2016 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 2-4, 2016 - NOVI, MICHIGAN

TACTICAL VEHICLE TO GRID AND VEHICLE TO VEHICLE DEMONSTRATION

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ABSTRACT

The roll-up roll-away Tactical Vehicle-to-Grid / Vehicle-to-Vehicle (V2G/V2V) system provides a plug-and-play, very fast forming, smart, aggregated, and efficient power solution for an emerging (including austere) contingency base that is ready to generate up to 240kW of 208 VAC 3-phase power in less than 20 minutes. The system is designed to provide grid services (peak shaving, Volt/VAR control, power regulation, and current source mode) beneficial to emerging and mature grids (CONUS or OCONUS). The system uses vehicle Transmission-Integrated Generators (TIGs) to produce 600VDC power for use by vehicle hotel-loads (electrification) and off-board loads (tents/shelters, communications centers, or other electrical loads). Each vehicle is equipped with a Vehicle Communication Module (VCM), which provided the communication capability prior to initiation of transfer of up to 100kW of power via the J1772 SAE Combo Connector between vehicles (V2V) and/or for export power off-vehicle (V2G). This effort involves four tactical vehicles; two M1152 HMMWVs equipped with 30kW of On-Board Vehicle Power (OBVP) and two MaxxPro Dash MRAPs equipped with a 120kW 3000 Transmission-Integrated Generators (3TIGs) with V2G and V2V capability, four 60kW DC-to-three-phase (3Ø) AC power converters with 600 VDC bus distribution systems and four 22.8 kWh Energy Storage Systems (ESU). This multi-vehicle based power system utilizes variable engine speeds for efficient power generation. The demonstration project included the sub-system development, communications systems development, system integration, testing, and demonstration. The system supports host-grid connectivity to reduce deployed fuel consumption for power generation by 20 percent. This can come through operation of the engines at their optimum speed based on the engine map, along with proper management of the generation and energy storage resources. In addition, one or more generation sources can be completely turned off (i.e. engine off condition) when possible depending on the load demand, thus resulting in fuel economy improvement. The system capability was first demonstrated at TARDEC and then with the Warfighter at Fort Devens, Sustainability Logistics Basing (SLB) Science and Technology Objective Demonstration (STO/D), in FY16. The paper includes test data and results collected during the; System Validation Test at TARDEC, APG Safety Release, Demonstration at Fort Devens. In addition, the paper includes test results of sub-system and some results from modeling and simulation (M&S) of the system. M&S will involve relevant logic for deciding which VCM module acquires the status of a Master Controller, and will also include droop control of the generation sources and integration of the energy storage sources (ESU), i.e. the batteries, so that proper grid voltage level can be maintained within limited boundaries.

INTRODUCTION

The goal of the V2G/V2V effort is to demonstrate the capability to assemble a vehicle based power supply for austere contingency bases. This demonstration achieves this by providing 240 kW of 120/208 three phase VAC power in less than 20 minutes while achieving an estimated 20% fuel savings over conventional methods. This project implements operational energy improvements on the move and when at a base by aggregating multiple vehicles into the grid. Currently there are multiple operational energy gaps identified by the Department of Defense (DoD). Vehicles that are not on a mission can use the onboard vehicle power systems to reduce the fuel consumption for generating power at the contingency bases - currently more than 50% of the Army fuel consumption supports power generation. Data shows that intelligent power distribution and management systems that aggregate power generation sources and manage prioritized loads reduce fuel consumption by more than 20%. Data shows that vehicles are not on missions 95% of the time; the demonstration will show that the vehicle's capability can be utilized when not performing on any missions. Vehicles with V2G capability can intelligently and securely contribute to the FOB's power grid and reduce fuel demand through use of the stored energy on the vehicles.

OVERALL SYSTEM

The system uses vehicle 3000 Transmission-Integrated Generators (3TIGs) to produce 600VDC power for use by vehicle hotel-loads (electrification) and off-board loads (tents/shelters, communications centers, or other electrical loads). This effort involves four tactical vehicles; two HMMWVS equipped with 30kW of On-Board Vehicle Power (OBVP) and two MRAPS equipped with a 125kW 3000 Transmission-Integrated Generators (3TIGs) with V2G and V2V capability, four 60kW AC to DC power converters with 600 VDC bus distribution systems and four 22.8 kWh Energy Storage Systems (ESU). Each vehicle is equipped with a Vehicle Communication Module (VCM), which provides the communication capability to transfer up to 100kW of power via the SAE J1772 Combo Connector between vehicles (V2V) and/or for export power off-vehicle (V2G).

