A Research and Development Program to Meet the US Army's Emerging Power and Energy Needs

Robert Hebner

Director, Center for Electromechanics

University of Texas at Austin

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Introduction

Modern warfare is increasingly more electric. Superiority in power and energy provides superiority in communications, situational awareness, low noise propulsion, and offensive and defensive electric weapons. While electricity generation is high quality and has been improving for over a century, the Army's needs are new and challenging. This situation provides a military advantage to the country that masters the suite of technologies the fastest. During the late 20th century, the US military achieved significant advantage over potential adversaries by exploiting Moore's law for advanced semiconductors. The development of new power and energy systems can quite likely confer similar benefit.

Two areas in which the Army needs to differ from the legacy grid are:

1. Electricity is not distributed via a geographically fixed grid.
2. High power and energy density (both mass and volume) are critical.

While commercial grid technology is mature, and there are tools to optimize the performance and versatility of the power systems for aircraft, ships, and forward operating bases, the Army is facing a fundamentally different future. Mobile, multi-domain operation requires a "grid" that is as dynamic as the unit is. There is not sufficient technical understanding to achieve quality dynamic performance, so research is a necessity.

In addition to the novel "grid" architecture, mobility requires power and energy density to be maximized. While there are promising paths through emerging material science, the advances must provide sufficient and predictable life. Yet it is difficult, if not impossible, to extract life information from legacy data in the emerging environment.

However, there is a sporting chance that all of these challenges are surmountable. Success is achievable via a focused program that stimulates technical advances and incorporates the technology into Army-relevant power systems. This approach can maintain US superiority next year and every year until the target date of 2035. The remainder of this paper outlines key attributes of a successful program.

Technical focus of the proposed program

Dynamic Network - The dynamic network consists of soldiers collaborating with wheeled, walking, and aerial platforms as an effective unit. Providing each person or machine with the total energy it might need for a mission is a solution that is too big and too heavy to achieve the required agility. With a seamless way to share energy, the unit versatility is increased. There has been research at the United States Military Academy West Point to develop techniques to quantify the difference between the energy the unit carries and the energy available to complete a mission. The better the unit understands where energy is going both from a mission effective perspective (i.e., energy on target, energy to move, etc.), and from a mission detrimental perspective (i.e., thermal, noise, etc.), the better it can manage these to improve mission effectiveness.

Control of the dynamic network is a major research question. Novel hardware and software are necessary so that energy and communications networks support team success. Success requires sharing energy among the unit members wirelessly, efficiently, and rapidly via an energy management system that recognizes the total energy state of the unit and provides the information to the unit commander to support rapid and effective unit deployment.

Power and Energy Density - Advances in materials science promise continuing increases in power and energy density. However, research and development is needed to transition new materials into robust military systems. First, the advances in materials science need to be augmented by the development of practical quantities of materials that promise higher power and energy density. Then, the materials can be used to assess, both theoretically and experimentally, their impact in power system components (e.g., motors/generators, cables, power electronics, electrical insulation, energy storage, prime power, and thermal management). The final step is to combine these in a model power system of minimum size and weight with adequate life. It is likely that augmenting deterministic or stochastic modeling using relevant advances in machine learning will enhance process effectiveness.

Finally, the Army's use of life models and data can benefit from emerging commercial practice. For example, utilities use life model information to schedule maintenance and replacement of power transformers. But the Army need is broader. The knowledge needed to operate Army power components beyond a factory-determined nameplate rating to a rating based on that system's age and other parameters provides a capability to dynamically trade immediate superiority and long component life.

Motors/Generators - Previous UT research, with American Superconductor and Northrop Grumman, showed that, given the state of the art in materials at the time, permanent magnet motors, and presumably generators, are the most power dense below about 5 MW, with superconductivity becoming interesting above 10 MW. Inductive machines were the second best choice across the range. Therefore, the Army focus should be on permanent magnet machines with some effort to continue to improve induction machines.

