STATUS REPORT AND TECHNOLOGY OVERVIEW OF LEADING EDGE DEVELOPMENT

In the field of

Increased Power Density Inverter Technology and the use of 105°C Engine Coolant for the DC Link Capacitor

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Executive Summary

SBE has developed an innovative new annular capacitor technology which when combined with integration of inverter semiconductors should provide the path to a significantly increased power density inverter. It should be capable of operating using the available HEV/PHEV 105°C engine coolant for both semiconductors and capacitors at similar or less expensive costs than today's technology

The research has crossed several important feasibility milestones. Early technology is being field tested by notable industry participants. The US Department of Energy (DoE) has provided some R & D funding. More research is needed to prove the accepted reliability and final optimization of the inverter.

An Industry Partner is sought and Advanced Inverter applications Solicited.

Identification and Significance of the Problem and Opportunity

Transportation systems, Electric Utilities, and the fuels used therein can have a dramatic impact on a nation's security, particularly with forecasts that the United States will import approximately 70% of domestically consumed oil by 2025[1] and that such imports could be higher for some other countries.

Hybrid vehicles (HEV) and Plug-In Hybrid Vehicles (PHEV) like those envisioned in the US Department of Energy (DoE) FreedomCAR & Vehicle Technologies (FCVT) program provide an opportunity to improve the security of a nation's energy supply by reducing the domestic demand for imported oil through vehicle-fleet energy efficiency improvements of up to 35%[2]. The reduced emissions of a high gas mileage rated internal combustion engine (ICE)/electric motor hybrid drive or an emissions-free fuel-cell system are additional compelling reasons propelling the development of hybrid vehicle technologies. As identified by the DoE Vehicle Systems Sub-program[3], the hybrid vehicle power system necessitates improved performance and reduced cost of an electric traction drive system. The power inverter systems integrated into an under-the-hood traction drive require capacitors capable of carrying substantial high frequency currents.They must minimize the impact of high ripple currents on high energy density storage devices (like super-capacitors and battery packs, load-sensitive power sources such as fuel cells) and ameliorate the impact of switching voltage transients on power semiconductor devices such as IGBT's and PowerFET's. Additionally, the inverter semiconductor devices themselves require cooling and an efficient topological layout to provide high volumetric power density.

Likewise, for Alternative Energy Systems in the Electric Utility Industry, long-term reliability of inverters is critical to the market adoption and installed system costs of the installation. Cooling considerations and overall inverter size vs. reliability trade-offs have limited the potential options of integrated packaging available to this industry. One of the leading obstacles of an electric utility alternative energy implementation is a concern about aesthetics and overall size[4]. The benefits to providing smaller inverter size without the added cost of additional thermal management systems are a greatly improved volumetric power density using simple and inexpensive cooling methods, and offering reliability over a wide temperature range.

Aluminum Electrolytic capacitors are prevalent in today's DC bus filter (or DC Link Capacitor) applications for inverters, especially lower voltage systems in smaller

HEV drivetrains and small electric vehicles. Along with standard, packaged semiconductor devices, they are typical for the active inverter electronics design. These combine for good energy and capacitance density, reasonable performance and low component cost, but at a price of stringent cooling requirements and sometimes significant volumetric inefficiency. This is partly because electrolytic capacitors have fundamental material limitations, which prevent their use at temperatures exceeding +70ºC when de-rated for even medium-term reliability and for operating voltages over 450 VDC[5]. The electrolytic capacitor's Effective Series Resistance (ESR) is high and rises dramatically at low temperatures, limiting its ability to absorb and deliver energy at the low ambient temperatures frequently experienced in a large portion of the nation. This limits the overall performance and power density of the inverter both directly due to the capacitor and indirectly as the semiconductors are affected by the ESR and the Effective Series Inductance (ESL) due to packaging inefficiencies.

Aside from the obvious technical limitations of electrolytics as a capacitor choice for the inverters, is the fact that they contain toxic substances that create a disposal hazard. This is particularly significant for hybrid vehicle applications, where accident impacts may release the electrolyte and public perception of environmentally un-friendly components will dictate acceptance. It is also significant in environmentally sensitive areas often chosen as sites for alternative energy - solar and wind - generation.