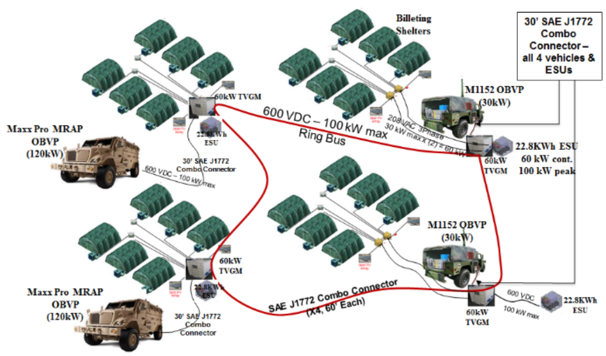

Figure 1: System Diagram

VEHICLE DESCRIPTION

DRS Technologies provided two OBVP-equipped MRAPs (80kW-capable, equipped with 125kW) and two OBVP-equipped HMMWVs (30kW-capable). The 3200MSG OBVP system in the MRAP, Figure 2, is a product of DRS and Allison Transmission Inc. It consists of an Allison 3200SP transmission with an integral 125kW Permanent Magnet Machine (PMM) built by DRS. A power electronics assembly, the Generator Controller Bus Regulator (GCBR), uses a switching regulator to manage the PMM and to generate the highly regulated 600 VDC bus used as the microgrid power source. Previous TARDEC testing of this OBVP system showed the average efficiency to be 93%.

Figure 2: MaxxPro MRAP Equipped with DRS/ATI 3200MSG 125kW OBVP System

The HMMWV OBVP system is a product of DRS; 30kW PMM mounted between the engine and transmission in a sandwich configuration, DRS PMM control and regulation electronics and a 30kW 208 VAC inverter. DRS removed the inverter for this project and replaced it with a 400VDC – 600VDC converter to bring it to the same bus voltage as the MRAPs and compliant with MIL-PRF-GCS600A.

Figure 3: M1152 HMMWV Equipped with DRS 30kW OBVP System

All vehicles were modified for remote start – stop. The remote start is triggered from CAN (standard J1939) commands from each vehicle's VCM when the voltage droop is detected on the 600V bus. Remote-starting occurs when electrical load demands exceed power generating capacity of the vehicles currently supplying power at the time the load excess occurs. This keeps the overall system operating at optimal (peak) efficiency.

The HMMWVs were further updated with a TARDEC – supplied throttle actuator control (described below) that allows the remote start-stop control network to use the vehicle throttle to vary the amount of power supplied to the microgrid. This function was implemented on the MRAPs by the use of CAN bus commands to the vehicle engine control module (ECM) that cause the idle speed to transition between pre-defined steps.

Throttle Actuator Control

The system uses a stepper motor driven by an H-bridge circuit. The system responds with a position sensor and the logic controls the mechanical linkage from the fully closed position to the fully open position. The stepper motor is also available to control the position using CAN messages, which are included below but for the purpose of this demonstration the H-bridge was used.

Software Controls

The software reads the following parameters to control the vehicle to the desired position:

- Engine Speed (Picked up off the transmission speed sensor)
- Stepper Motor Position (Fully extended = 0% Throttle and Fully Closed = 100% Throttle)
- Requested Engine Speed (Generator Controller Desired Engine Speed)

Using these variables the logic will arbitrate on how it commands the desired stepper motor position.

Drivers Stepper Motor Position

The logic was designed to override the drivers throttle position for testing purposes and for test cell uses. This allows the greatest flexibility with testing and usage cases. The logic using calibrations allows the user to request throttle via CAN (Test cell case), INCA (calibration), and throttle hardware. Once the source is determined, the logic will convert the desired throttle position to a desired stepper motor position using a calibration table. The speed request logic from CAN will need to be updated with enable conditions to verify the request, the vehicle is stationary, and the vehicle transmission is in park or neutral position. These details can be quickly added in the future based on available CAN messages.

Stepper Motor Commanded Position Controls

Based on the drivers and speed requested stepper motor positions the logic will control to the largest position. The logic uses the H Bridge circuit and the position feedback to control the stepper motor to the correct position changing the magnitude of the request based on the position error. This allows for optimal controls and limits overshoot. As seen in Figure 4, a step request from the throttle (red) results in a response time around 0.6 seconds from 0 to 100% and back to 0% from 100% (grey).

