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The Next Generation Combat Vehicle Electrical Power Architecture (NGCVEPA): An Overview

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ABSTRACT

The demand for electrical power in ground combat vehicles has been consistently increasing over the years. In the years to come, abundant onboard electrical power, along with a modernized power system to manage and distribute it, will enable leap ahead capabilities for the warfighter. A carefully architected electrical power system will also help to improve fuel efficiency while reducing maintenance and logistics burden.

INTRODUCTION

Increasing Demand for Electrical Power

There are many things that have driven the need for increasing electrical power on combat vehicles over the years. It started with the increase in demand for electronics in standard automotive loads and radios. Since then, the ever increasing use of electronics and electromechanical devices in every aspect of combat vehicles continues to grow. Powerful radio transmitters and jammers have become huge consumers of electrical power, as have the computerized devices that support them. Also, as technologies improve for surveillance of the enemy, mission planning, and mission coordination, so does the demand for power that enables those technologies.

Figure 1 shows how the demand for electrical power onboard combat vehicles has increased in recent years and is poised to continue growing in the future. The response to the demand has been to incorporate larger and larger alternators to supply power at $28V_{DC}$. For reasons that will be discussed, this approach is unsustainable and just plain infeasible for some of the electrified capabilities that are being pursued for use in the next generation combat vehicle.

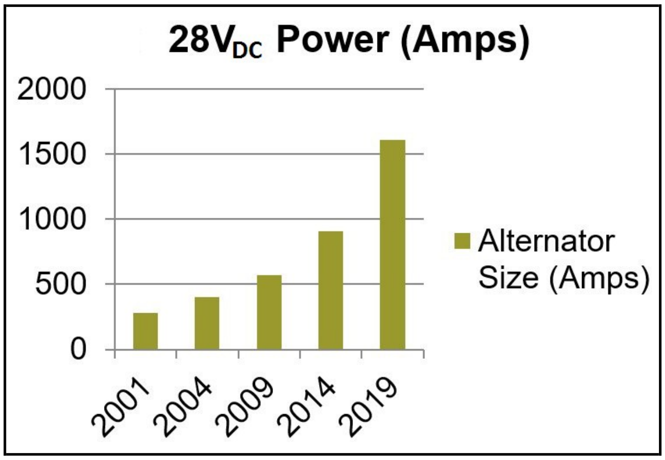

Figure 1: 28VDC Vehicle Power Demand

Electrification of Existing Capabilities

As the Army continues to look to increase the capabilities of its combat vehicles, it is becoming necessary to do much more in the limited space under the armor of those vehicles. The best way to increase available space under armor is by modernizing legacy power-consuming hardware with more efficient, electrified systems. These electrified systems will not only use less power, but will generate less heat because of their high efficiency. This, in turn, reduces the overall vehicle cooling burden, which further reduces both the size of cooling system components and overall power consumption.

Some obvious targets for modernization are the large consumers of power that are traditionally driven by hydraulic systems. These include cooling fans, turret drives, and vehicle height management systems. Not only are these hydraulic systems inefficient, they are difficult to maintain as they leak, requiring significant additional logistics to supply hydraulic oil and spill containment material. Electrical systems eliminate those logistical burdens.

Other targets for electrification include automotive loads typically driven off the engine accessory drive, like power steering, air-conditioning compressors, air and coolant pumps. The largest benefit from electrifying these loads is having the ability to vary the power they consume as needed and independent of the engine speed, including the ability to run the loads while the engine is not running. It is not possible to do this efficiently in traditional systems where input shafts are mechanically coupled to the engine drive shaft.

New Electrified Capabilities

In addition to reducing the size of current systems and increasing their efficiency, vehicle electrification also make exciting new capabilities feasible. A number of lethal and non-lethal weapons that use kinetic and directed energy in large quantities promise to make the next generation combat vehicles an effective force. Abundant electrical power will also enable the use of various active and passive electrified defense systems. Power management algorithms will increase fuel economy by reducing the amount of time a vehicle idles its engine, while simultaneously improving vehicle acceleration by maximizing the amount of engine power allocated to tractive effort during a vehicle dash event.

