reduces winding inductance to 20 µH. The winding-induced voltage from the rotor magnets has a sinusoidal waveshape. The winding-referred flux amplitude, referred to the mechanical rotor speed, is λ_{me} = 250 µV/rpm—what motor specifications call the "voltage constant".

Mechanical output power varies with the radius-squared, r^2, the rotor length, l and the rotor speed, ω_{me}. The design challenge is to maximize power density by choosing optimal r and l. Making r larger increases magnet and sleeve stress proportionately with r, increases air-friction loss by r^4, and has worse temperature distribution in the magnets.

Increasing rotor length reduces the fundamental mechanical resonant frequency to near the rotational frequency, causing shaft instability. High shaft speed in mechanical FEA shows four resonant frequencies, spanning 95 Hz to 17,053 Hz. The shaft interacts with the bearings, and shaft modeling led to the selection of the optimal ball bearing stiffness. The rated speed falls between the second and third critical speeds.

Bearing run-out is the amount of displacement of the shaft from its center position in a bearing as it turns. In spindle motors for hard disk drives, bearing run-out is a constraining parameter because the read-write head positioning has low tolerance, but in their paper, the authors say nothing about run-out—only about a reactive element of interest in the bearings, that of stiffness. Its inverse is compliance, analogous to electrical inductance (in the force-current analogy), and resonates with rotational inertia, which is analogous to capacitance, causing the four resonant modes within the frequency range of interest for the rotating shaft at rated speed.

The mechanics of the high-speed motor are complicated by the bending modes of the shaft, which cause the mechanics to be nonlinear. A bending shaft is a component that is changing its inertia dynamically. Like nonlinear circuits analyzed numerically with a simulator program, an accurate solution is found by mechanical FEA simulation. Both thermal and mechanical FEA were used in this project.

**Note: This talk also referred a 1.2-million RPM prototype. Hence, the title of this article.*

Looking Ahead

Next year, virtuality will revert to actuality by locating the event in Houston, Texas. Technical session digests for APEC 2022 are already being accepted. For more details on next year's conference, see the APEC website.

References

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3. "The Present and Future of Magnetics and Other Power Passives" by Charles R. Sullivan, APEC 2021, plenary session, June 16, 2021.
4. "Modeling and Design of a 6-Phase Ultra-High-Speed Machine for ELF Wireless Communication Transmitter" by Md Khurshedul Islam and Seungdeog Choi, APEC 2021, Session T27 Motor Drives & Control.

About The Author

Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.