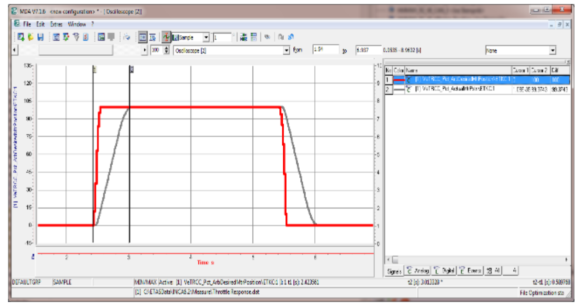

Figure 4

Stepper Motor Commanded Diagnostics

The control logic has a secondary circuit to drive the stepper motor back to the idle (0%) position in case the absolute error in the commanded position is greater than a diagnostic delta for a calibrate-able period of time. In the case the motor does not return to idle (i.e. blown fuse), the logic sets a fault and changes the settings on the relays to switch to a low side driver circuit allowing power to close the throttle. Once the low side driver is connected it commands a constant PWM to drive the throttle back to the closed position.

VIRTUAL IMPEDENCE EXTENSION

The microgrid presented the problem of how to connect multiple low-impedance DC sources to a common bus while avoiding the danger of large circulating currents between sources. Since the sources were to be separated by large distances (about 60 feet in the case of vehicles), only locally-measured voltages and currents could be used to control the sources and implement a degree of load sharing. In order to allow parallel operation using only locally measured voltage and current, these vehicles included modified power conversion electronics to provide droop control of the output voltage based upon local load current. This control scheme effectively inserted an impedance in series with each voltage source in the system; not a physical resistance (which would waste power), but a “virtual resistance” which caused the output voltage to “droop” as load current increased. This modification to existing generator controls was internally referred to as the Virtual Impedance Extension (VIXN). Due to differences in the design of the power electronics for the two vehicle types (MRAP & HMMWV), the implementations were different in each case. The droop voltage delta; the change in setpoint voltage from no load to full load for all sources was 40V. The droop voltage delta was established through consideration of a reasonable setpoint range for the vehicle sources and test results from the power conversion electronics used in the ESUs. Using this number and either rated current or power information for each source (including power capability variation versus engine speed), virtual impedances were calculated to implement droop control. By “standardizing” the droop voltage delta (ΔV) across the system sources, load sharing proportional to output power capability in the steady-state sense was achieved.

From the systems perspective, the VIXN modification represented a supervisory local control loop that adjusted the setpoint of each source based on load:

$$V_0 = V_{ref} - I_{out} R_d$$

That is, the no-load setpoint (V_0) was reduced by a value proportional to the load current (I_{out}), with virtual impedance (R_d) determining the amount of droop per unit current. At rated current (determined by maximum current or current at maximum power depending upon the source), the agreed-upon droop voltage was reached. The value of the virtual impedance was a function of engine speed, since power output capability (and therefore rated current) of the sources was also dependent on the torque/speed curve of the engine. For a given rated current:

$$R_d = \Delta V / I_{rated}$$

Typical values of R_d for individual sources in this demonstration system were on the order of 300 to 800 milliohms, with the larger value for the lower-power sources; four vehicles represented approximately 100 milliohms to the DC bus, neglecting wiring and contact resistances.

In the case of the HMMWVs, the equipment included the addition of a DC-DC converter to boost the 400VDC nominal output of the OBVP Generator/System Controller to 600V, plus a High Voltage System Control Box (HVSCB) to provide power, operator, and signal interfaces to the VCM. The HVSCB handled the details of connection/disconnection to/from the microgrid when commanded to do so by the VCM (reference paragraph titled Vehicle Management). The VIXN modification for droop control was implemented on the HMMWVs by programming the HVSCB microcontroller to read the analog current sense output current of the DC-DC converter and to reduce the analog voltage setpoint of the converter as the load current increased. This was in effect a “hybrid” approach to droop control, implemented to allow the existing 400V HMMWV OBVP system to be used. The virtual impedance (a scale factor internal to the microcontroller) was set so that the output voltage (V_o) would decrease from the no-load setpoint as the load current increased from zero to up to 50A, depending upon the engine speed, which determined the maximum available load power.