ARCHITECTURE OVERVIEW

To create an electrical power system architecture able to meet the needs of the disparate combat vehicles in the Army's fleet, as well as the next generation combat vehicle and all its possible variants, VEA created an overarching set of requirements from the Abrams, AMPV, Bradley, GCV, and Stryker vehicles. Being able to meet the most difficult requirements from all five vehicles was the objective. This meant making provisions for a vast amount of electrical power generation. In order to manage that power, a networked controller would be needed to coordinate the operation of the various components that convert and distribute that power, making it useable by all electrified loads. While the ability to handle considerable amounts of power is important, it was also important to recognize that the power demands of some vehicles are a fraction of the most difficult case. In order to be relevant for all vehicles, the architecture would need to be flexible and scalable.

Abundant, Dense, Efficient Power

The principles behind improving power density involve the application of a couple simple laws of physics.

$$P = IV \qquad \text{[Watt's Law]}$$

$$V = IR \qquad \text{[Ohm's Law]}$$

...from which can be derived:

$$P = I^2R \qquad \text{[Power Loss]}$$

In most cases, this latter equation represents the largest portion of electrical power (P) that is lost to inefficiency. Reducing either the current (I) or the resistance (R) will decrease power losses, but clearly, reducing the squared term, current, will have the most dramatic affect. If we reduce current, Watt's Law tells us that voltage (V) must be increased proportionally to produce the same amount of power. These basic rules of physics led to the development of a power system that uses high voltage to reduce power losses. Power savings are proportional to the amount of power consumed, so high power devices are placed on the high voltage bus to capitalize on the benefits of high voltage, while low power and legacy devices reside on the $28V_{DC}$ bus.

Wide Bandgap (WBG) Semiconductors

Modern power systems rely on solid state components and closed loop control to provide better performance, improved reliability, and increased efficiency. From this, it is clear that solid state components that reduce conduction losses and perform well at elevated voltages offer a clear advantage for reducing power losses.

Reduced conduction losses and elevated voltage operation are only two characteristics that WBG semiconductors provide when compared to their silicon (Si) counterparts. WBG semiconductors also provide other benefits that make them more attractive for use in solid state power electronics. For one, they are able to operate at elevated temperatures, which allows any heat that they produce to transfer more readily to their cooling medium, per Newton's Law of Cooling. They also switch between their on and off state more quickly than Si. This switching period is inherently a source of losses for all semiconductors. Faster switching means that WBG semiconductors spend a fraction of the time in this transitional state for each control cycle, increasing efficiency and reducing losses.

The two WBG materials recently introduced for power applications at significant levels are Silicon Carbide (SiC) and Gallium Nitride (GaN). Both perform better than Si in various ways, but they both have their own strengths in comparison to each other. The two most significant benefits of SiC are better voltage blocking ability and much better thermal conduction, which makes cooling it easier. It is also able to switch much faster than Si. Excellent voltage blocking makes SiC attractive for high power, high voltage applications.

GaN, while not as good at thermal conduction and voltage blocking, outperforms SiC in the areas of conductivity and switching speed. These characteristics make GaN attractive for low voltage applications that benefit from high frequency switching.

WBG in Switching Power Converters

Taking advantage of high voltage to increase electrical power levels on combat vehicles requires an effective way of converting power to voltage levels that are usable by the soldiers and their mission equipment. Switching power converters are the most effective way to do that.

As the name implies, these devices rely on high frequency switching to do their job. In addition to the advantages already stated, WBG semiconductors' ability to switch quickly can further be exploited to reduce the size of the inductors and transformers these devices use, since frequency of operation is a key limiting design criteria when selecting these components. The same holds true for components selected to reduce the electromagnetic interference (EMI) of a device. The benefits of WBG semiconductors combine to result in power conversion devices with dramatically improved performance and efficiency with reduced size.