Recent efforts by many in the industry to substitute polymer film capacitors, with higher voltage ratings of 500 – 1000 VDC, for electrolytic capacitors in inverters have used banks of parallel and series connected conventional cylinder-shaped, or flattened cylindrical sections, of smaller capacitors to form a complete module. This is done to achieve the required voltages such as shown in Figure 1, to distribute the current flow, or achieve the desired amount of total capacitance required. This approach severely limits the designer's ability to remove heat generated by the capacitors and interconnects, limits the choices on locations for the capacitor bank, increases the ESR, increases the total volume needed, and adds considerable complexity and cost. Similar packaging issues remain a problem for typical electrolytic capacitor form factors, as well but are increased with film solution due to the natural disadvantage that film capacitors have in terms of capacitance density. In fact, universally, it has been found that, unless a capacitor has been carefully designed for long-term operation at elevated temperatures, high-temperature failures observed in commercially available components will most often be related to the individual devices' packaging and contacts technology, rather than the dielectric materials employed[6,7].

Consequently, it is the heat dissipation of the DC Link Capacitor bank while it is under the load of 100 – 400 Arms ripple current, which is rapidly becoming one of THE design limiters for the HEV and PHEV transportation inverter solutions available to industry today.

"Hybrid Electric Vehicles (HEVs) and Plug-in hybrids (PHEVs) require advanced technology in the areas of Energy Storage and Ripple Current Capacitors. These technology areas represent some of the most critical barriers to the development and marketing of cost competitive HEVs and PHEVs."[8] This quote taken from the DoE's own SBIR solicitation from 2006.

Figure 1: Typical DC Link Capacitor Bank[9]

One of the more significant issues preventing the largest reduction in system volume, weight, and cost in the HEV and PHEV traction drive inverter systems envisioned for a next generation of these vehicles is the requirement of currently available polymer film, such as polypropylene (PP) film, capacitor technology to be cooled so that the hot spot temperature of the capacitor, while under load conditions, is lower than 85°C for long term reliability[10]. In order to achieve this condition, the capacitor solution must be cooled to be below that point even as it is self heating due to ripple current pass-through. In a traditional film capacitor form factor, such self heating can result in a 35 - 50°C rise from ambient surrounding temperature[11]. This can necessitate coolant temperatures of between 35 - 50°C in order for the film capacitor solution to remain reliable under full current rating conditions.

A typical system design engineering approach to this self heating and subsequent cooling requirement need of PP film capacitors is to allow the temperature of the hot spot to rise above the accepted 85°C long term reliability temperature point and distribute the inverter's DC Link ripple current across a larger number of PP film capacitors. This technique, known in the industry as "de-rating" can allow the temperature to rise within the capacitor to as much as 95 - 105°C and still remain a long term reliable solution but at reduced maximum total current allowed through any individual capacitor section[12]. However this technique still requires coolant systems delivering 55 to 70°C because the "more capacitor sections in the bank" solution does nothing to help the temperature rise expectation of any individual capacitor section per unit of RMS current (temperature rise is proportional to RMS current squared). And a cooling system of this temperature level means that a separate cooling line, infrastructure, and power drain will reduce the HEV or PHEV's overall drivetrain efficiency due to added weight and volume, to say nothing of costing more than desired. It also requires many more PP film capacitor sections in order to distribute the current. This adds cost, volume, and weight and is not desirable.

A further enhancement to this solution is to use High Temperature PP film such as High Crystalline PP film. Such film is described to have increased high temperature characteristics which may make it usable up to 115 or even 125°C[13]. This would allow the possibility of current distribution across a somewhat smaller number of sections than that required by standard PP film or might allow a somewhat higher coolant temperature for a single capacitor. However, such PP film material capacitors of this design would still require a coolant temperature of 65 to 90°C. This is still too low to use an available 105°C ICE coolant for efficiency and lower cost.

What is required is a single capacitor design which can operate reliably using 105°C coolant. Such a design would achieve the lowest possible weight, volume, and system cost if it utilized relatively inexpensive film capacitor materials such as PP or HCPP.

This desire was specifically stated by the DoE itself in the "Advanced Technology Solicitation" of the FreedomCAR program dated December 2006[14].