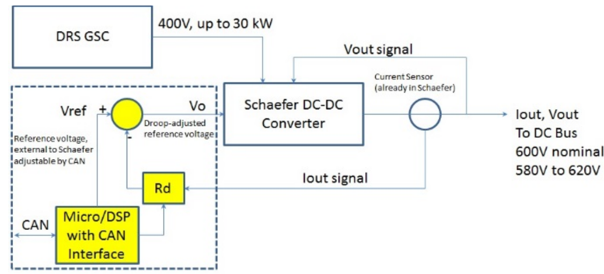

Figure 5: HMMWV Generator Control Block Diagram

For the MRAPs, a HVSCB was used to provide power, operator, and signal interfaces to the VCM. The HVSCB handled the details of connection/disconnection to the DC microgrid. The VIXN modification for droop control was implemented as a firmware change to the Control DSP in the GCBR. The virtual impedance was set so that the GCBR output voltage would decrease from the no-load setpoint as the load current increased from zero up to a maximum determined by the available power, which was dependent upon the engine speed. The range of virtual impedances over the allowed engine speed range was handled by a look-up table with an index representing 50 RPM increments from 800 to 2400 RPM. Due to limitations of the engine speed control system, only two operating speeds were used for this demonstration: 800 RPM (idle) providing up to 65 kW, and 1150 RPM providing up to about 80 kW.

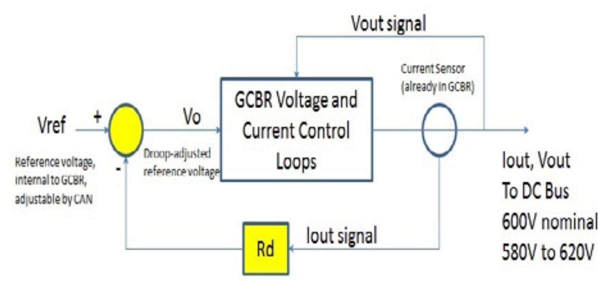

Figure 6: MRAP Generator Control Block Diagram

HIERARCHICAL CONTROL

In terms of the hierarchical microgrid control system as detailed in [1], the VIXN-modified/OBVP-equipped vehicles represented the primary control; the DRS HVSCB represented secondary control, in charge of connection/disconnection details; the IPERC VCMs and their associated network represented tertiary control, orchestrating the dispatch of vehicles, ESU operations, etc., based on load demands. Looking deeper into the system, the inner current and voltage control loops of the generator controllers could be thought of as “sub-primary” controls. The overall system can be understood as having several layers, the outermost layer being the operators.

Hierarchical Control: Primary

Droop control was implemented as the primary control to handle the *steady-state* load sharing of the vehicles based on output power capability. The HVSCB on each vehicle was programmed to handle the switching operations when commanded to connect or disconnect from the DC microgrid by the VCM. That is, if a connection was commanded by the VCM, the HVSCB would adjust the no-load voltage setpoint of the source until the output voltage approximately matched the microgrid voltage before closing contactors. This was done to reduce the unavoidable current *transient* (due to the capacitance at the outputs of the various system sources) that occurred when closing contactors. At least one author [1] suggested temporarily using the bus voltage as the setpoint for a source about to be connected to the microgrid in order to force the source output to accurately track the bus voltage. This was fine in theory, however, a practical implementation would have required hardware and firmware modifications (to the OBVP systems) beyond the scope of the project. For this demonstration; the bus voltage was approximately matched by the HVSCB using a fairly high sampling rate; based on testing done to date, this approach appeared to provide satisfactory operation without "nuisance trips" due to large transients during contact closure. The HMMWV version was modified during integration so that the setpoint was intentionally set to the minimum set point (580V) at contact closure, taking advantage of a blocking diode within the DC-DC converter so that essentially no current was drawn. This allowed for a clean transition to sourcing when the DC-DC converter setpoint was subsequently ramped above the bus voltage.

Hierarchical Control: Secondary

Disconnection of a source from the microgrid presented a similar problem- specifically it was desirable to exit the microgrid without causing a large transient on the bus and without damage to contactors. If a disconnection was commanded, the HVSCB adjusted the voltage setpoint of the source in an attempt to reduce the current well below the rated current of the contactors before opening. In this case, driving the current to exactly zero before opening contactors was not attempted nor was it necessary. In the case of the MRAPs, vehicle-specific loads (a local inverter and DC-DC converter) prevented the load current from being reduced to zero before the contacts could be opened.