WBG in Motor and Generator Control

High voltage synchronous machines have become the devices of choice for converting rotational power to and from electrical power in commercial, industrial, and military applications. Conduction losses, represented by the power loss equation, factor heavily into the choice to operate these machines at high voltage levels. In order to take advantage of their improved performance, precise control of the machine is required. This is done with power electronic devices designed specifically for this task. Similar to switching power converters, the controllers used to transfer power to and from these machines rely on switching power at high frequency. The high voltage nature of these controllers makes SiC the semiconductor of choice. SiC provides the same advantages, reduced conduction losses and improved high temperature operation, for these controllers as it does for switching power converters. These controllers do not rely on inductors and transformers, so high frequency operation cannot be exploited to the same extent it is in power converters; however, lower switching losses do further improve efficiency.

WBG in Power Distribution

Another advantage of high voltage is that a given amount of power can be distributed using much smaller, lighter wire. Again, this is achievable due to Watt's Law. Since the voltage is increased over 20 times, the amount of current is reduced by the same amount. That means that the conductors can have roughly 1/20th the cross sectional area. This is demonstrated in Figure 2, which shows two wires that are both sized to distribute 12kW of power. At 28V_{DC}, a 500MCM wire is required, but only a 12AWG wire is needed at 600V_{DC}.

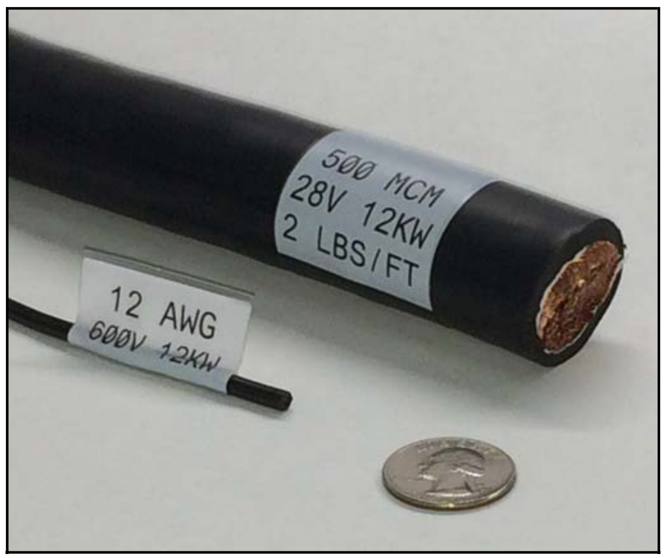

Figure 2: 28V_{DC} Wire vs. 600V_{DC} Wire

However, distributing electrical power at elevated voltages requires precautions so power remains controlled and isolated to ensure reliability and safety. This requires constant monitoring of both isolation and over-current conditions, as well as response speed adequate to mitigate the impact of both.

To address isolation, the high voltage system requirements chosen for use in NGCVEPA call for isolation from vehicle ground through a high resistance network (MIL-PRF-GCS600A, Section 3.4). Any change in isolation will be detected and reported in software so appropriate actions can be taken to ensure safety.

Over-current conditions call for response times that vary with severity. The more the current exceeds the current rating of the supply cables, the faster the response needs to be. At lower levels of over-current, cable heating is relatively slow and the maximum temperature rating of the cable insulator is the limiting factor. "Slow over-current" conditions occur over periods long enough to allow software to determine when to remove power to prevent cable failure. Extreme over-current conditions are indicative of short circuit conditions where the hazards are arcing and molten metal. These "fast over-current" conditions require response times much faster than are possible with software. Detection and response must take place in hardware to be effective. This is also where the fast switching speed and high voltage blocking ability of SiC provides a response time that is not possible using Si. Of course, SiC also provides the added benefits of low conduction losses and high temperature operation that Si cannot match.