Currently, inverter technology used in hybrid electric vehicles uses 70°C coolant that is supplied via a separate cooling loop in the automobile. It is desirable to eliminate the need for an additional cooling loop to reduce cost and complexity in the vehicle.

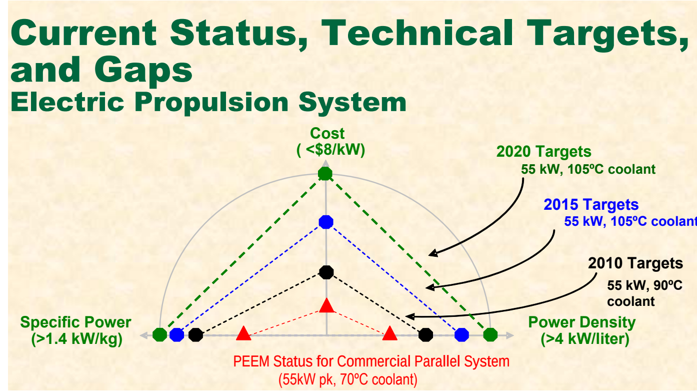

Figure 2: Presentation by DoE in 2007 showing goals of technology progression[15]

And if such a design did exist, the volumetric efficiency of the inverter could additionally be increased if the semiconductor topology of the devices could be integrated into a successful capacitor design.

Lastly, the combination of the successful capacitor design and the optimization of the inverter semiconductor topology could, actually further increase the total inverter system performance if electrical and/or cooling characteristics might be enhanced by the integration.

This identifies the goal of the innovative new technical approach by SBE Inc.: To create a 105°C coolant capable capacitor design which exhibits long term reliability and enables greatly increased volumetric density and electrical performance of the entire inverter system at low cost.

Innovative Technical Approach

The wound-film capacitor ring geometry shown in figure 3, and recently introduced by SBE Inc. to industry, has been demonstrated to greatly increase capacitance density for film capacitors[16].

Terry Hosking, SBE VP Technology, invented the technique of locating a load (i.e. electronic, semiconductor package, etc.) inside the center hole of the annular capacitor for the specific purpose of reducing the ESL (inductance) of an application, which uses the capacitor[17] (issued patent number 7,289,311). One of its applications is the inverter and DC Link Capacitor relationship.

Over the past year, SBE has worked on joint research and development involving installing inverter semiconductors in the hole of the annular form factor film capacitor with the US DoE Oak Ridge National Labs (ORNL). Excellent initial improvement has been observed[18]. Concept designs that have been jointly investigated by SBE and ORNL suggest that simple cooling could be implemented, and that significantly greater volumetric power density could be achieved, if an optimized design of capacitor and unpackaged semiconductors were assembled in the hole on a bonded substrate.

Figure 3: Photo of the new innovative annular ring geometry capacitor using metalized polymer film with a center hole area sufficient for inverter semiconductor population

However, in order to achieve the desired results, the research must understand the following critical elements:

1. what the thermal effect on the DC Link capacitor will be under the proposed load conditions
2. what the various cooling techniques possible are
3. what the net effect of having the semiconductor die topology in the center, both electrically and thermally will be.

SBE Inc has performed significant work in the area of heat dissipation in PP Film capacitors and together with its partnering consultant, Fieldmetrics Inc, has developed temperature models of how heat transfer occurs in PP Film Capacitors of a given section width and for a given AC current. Such current waveforms would be similar to those in the DC Link Capacitor ripple current case for a typical HEV or PHEV inverter. However, closed-form solutions for capacitor temperature profiles exist only for very specific cases. Efficient evaluation of practical geometries for this solution over a wide range of parameters will require the use of finite element analysis (FEA) to address spatially varying losses and temperature dependent, anisotropic thermal conductivities. Furthermore, the FEA approach offers a variety of boundary conditions that can account for fixed temperatures in addition to convection (natural or forced) and radiation. Recent studies by the authors of an early prototype annular capacitor indicate that the thermal profile is highly complicated by the material properties, loss distribution, geometry and boundary conditions as shown in Figure 4.