Magnax, in Belgium, Yasa, in England, and Emrax in Slovenia are aggressively developing high-speed axial flux machines to achieve high power densities. Composite arbor technology shows promise for power dense machine development. Preliminary assessments show that dual-rotor radial flux machines will outperform the axial flux counterparts. At high rotational speed, the composite arbor machine has a specific power of 9.26 kW/kg with air-cooling. Adding conventional liquid cooling raises the power density to 13 kW/kg.

A second competitive topology is a doubly-fed induction motor. It provides a 4% increase in efficiency and a 40% weight reduction over a conventional induction motor power train, primarily by reducing the power electronics. It is also prudent to keep an inductive motor in the mix because the Navy, NASA, and some oil and gas companies limit the use of permanent magnet motors, because the magnetic field cannot be removed quickly if the stator shorts, and since pulsed currents (e.g., from lightning), can weaken the magnetic field.

Using structural composites reduces motor/generator weight. UT has the modeling and fabrication capability that has achieved the highest strength reported for a rotationally symmetric carbon composite structure. Modifying the model to address robotic fiber placement should permit similar performance in components that are not rotationally symmetric. Moreover, the use of nanoparticles in the composite resin yields even better mechanical performance than the neat resin alone, promising even better performance. Clearly, there is significant competition and effort toward higher power density machines that the Army can tap and accelerate.

Cables - The Army, like automobile manufacturers do with cars, has a problem with cable weight on increasingly electrified platforms. The cables are too big and too heavy. Laboratory data and modeling suggest that the weight can be reduced by about 75%. While there are no commercial cables that have the requisite combination of properties to meet that target, the target appears to be achievable. Thus, the cable plant is ripe for weight reduction.

Nanotechnology is an enabler for this reduction, it promises to improve both the insulation and the conductors in cables. Nanotechnology is relevant, as it shows a heretofore unknown route to increase the electrical breakdown strength, the glass transition temperature, and the thermal conductivity. Additionally, nanostructured materials can increase the conductor's electrical conductivity, reducing heat loss.

Power Electronics - Improvements in system density are being made possible by the emergence of systems incorporating wide band gap semiconductors that use higher frequency, higher voltage, and higher temperature to achieve greater power density. For example, UT is developing high-specific-power power electronics to enable electrified transportation. An important contribution is the development of a 100 kW module that consists of a single-stage soft-switched 3.6 kV ac to 800 V dc converter. To accomplish the objective, a silicon carbide 7.2 kV/60 A switch, the Austin SuperMOS, has been developed. It is a cascode connection of SiC mosfets, and is capable of high speed switching. The switch has demonstrated a turn-off dv/dt of 120 kV/µs during double pulse testing. The Austin SuperMOS (Fig. 1) is an intelligent module with an integrated gate driver and an isolated power supply with 10 kV isolation capability. While this is current state of the art, there is no reason to believe the ultimate power density has been achieved.

Fig. 1: A tested module near the required performance level. Improved thermal management may make 30 kW/kg possible.

Electrical Insulation - Researchers are transitioning emerging insulating materials to practical application in power electronics, cabling, and machines. A challenge is that the enabling benefits of polymeric insulation define the maximum operational temperature. Higher temperature operation would enhance specific power. Therefore, the best material to build on the existing experience base would be polymeric insulation with 200°C+ operating temperatures and enhanced thermal conductivity, which is a focus of global materials research. Commonly used polymers and epoxies have thermal conductivities ranging from 0.1-0.4 W/mK, with a maximum commercial availability approaching ~10 W/mK. Recently, novel materials report thermal conductivities >50 W/mK, with some studies reporting values >100 W/mK. Holistic multifunctional assessments of these materials, which requires optimization of thermal, mechanical and electrical properties, has not been done. Other considerations involved in the development of materials include manufacturability and resistance to harsh environments (e.g., sand, high humidity). Overall, while emerging materials are promising, significant research is necessary for assessing their life in the use environment. If the Army is to benefit from the developed materials, the ability to accurately conduct multi-physics modeling of new materials, to predict lifetime and performance degradation, is of critical importance.