Vehicle Power Management

Integrating various components that generate, convert, and distribute electrical power requires coordination. The dynamic conditions in which a combat vehicle operates calls for quick responses to changing conditions and power demand. This is accomplished in the NGCVEPA by a networked supervisory controller called the Vehicle Power Management Controller (VPMC).

The primary job of the VPMC is to manage the electrical power budget of the vehicle. It keeps track of available power and power demand and uses that information to make decisions to ensure power supplied to various loads remains within specified standards. In calculating the power budget, the VPMC takes into account all available sources of electrical power, including the vehicle main generator, batteries, and any auxiliary power units (APU), as well as other off-board sources. The VPMC also takes into account all electrical power being consumed or requested by vehicle systems and the crew.

The VPMC does not directly control the power generated from sources. Rather, it communicates with the sources to determine the amount of power that each is able to provide and directs that power based on which source can most efficiently meet the changing needs of the vehicle and its crew. For example, during a hard acceleration event, the VPMC would respond to the demand for more tractive effort by reducing the power output from the main generator and allowing the batteries to pick up as much of the load as they are able, which is a capability that we call a Dash Event.

Power allocation to high power, variable loads works in a similar fashion. The VPMC does not directly control these loads. Rather, it communicates with the loads to determine both the minimum amount of power needed to provide acceptable performance and the maximum amount of power the load could use to provide peak performance. The VPMC then uses the power budget to allocate the appropriate amount of power for the conditions of operation. Using the same example of supplementing power for mobility, the load on the main generator can be temporarily reduced by reducing power allocated to vehicle and crew cooling. The relatively slow thermal change and tolerances of such systems allows for a significant amount of cooling power to be temporarily diverted without significant impact to the overall performance of those systems.

The ability of the VPMC to decide both which source provides power at a given time, as well as how much of that power is used by a load, means that it can make decisions that have the potential to significantly reduce fuel consumption. Combat vehicles can spend a significant amount of time stationary while on a mission. Standard operating procedure is to keep the main engine idling to provide electrical mission power. In an NGCVEPA equipped vehicle, the VPMC can automatically detect that power for tractive effort is not required and make the decision to conserve fuel by turning off the engine and operating off batteries or an off-board power source, if present. Studies have shown that this can provide an estimated 10% to 20% fuel savings on a typical mission.

In extreme cases, the VPMC can also decide to remove power from noncritical loads to maintain power to vehicle functions crucial to the mission. This is a behavior known as load shedding.

Other critical functions the VPMC provides are managing vehicle power up, coordinating vehicle power down, and performing configuration management for the complete power system. Management of the power system and all its parts requires the VPMC to detect and, in most cases, communicate with the various components. This requires the VPMC to store information about all those devices so that it can apply/remove power to/from them in a sequence that both allows them to behave correctly and minimizes the time it takes for the vehicle to power up.

One of the most important features of the VPMC is that it is not a specific piece of hardware. The VPMC can be any networked computer or microcontroller that complies with the performance and interface capabilities defined by its NGCVEPA hardware specification. Those capabilities include a software interface with a Hardware Abstraction Layer (HAL), a network message set, and an electrical interface, all clearly defined in a standard that will be made publicly available to industry. This framework allows vehicle-specific power management algorithms to be developed independently and ported onto any VPMC-compliant hardware. This also gives those that know the vehicles best, the OEMs, the ability to determine the power system optimal behavior using a combination of deep-rooted knowledge, algorithm testing on vehicle emulators, and/or modeling and simulation. Validation of algorithms through modeling and simulation is just a step away from auto code generation and hardware-in-the-loop (HIL) power system development.