The process of capacitor analysis is complicated by the relationship between various geometric and material properties. The following parameters are interdependent and any final capacitor design solution will involve “trade-offs” between them:

1. Film thickness: energy density + thermal conductivity
2. Metallization thickness: thermal conductivity + losses
3. End connection configuration: losses + thermo-mechanical limit
4. Package aspect ratio: energy density + thermal expansion + thermal mismatch

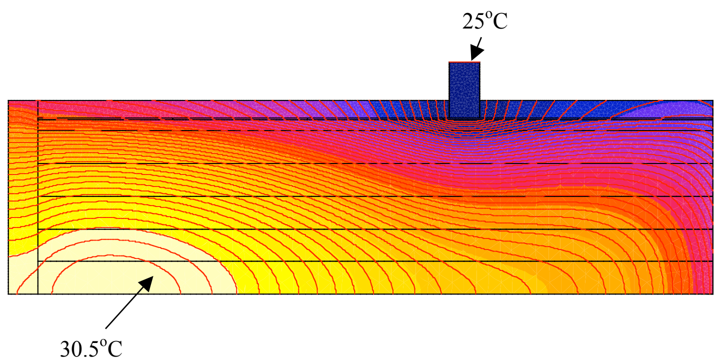

Figure 4: Thermal profile for an early prototype annular form factor capacitor with a symmetric contact located outside the mean radius[19]

SBE Inc has conducted some of this research on similar film capacitor materials but never using high crystalline PP film or under these thermal conditions. The performance must be optimum relative to hot spot temperature rise in order to accomplish the proposed inverter goal. SBE believes that the results will be positive but they are currently not known.

From the preliminary design and analysis already performed by the company, it is believed that the optimum thermal and volumetric efficiency will come from locating the inverter semiconductors inside the hole of the inverter.

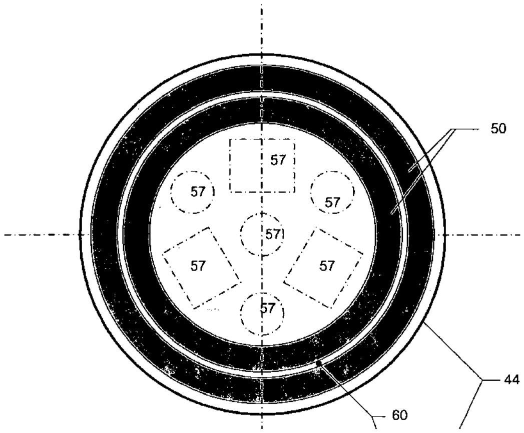

Figure 5: from Oak Ridge National Labs Patent Application 2006/0144069[20]

Some initial testing has been done in this area by Oak Ridge National Labs using the SBE annular form factor capacitor. This work was done solely in attempt to take best advantage of space in a circular cooling vessel which has been invented by ORNL (issued patent).

The SBE Innovative design will improve the cost and efficiency of the ORNL technique by attempting to co-locate the semiconductors inside the hole and the annular form factor capacitor on a single cooling plate as shown in figure 6.

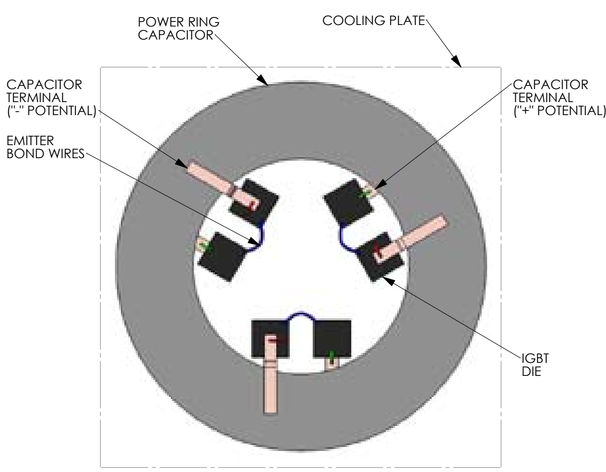

Figure 6: From SBE Provisional Patent application Filed November 1, 2007[21]

This arrangement represents the best ratio of cooling plate surface area to current density within the capacitor and subsequently the lowest possible temperature rise under the conditions.