The electrical environment is particularly significant due to the use of wide band gap semiconductors. Fig. 2 shows the partial discharges (red dots) under an inverter waveform (dashed lines). While there is extensive lifetime data under 60 Hz waveforms, approaches to estimating life under these novel waveforms are only now emerging. These pulses can affect the power electronics, cables, motors and generators, as well as the power inputs to the mission systems. Filtering adds size and weight, so life effects must be understood.

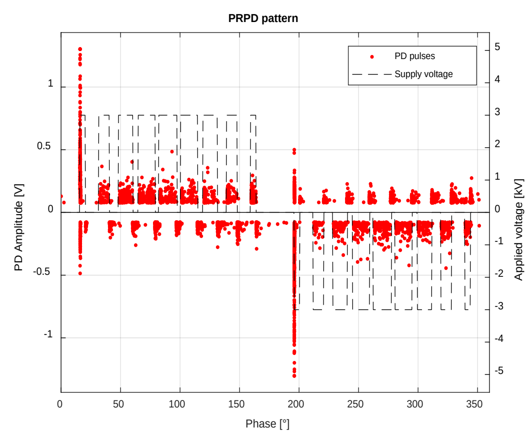

Fig. 2: The red dots are partial discharges for the inverter waveforms shown by the dashed lines. This has a very different influence on system life than the partial discharges that would occur at 60 Hz.

Storage - Energy storage is important to support loads during a loss of power generation, to provide for the difference in load application rate and generator response rate, or to deliver

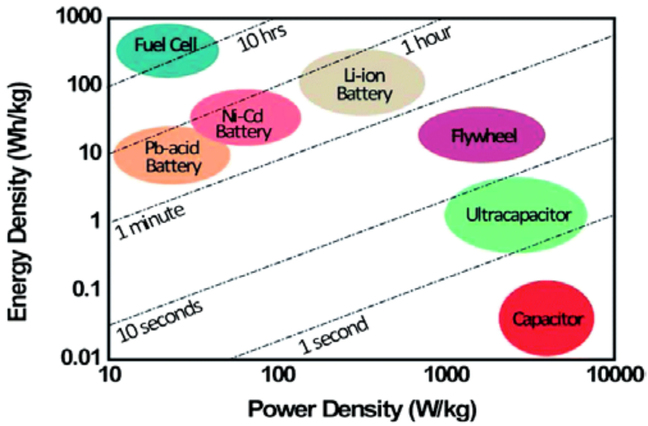

Fig. 3: A conventional Ragone plot for energy storage technologies.

pulsed power in excess of the continuous power rating. In addition to the fuel, today's primary energy storage technologies are ultracapacitors, rotating machines, and batteries. The choice of a storage technology has frequently been justified using one of many published Ragone plots (Fig. 3).

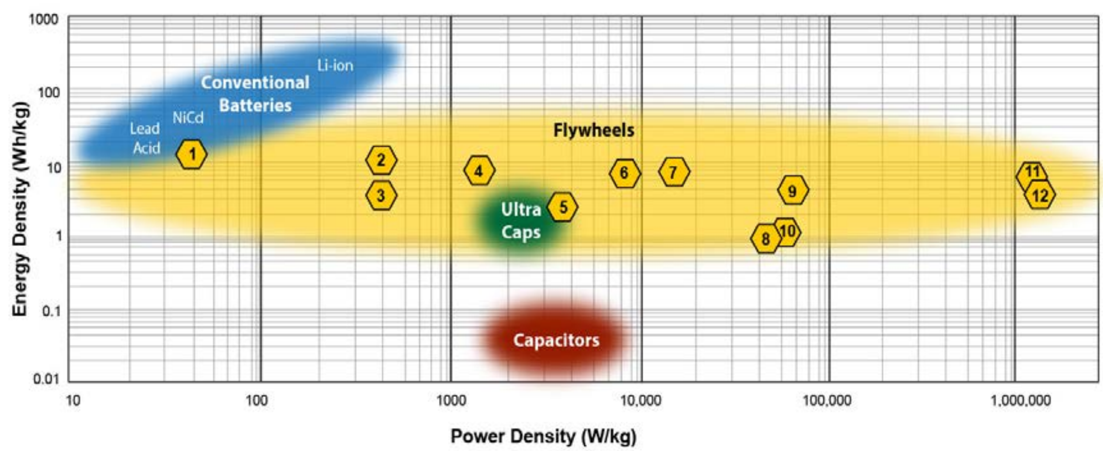

Fig. 4: A Ragone plot with 12 rotating machine systems that have been developed. Thsi shows that the regions of the plot for each technology are notional, not rigorous.