Flexible Power Electronic Hardware

Making effective use of the VPMC's capability requires that the hardware it controls be flexible, both in how it is applied to a vehicle power system and in how it behaves in its assigned role. Much of that flexibility is provided through well-defined message sets for power sources and converters. These power providing devices need to be able to share their role with other power devices. This requires them to be able to send, receive and understand various messages to and from the VPMC, which coordinates that behavior.

In NGCVEPA, potential power sources include any or all of the following:

- Main vehicle generator controlled by the Integrated Starter/Generator Controller (ISGC)
- Off-board power supplied by another NGCVEPA-equipped vehicle
- Imported AC power from a power grid or external generator controlled by the Import/Export Power Converter (IEPC)
- Onboard electrical energy storage
- Various auxiliary onboard power generators, generally referred to as APUs

There are also power converting devices that provide the function of converting the power from one source to a form usable by the loads. These converters include:

- Bi-Directional Converter (BDC) for converting between $28V_{DC}$ and $600V_{DC}$
- Bus Isolating Unit (BIU) for isolating and converting between different $28V_{DC}$ devices
- Universal High Voltage Converter (UHVC) for isolating and converting between different devices that operate at elevated DC voltages

NGCVEPA's ability to accommodate this broad assortment of power hardware gives vehicle integrators maximum flexibility for deciding the optimal power system arrangement that is suited to the vehicle's mission profile.

Scalability and Expandability

In order to be relevant to all combat vehicles and many tactical vehicles, NGCVEPA was designed to meet the most demanding power needs, yet be able to be sized for vehicles with a more modest demand for electrical power. The technology in all the power system devices is scalable to any power level required by military ground vehicles. These pieces of NGCVEPA hardware were specifically designed to be used as building blocks for supplying power of the different vehicle needs, including:

- BDC, 15kW converter (See Figure 3)
- BIU, 250A converter
- UHVC, 50A converter

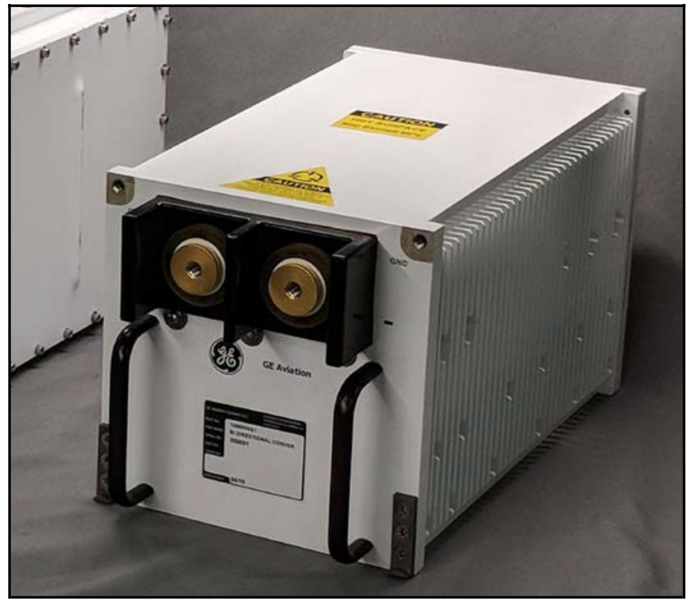

Figure 3: Bi-Directional Converter (BDC)

Each of these devices has the ability to work in parallel with other like devices. By selecting the appropriate number of devices, a vehicle integrator can choose the optimal configuration to meet the power demands of their vehicle.

These devices are designed to be platform-agnostic by utilizing a flexible network command structure that allows them to be used and interchanged between any NGCVEPA vehicle due to an absence of unique, vehicle-specific configuration parameters.

One challenge for vehicle integrators is accommodating a variable number of electrical loads that depend on the vehicle specific mission profile and load configuration. NGCVEPA power distribution building blocks that serve that purpose include:

- Low Voltage Power Controller (LVPC), 270A power distribution device (see Figure 4)
- High Voltage Power Controller (HVPC), 350A power distribution device (see Figure 5)

The LVPC has 24 – 20 Amp channels and the HVPC has 12 channels varying in current handling capability from 10 Amps to 350 Amps.