SBE Inc has conducted preliminary tests and performed parallel modeling of this arrangement under room ambient conditions for a 240 Arms PHEV type ripple current application[22]. The temperature rise observed, and confirmed with modeling, was low enough to support the goals presented here in this paper if the appropriate PP film were to be used and proven to be reliable under the defined transportation environmental conditions.

In order to be successful for the goal of long term reliability using the 105°C ICE coolant temperature, SBE believes that a temperature rise of less than 15°C will be required while operating at maximum rated operating temperature. This would establish a maximum hot spot temperature of less than 125°C within the capacitor. Preliminary data obtained from suppliers of high crystalline PP film establish that a 120°C - 125°C hot spot could support long term reliability with moderate de-rating. Data is not conclusive yet on this point however so SBE is now conducting research to perform the necessary tests under the required transportation conditions to make this determination of de-rating vs. acceptable long term reliability for industry use.

The author is not concerned about the fact that this solution might also require some film capacitor de-rating and consequently additional film capacitance to reach the desired HEV/PHEV inverter ripple current requirements. The reason for this is that the volumetric efficiency of the annular form factor is up to 35% more efficient than a corresponding capacitor bank solution by design[23], so some additional capacitance for this purpose will have a minor effect on total volumetric efficiency vs. existing designs, especially when the complete elimination of the additional cooling loop is factored in.

Similarly, once the temperature affects are understood about the DC Link Capacitor in the annular form factor, similar information must be generated from semiconductor thermal analysis of inverter switching semiconductors located within the hole and co-located on the same cooling plate. The authors have performed previous work on understanding the cooling requirements of semiconductors under power in the center hole of an annular form factor DC Link Capacitor[24,25]. However detailed thermal analysis has not been performed yet. Also the resulting increase in volumetric power density with an optimized heat exchanger, cooperatively simulated thermal analysis and optimized modeling of the capacitor and semiconductors acting in the inverter environment have never been performed. This research is currently planned for early 2008.

In theoretical analysis of understanding the current flow in a large distributed capacitance where single element analysis is no longer sufficient to describe the self heating properties (i.e. an annular form factor), SBE has demonstrated that in order to maximize the total current handling capabilities of the capacitor, equal currents (to as great an extent as possible) need to be flowing through the capacitor[26]. This is because the maximum current rating of the device under long term conditions will come from identifying the worst case hot spot temperature and establishing current limits to keep this hot spot below the point where permanent heat damage will occur to the PP film in that area.

One can therefore conceive that the more uniform the current distribution in the distributed capacitor element is, the lower the current will be in any one spot in the capacitor and the lower the resulting internal heat generation from any spot will be. Ideally, the hot spot will not actually be a "spot" but a well distributed region of similar temperatures which will collectively be kept below a damaging temperature for the film.

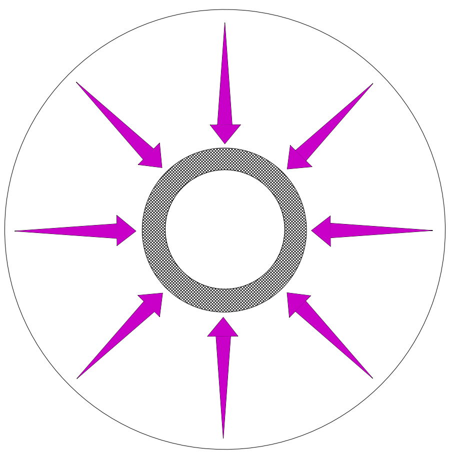

Figure 7: Distributed Current in an Annular Ring Form Factor Capacitor[27]

The optimum designs for a switching semiconductor layout of devices within the hole will take best advantage of this uniform current flow within the DC Link Capacitor to best reduce temperature rise under full current load conditions.