Plots of this type are typically based on the literature the investigator has surveyed, not the fundamental performance that is available. To highlight the significance, Fig. 4 shows the same information, but includes 12 flywheel energy storage systems have been built. This plot is intended to underscore the fact that there is significant density improvement available with more effort on point designs for rather than generic assumption of ranges of applicability. Moreover, nanoparticle additives are promising significant improvements in batteries, flywheels, and capacitors, broadening the range of future choices.

Prime Power - The Army has assumed that batteries and hydrocarbon fuel are the two viable prime power options. On the civilian side, there is a global, largely industry led effort to also use hydrogen fuel-cell augmented battery systems, because battery packs that can provide a drop-in replacement for fuel are too big and heavy. In addition, fuel cells are providing range extension for unmanned aerial vehicles. The Army would benefit from these systems for silent operation and possibly from logistics.

The potential logistics benefit comes from the development of electrolyzers and compressors by the Department of Energy and catalysts by the Army Research Laboratory, permitting the harvesting hydrogen from water. Commercial use today should pave the way for Army use in the future.

Thermal Management - Emerging mission systems will exacerbate the Army's current thermal challenge. The Army generally has air at ambient temperature as the available heat sink. Moreover, access to cooling air is limited by the degree of armor required. The coming challenge is that some mission systems have transient requirements for up to 100x the propulsion power and may well be less than 25% efficient. Consequently, the peak demand for thermal management may increase on some platforms by 400x – 500x. The solution will certainly require new materials and new component cooling approaches. In addition, thermal storage may play a role analogous to electricity storage, i.e., material heated to high temperatures quickly, then cooled over a longer time.

While the problems are daunting, there are a number of promising solutions. First, the high-thermal-conductivity encapsulant materials being developed can significantly aid in local (hot spot mitigation) as well as system-level heat removal. Second, the benefits of liquid cooling (single and two phase flow) need to be studied for Army- specific applications. The research will build on the significant research on liquid cooling techniques over the past two decades for industrial and consumer applications. In particular, additive manufacturing with high thermal conductivity polymers can enable integrated fabrication of required fluid circuits and manifolds as well as functionally graded materials, providing unprecedented cooling opportunities. Third, incorporating heat sinks having liquid flows through channels with phase change materials (PCM) can provide greater ability to manage thermal transients.

In terms of coolants, galinstan (non-toxic liquid metal, alternative to mercury) has 28x thermal conductivity of water, which is terrific for a coolant. However, it has low specific heat, which implies that it needs to flow at high speeds, imposing a pumping power penalty. Extraction of 1.5 kW/cm^2 of heat using galinstan has been demonstrated, but a robust application of the technology requires research.

Machine Learning - Several of the areas described above can benefit from the adoption of machine learning-based modeling approaches. The use of machine learning-based statistical modeling is very attractive for complex, but data-rich systems, as an alternative to physics-based models. Machine learning can potentially assist the above areas in several ways, like the development of novel, lifetime prediction tools, optimized selection of coolants, development of new insulation materials, etc.

Conclusion

Advances in mobile power and energy systems is critical to maintain battlefield superiority. The fastest and least costly path to success is to focus the Army programs in this area, exploit other government and civilian advances, and to focus appropriate university research on to developing the emerging needed capabilities. At the same time, the Army has to be nimble in prudent technology insertion. So, a reliable path to continued superiority is for the Army to support the basic material science and to accelerate adoption of intermediate improvements by funding “valley of death” transitions through a comprehensive program that enhances communication among contributors throughout the process. The proposed approach is summarized in Figure 5.

Traditionally, technical advance has been envisioned as a flow over time from research to testing to insertion. A better approach in a time of rapid change in both technology and threats is a system devoted to maintaining power and energy superiority that incorporates robust feedforward and feedback mechanisms leading to rapid and continuous improvements in capability based on emerging technology.