The circuit protected outputs of both devices can be configured for the loads they are servicing, including being used in parallel to accommodate larger loads.

Both the LVPC and the HVPC have unique behavior specific to the loads that they are connected to, so they have each been designed with the ability to automatically receive the correct configuration based on their physical location in the vehicle. Their physical location is determined through an identifier associated with their physical network connection.

Figure 4: LVPC with and without Connector

Adding and removing $28V_{DC}$ loads to or from a vehicle occurs regularly, so special attention was taken in the design of the LVPC to accommodate these changes. The connector, shown in Figure 4, is designed to allow easy connection and removal of individual power cables, while providing maximum current density.

DELIVERED HARDWARE

To date, TARDEC VEA has received and tested four devices that contribute to NGCVEPA. Each has been tested to TRL 5 and is targeted for further development and integration into a vehicle, moving them to TRL 6.

High Voltage Power Controller (HVPC)

The HVPC, shown in Figure 5, functions as the primary $600V_{DC}$ distribution device in NGCVEPA, and it incorporates a number of features that make the system both versatile and safe. It provides an interface that allows the VPMC to apply and remove $600V_{DC}$ power to and from high power devices as needed by the vehicle or its crew. The HVPC takes advantage of SiC to effectively and efficiently perform its job.

Figure 5: High Voltage Power Controller

Turning on $600V_{DC}$ power requires that it be applied gradually to prevent a large inrush of current from damaging components in the loads. The HVPC showed its ability to do that, as shown by the purple trace in Figure 6. The controlled pre-charge of the circuit also allows the HVPC to monitor behavior as power is applied and halt pre-charge if it detects an unsafe condition.

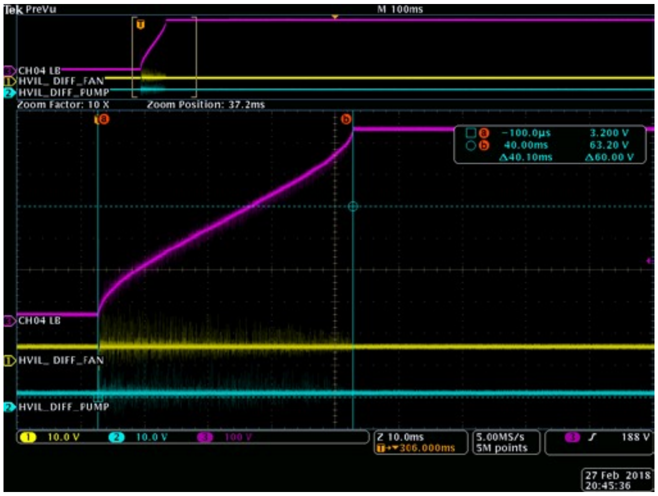

Figure 6: HVPC Precharge

One of the unsafe conditions the HVPC is responsible for detecting is a Ground Isolation Fault (GIF). Normally, the $600V_{DC}$ system is electrically isolated from the vehicle chassis, and it is the HVPC's job to detect when there is any failure of that isolation. If the HVPC detects this condition while pre-charging a load, it will halt pre-charge. If the HVPC detects this condition when $600V_{DC}$ has already been applied, it sends a status message to the VPMC so that it can make a determination about safe operation and act accordingly.

Another safety feature the HVPC provides is the ability to sense over-current conditions on each of its channels. Based on how much the current exceeds the trip setting, the HVPC can reliably respond in as fast as 300 microseconds. This greatly reduces hazards associated with electrical arcing.

Finally, for an extra level of safety, the HVPC accommodates an interlock circuit for each of its channels. Interlocks provide a way to detect when a power cable is disconnected or damaged. The HVPC treats an interlock interrupt as quickly as it does the fast over-current condition, within 300 microseconds.