One might consider that if the hole of the capacitor needs to become too large to accommodate the necessary power semiconductors then the resulting circle of the annular form factor capacitor might need to become too large for the necessary capacitance of the DC Link. However, math is helpful in this regard since a reasonably large center hole can be created without great loss of capacitance of the remaining ring due to the volumetric formula of:

$$\pi r^2 w$$

Where r is the radius of the capacitor area and w is the width of the capacitor film. A reasonably large portion of the total radius of the annular form factor capacitor can be removed for electrical use and still leave useable capacitance. As an example, 50% of the radius could be left available for electrical use and the corresponding reduction of capacitance would only be approximately 25%. Since the author has calculated that the annular form factor shape results in up to a 35% increase in volumetric capacitor efficiency vs. the currently used capacitor banks in many HEV inverters, it is quite possible that the power electronics of the proposed inverter could be completely contained within the "underutilized space" of today's HEV inverter capacitor banks.

In summary, the annular form factor Inverter/Capacitor enabled by this innovative approach presented by SBE Inc could simultaneously provide a number of technical advantages over competing approaches, including:

1. High current handling capability due to the large surface contact area for cooling and low internal heat generation by optimized design.
2. High temperature capability in the 105ºC coolant regime using highly crystalline PP as the dielectric film with long-term reliability.
3. The highest possible current capability by specifically establishing the semiconductor topology in the center hole of the capacitor to equally divide the ripple current in the capacitor.
4. Electrical performance improvement as a result of the extremely low inductance (ESL) possible when using connections to the capacitor of short and symmetric design.
5. An overall reduction in volume vs. current design approach.

This innovative approach should cost no more than current Film Capacitor technologies and is anticipated to cost less since it is of simpler capacitor construction.

The reason why the costs of the innovative new design should be less than the current film capacitor technologies employed, is that it uses the same type of PP film being used today (with slight increase due to higher temperature film PP planned). SBE has developed capacitor winding equipment which produces annular form factor capacitors at a speed of capacitance per minute equal to the conventional machines used to build smaller capacitor sections. Yet when the annular form factor capacitor comes off the machine, it is already the appropriate size. Conventional sections are typically then assembled into a large bank as shown earlier in Figure 1.

The impact of the successful discoveries outlined in this paper is significant. Currently the volumetric power density of inverters is greatly limited due in great part to the temperature limitations of the DC Link Capacitor for long term reliable use. As a result, significant complex cooling schemes are attempted[28] at a much higher cost than the industry can bear, and thus impeding substantial adoption of new alternative energy technologies in the marketplace. A breakthrough in inverter technology, as described in this paper, will have great commercial potential and will be an enabler in accelerating the wide-scale adoption of high gas mileage and low CO^2 producing vehicles around the world.

SBE believes that the annular form factor capacitor and associated inverter integration described in this paper could provide the enabling technology needed to allow reasonable discussion for the rest of the HEV Powertrain industry on how to implement a single coolant system transportation solution. The conventional capacitor bank is currently a "road block" to a meaningful solution to the small, inexpensive, single coolant, inverter for the FreedomCAR vision of an affordable high mileage transportation solution for the United States and equally around the world. There is a push for lower cost across the entire system and - in addition to the elimination of the additional cooling system - the simpler capacitor construction and package integration will more than overcome the anticipated volume price incremental of high crystalline (high temperature) PP film.

Where does the Research need to go from here?

SBE is currently conducting final stage research with some funding by the US DoE as well as industry sources and private funding. The early technology is already being field tested in first stage field trials and in less than optimum configurations by a small group of industry participants.

What remains to be done is to perform the integration of inverter semiconductors with the annular capacitor ring into a single unit and perform long term reliability tests to prove that this new innovation is sustainable as a reliable inverter in the transportation environment using single 105°C coolant. Only with this data, will the industry move to adopt the technology and enable a break-through to be made.

SBE is seeking an industry partner, who shares this vision, to help fund this ground breaking work. Success will literally lead the way in the inverter Power-Train and Alternative Energy Industry.

Also of interest to readers is the SBE "Improve Your Inverter Performance" handout which describes the many other implementations of the innovative annular capacitor breakthrough which are being conceived and tried by designers in the industry. The integration of semiconductors in the hole is just one of the many ways that the technology can advance the state of the art of the inverter industry across the world.

SBE is also actively seeking challenging Advanced Inverter applications which will benefit from this leading edge technology.

Edward Sawyer, President and CEO of SBE Inc. holds a BSEE from Tufts University and a MBA from Colorado State University. He has been President and CEO of SBE Inc. since 2002.