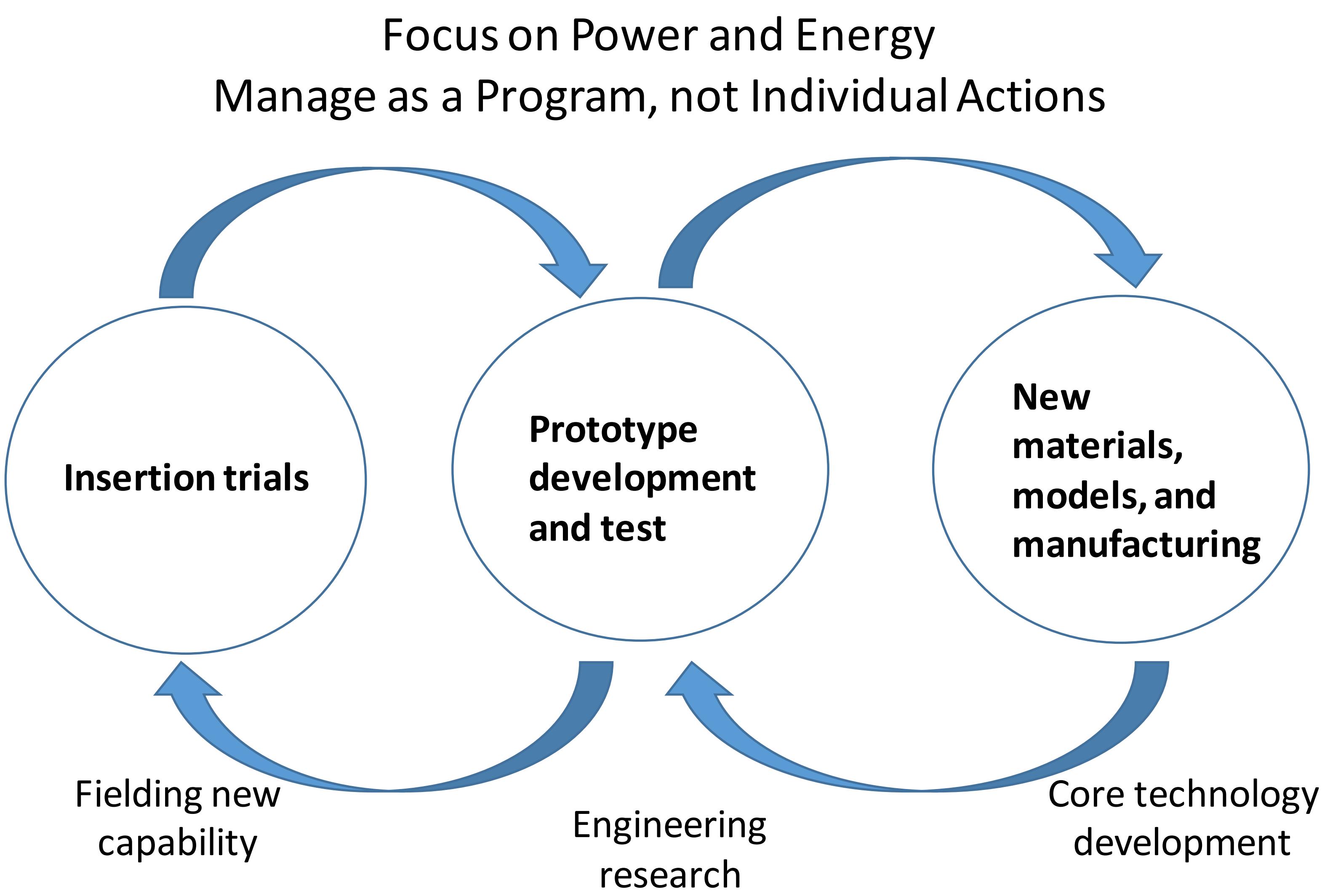

Figure 5 Effective approach to maintaining superiority via emerging technologies in a rapidly changing environment