Low Voltage Power Controller (LVPC)

The LVPC performs some of the same functions for $28V_{DC}$ power that the HVPC does for $600V_{DC}$ power. The LVPC provides the ability to turn loads on and off, and it provides protection from both fast and slow over-current; however, it is less complex because it does not require the safety features necessary when dealing with $600V_{DC}$. The area of greatest improvement for the LVPC over legacy hardware is current density. The thermal design, the rack-mount approach, and the rectangular electrical connector are the LVPC's most innovative features. These features, combined with efficiency improvements, make the LVPC six times more current dense than the legacy devices it replaces, as shown in Figure 7. The LVPC currently uses Si semiconductors to control power to loads, but future LVPC efforts will make use of GaN to further improve current density.

Figure 7: Functionally Equivalent - 2 Legacy Devices vs 1 LVPC

Power Electronics Cooling Pump (PECP) and Main Cooling Fan/Controller (MCFC)

WBG semiconductors have applications beyond power conversion and distribution. High efficiency, high reliability brushless DC motor applications require switching devices to control their mechanical output. These applications are well aligned with the strong points of SiC semiconductors. To demonstrate these benefits in high power servo-type applications, VEA contracted development for a $600V_{DC}$ pump and a $600V_{DC}$ fan, each with an integrated motor controller and each suitable for use in a ground combat vehicle.

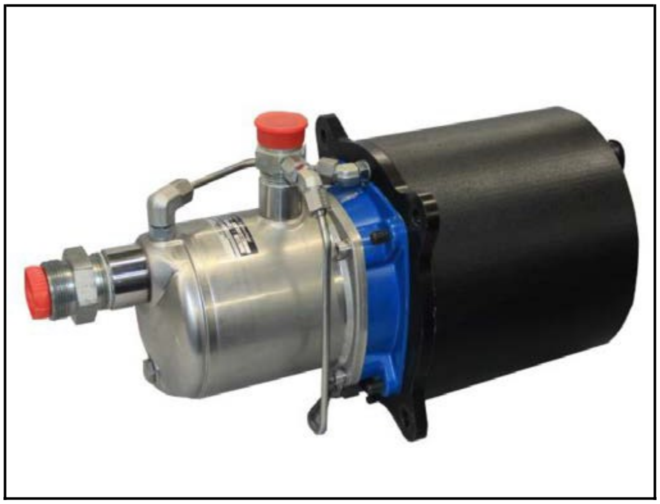

Figure 8: Power Electronics Cooling Pump

The PECP, shown in Figure 8, is powered by a $600V_{DC}$, 2kW motor and is capable of a 24gpm flow rate at pressures up to 42psi. The pump and its controller are cooled by the 105°C coolant that the pump circulates for cooling other devices. The pump is currently used on a regular basis in the VEA lab to cool NGCVEPA hardware.

Figure 9: Main Cooling Fan Controller

The MCFC, shown in Figure 9, uses a 35kW motor to provide sufficient airflow to cool the main engine, air-conditioning, and accessories of a Stryker vehicle. The fan motor and its controller are both air-cooled directly by the same air that the fan moves. The fan has demonstrated full capability in a lab setting and is being run in the VEA lab on a regular basis for test and demonstration purposes.

HARDWARE UNDER DEVELOPMENT

To round out the full system necessary to demonstrate the capabilities of NGCVEPA, VEA is managing efforts for several additional pieces of hardware.

Vehicle Power Management Controller (VPMC)

The VPMC is not a specific piece of hardware. Instead, it represents a set of functionality that may be provided by any typical microcontroller device. In order to demonstrate the ability to apply VEA's VPMC performance specification to any typical microcontroller, we are working with a contractor to develop a device that is compliant. Once the specification is complete, VEA will work to develop a second compliant VPMC, which will demonstrate the ability to port the control algorithms between different controllers from different companies. In addition to promoting competition for this piece of hardware, this will demonstrate the ability to port software to new controllers as hardware becomes obsolete.