Prior to that, Mr. Sawyer held executive positions at Emerson Electric Co. and Banta Corp. and has 20 years experience in the passives and semi-conductor electronics industry.

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References

1. Howell, David, 2005 Annual Progress Report for Energy Storage Research & Development, DOE Freedom CAR and Vehicle Technologies Program, 2006.

2. Tuttle, B "Capacitor Technologies: A comparison of competing opinions", presented at the DOE Hi-Tech Inverter meeting, Baltimore, MD, October 13, 2004

3. Greene, Duleep, and McManus, "Future Potential of Hybrid and Diesel Power Trains in the US light-duty vehicle market" US DOE July 2004.

4. Good, Justin, "The Aesthetics of Wind Energy", Human Ecology Review, Vol. 13, No. 1, 2006.

5. Tuttle, B "Capacitor Technologies: A comparison of competing opinions", presented at the DOE Hi-Tech Inverter meeting, Baltimore, MD, October 13, 2004.

6. Grzybowski, R.R. "Characterization and Modeling of glass and glass-k capacitors to 450c." Proceedings of the 12th capacitor and resistor technology symposium, 1992, Tucson, AZ pp 114-120.

7. McCluskey, F.P. et al, "High Temperature Electronics" 1997 (CRC Press), chapter 4.

8. Marckx, D.A., "Breakthrough in Power Electronics from SiC", Subcontract Report, NREL, May 25, 2005.

9. Tuttle, B "Capacitor Technologies: A comparison of competing opinions", presented at the DOE Hi-Tech Inverter meeting, Baltimore, MD, October 13, 2004

10. Grasshuff, Thomas, "The performance of new IGBT Chip Technologies- soft switching and low conduction losses for cost efficient inverter design". www.semikron.com, 2006.

11. Marckx, D.A., "Breakthrough in Power Electronics from SiC", Subcontract Report, NREL, May 25, 2005.

12. Hornkamp, M, and Munzer, M, "IGBT Module Optimizes Inverter Solutions", Power Electronics Technology, April 1, 2001

13. Steiner Films Website, www.steinerfilm.com

14. Department of Energy SBIR solicitation, December 2006

15. IMAPS 40th Congress, San Jose, CA Nov 3 – 7, 2007

16. Hosking, T, "Ring Form Factor Film Capacitors for Embedded Motor Controls", Proceedings of the Motor & Drives Systems Conference, Miami, Florida, February 15, 2006.

17. Hosking, T, "Power Ring Pulse Capacitor", US Patent 7,289,311 October 30, 2007.

18. Marlino, L. "Advanced Inverter Technology", HEATCAPS, October 3, 2007, Penn State University

19. Hosking, T and Brubaker, M, "An Extremely Low ESR and ESL Annular Film Capacitor", Proceedings of Power Systems Conference, October 2005.

20. Hsu, John et al, "Refrigerant Directly Cooled Capacitors", US Patent Application, 2006/0144069

21. SBE Provisional Patent application Dated November 1, 2007

22. Hosking, T, "Thermal Considerations for the use of Annular Form Factor Film Capacitors in High Ripple Current Applications, such as AC Electric Motor Drive Inverters", Proceedings of the 2007 Motor & Drives Systems Conference; Dallas, Texas, February 7, 2007.

23. Hosking, T, "Ring Form Factor Film Capacitors for Embedded Motor Controls", Proceedings of the Motor & Drives Systems Conference, Miami, Florida, February 15, 2006.

24. Marlino, L, "Annual Progress Report for Advanced Power Electronics and Electric Machinery Program", US DOE, November 2006.

25. Marlino, L. "Advanced Inverter Technology", HEATCAPS, October 3, 2007, Penn State University

26. Hosking, T, "Ring Form Factor Film Capacitors for Embedded Motor Controls", Proceedings of the Motor & Drives Systems Conference, Miami, Florida, February 15, 2006.

27. Hosking, T, "Ring Form Factor Film Capacitors for Embedded Motor Controls", Proceedings of the Motor & Drives Systems Conference, Miami, Florida, February 15, 2006.

28. Nagashima, James et al, "Cooling Arrangements for Integrated Electronic Motor Inverters", US Patent 7,210,304.