Hierarchical Control: Tertiary

Tertiary hierarchical control of the microgrid was provided by the VCMs and the associated communications network. That is, the setpoints of the various sources could be adjusted (as a group) to affect the overall bus voltage, or individually to "trim" the share of the total load handled by a given source. It was suggested that this "trim" adjustment would be necessary due to unavoidable gain and offset variations in the voltage measurement/feedback networks of the various sources (consider that a 1 volt variation in voltage setpoint could result in several amperes of current variation from a given source, corresponding to kilowatts of power, a significant fraction of the source power capability).

The Generalized Virtual Impedance Concept

A key concept in understanding the intended operation of the droop-controlled microgrid is that of a *generalized virtual impedance*- that is, not only droop-controlled sources (with virtual impedances, such as the VIXN On-Board Vehicle Power sources, but also sources with *non-linear* or even *zero* virtual impedances (such as the ESUs provided by Navitas). Included in the conceptual sketch below (Figure 7) is a source with a zero virtual impedance; while not used in the demonstration, a single source of this type could be used as a "bus stiffener" to lower the overall bus impedance in a droop-controlled system. Another way to think about this source would be a clamp that was already active, which would have a near-zero impedance (at least until the current limit of the clamp supply was reached). It could also possibly represent a bidirectional inverter interface to an AC grid- but that was beyond the scope of this demonstration.

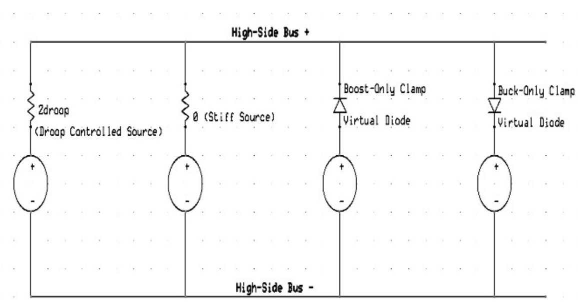

Figure 7: Generalized Virtual Impedance Concept

TVGM SYSTEM OVERVIEW

The TVGM (Figure 8) is the DC bus backbone architecture for the V2G system. The TVGM's establish a common 600VDC bus, per MIL-PRF-GCS600A, with the other power sources (OBVP Vehicles and ESUs) in order to facilitate the creation of a tactical microgrid. The TVGMs can accept/deliver 100kW of power at 600VDC to the vehicles. The power supplied to the TVGM by the vehicles and/or ESU is inverted to 120/208 3PhaseVAC, 60Hz output power to serve the connected loads. The TVGM also interconnects with other TVGMs to form a high voltage DC ring bus. Power from one TVGM can then be transferred to one or more connected TVGMs via the common 600VDC bus.

Figure 8: Tactical to Vehicle Module (TVGM)

Figure 9 illustrates how multiple TVGMs interconnect with each other the vehicles and ESUs.

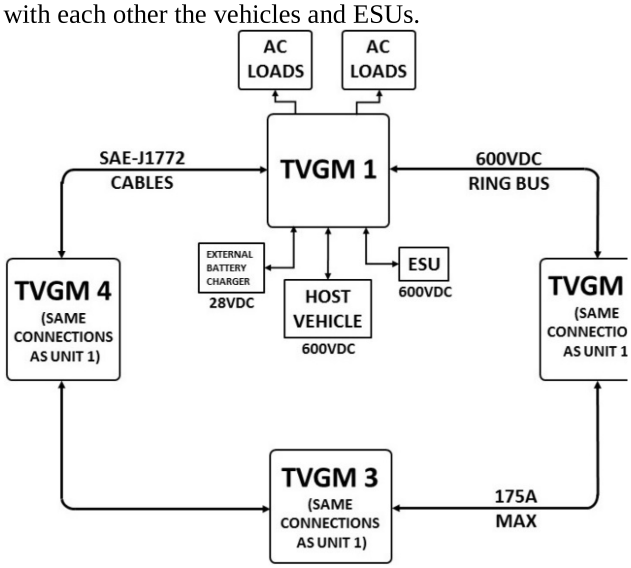

Figure 9: Multiple TVGMs Interconnected by a Common 600VDC Bus

TVGM System Description

The TVGM has the following INPUT ports

- Port 1 – J1772 Receptacle, ESU Port, 600VDC, 175A, Bi-Directional
- Port 2 – J1772 Receptacle Vehicle Port (for OBVP equipped vehicles), 600VDC, 175 A, Bi-Directional
- Port 3 – J1772 Receptacle, DC/TVGM Port, 600VDC, 175A, Bi-Directional
- Port 4 – J1772 Receptacle, DC/TVGM Port, 600VDC, 175A, Bi-Directional
- External DC Power Port – NATO Connector, 28VDC, 20A, Uni-Directional port for charging the control battery and bringing up control voltage to power the TVGM Controller and the VCM

The ESU (Port 1) and Vehicle (Port 2) ports are purpose-built ports and are not interchangeable under normal operating conditions. The DC/TVGM ports are interchangeable – any TVGM can connect to Ports 3 and 4.