Integrated Starter / Generator Controller (ISGC)

The ISGC, shown in Figure 10, is scheduled to be delivered in late 2018. Largely because of its use of SiC, it will demonstrate unprecedented power density. In addition to converting as much as 200kW of power from a permanent magnet machine into $600V_{DC}$, it will provide an abundance of torque to that same machine for a fast, reliable engine start in just about any condition.

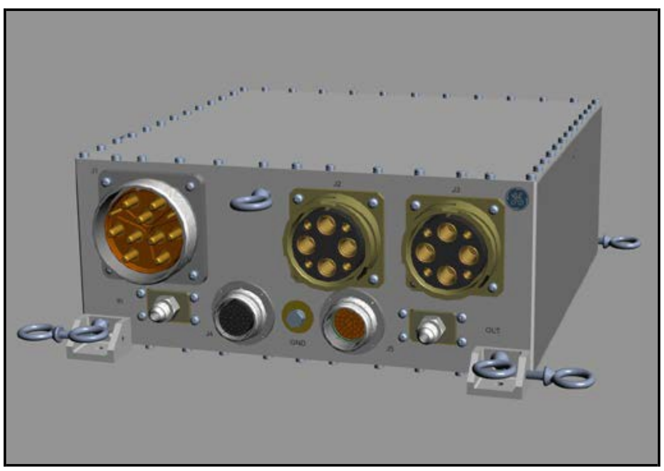

Figure 10: Integrated Starter/Generator Controller

Bi-Directional Converter (BDC)

The BDC, shown in Figure 3, was nearing the end of development at the time this paper was written. The successful completion of the BDC effort will bring to NGCVEPA the ability to convert $600V_{DC}$ power produced by the ISGC to $28V_{DC}$. This allows it to be used to charge batteries and power all legacy vehicle loads. The BDC will be able to do this in parallel with up to two other BDCs. It will also be able to convert power from $28V_{DC}$ batteries to $600V_{DC}$ for starting the main engine or powering $600V_{DC}$ loads, including when the engine is not running. Another function of the BDC will be to dynamically supplement the 600VDC system to improve its overall stability through load transients and surges.

Import/Export Power Converter (IEPC)

The IEPC is not yet on contract, but once developed, it will provide the ability to bi-directionally transfer power between the NGCVEPA $600V_{DC}$ system and various types of utility power. It will import and export up to either 10kW of $120V_{AC}$ power, 20kW of $240V_{AC}$ power, or 30kW of $208V_{AC}$ 3-phase power. The IEPC will take advantage of WBG semiconductors to provide this power conversion in an extremely dense, efficient package. By providing this capability, the IEPC will provide vehicles with the same capability as tactical generators with higher reliability and efficiency, potentially making stand-alone tactical generators obsolete.

Bus Isolating Unit (BIU)

VEA is expecting to take delivery of the first BIU prototype by the end of 2019. The BIU will provide a function never implemented before on ground combat vehicles. It will replace and provide capability beyond diodes and relays currently used to connect $28V_{DC}$ systems within a vehicle. It will use WBG semiconductors and buck-boost technologies to move power bi-directionally between two $28V_{DC}$ buses, protecting power quality of one or both of the buses, preventing one from adversely affecting the other.

Universal High Voltage Converter (UHVC)

The UHVC will do the same job as the BIU, but on high voltage systems. Typical applications for the UHVC will allow far more interoperability between NGCVEPA vehicles and other high voltage components, like directed energy weapons and high voltage batteries.

NEXT STEPS

- Updating hardware specifications and publishing them to make them available to industry to help spur competition.
- Integrating delivered hardware into the VEA Mobile Demonstrator (VMD) on a Stryker ECP vehicle with a Caterpillar C7 engine.

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