The TVGM has two (2) AC OUTPUT Ports:

- Port 5 – MIL-C/DTL 2992 Class L Connector, 208Y/120VAC, 60Hz, 100A
- Port 6 – MIL-C/DTL 2992 Class L Connector, 208Y/120VAC, 60Hz, 100A

The NATO connector is strictly for bringing up control voltage and charging the control battery should it be required upon initiating a battery check and or a black-start. The source plugging into the NATO connector must be a voltage source. The current is limited to 20A by a simple internal control battery charging circuit.

TVGM OPERATION

The TVGM interfaces with the vehicles, ESU and other TVGMs via the VCMs. The VCM serves as the master microgrid controller. Under normal operating conditions, the VCM receives data from and gives commands to the TVGM controller. When a command is given, the TVGM assesses whether or not to execute the command through a series of permissive checks. If it is safe to do so, the command is executed. *(Reference TVGM Management)*

Inverter and System Efficiency

The TVGM provides the necessary link for interconnecting the power sources to the loads within the tactical microgrid. High total system efficiency is therefore a very important attribute. The total system efficiency of the TVGM is a product of the inverter efficiency and the parasitic loads (controls, cooling, etc.).

The TVGM employs a highly efficient DC to AC inverter to convert the 600VDC power from the sources (vehicles and ESUs) to 120/208VAC power. The inverter is approximately 96.5% efficient when operating from within 50% to 70% of its nameplate rating. Efficiency drops to its lowest at 90% when operating at 5% to 10% of nameplate rating.

The parasitic loads are all fed from one of two power supplies within the TVGM. One supply is 1000 watts and the second is 500 watts for a total of 1500 watts. This load is dynamic and varies according to operating conditions.

At full output of 60kW under operating conditions calling for maximum parasitic load of 1.5kW, the TVGM overall efficiency is 94% exceeding the 93% requirement for total system efficiency.

Operator Interfaces

The TVGM was not required to employ any operator interface other than some switches, push buttons and a couple of analog gauges to show whether or not the 600VDC and the 24VDC bus were energized. A final decision on which controller to employ as the TVGM main controller resulted in a Human Machine Interface (HMI) (Figure10) being an additional operator interface that provides additional system status and control of the TVGM without increasing the complexity or time of TVGM startup.

The HMI is the TVGM main controller and allows a local operator access to more information than can be seen on the IPERC Graphical User Interface (GUI), which displays overall system data. The HMI has proven invaluable during integration testing and remains an important feature of the TVGM.

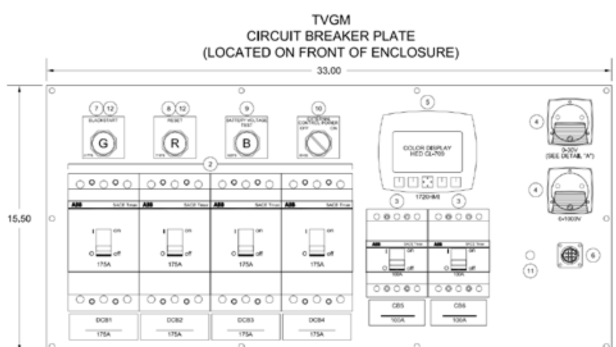

Figure 10: TVGM Operator Controls including the HMI

Challenges

The tactical microgrid for which the TVGM serves as the link between unique power sources (vehicles and ESUs) and loads is a complex power system that is markedly different from traditional tactical power systems and therefore comes with some unique challenges.

Two of the more unique challenges for the TVGM that became evident during integration testing were grounding/ground fault detection and the use of SAE J1772 combo connectors for connecting sources to the TVGM and connecting TVGMs to other TVGMs.

Ground Fault Detection

Early on within discussions of the Integrated Product Team (IPT) it was decided that each TVGM would employ a differential scheme for detecting ground faults on the 600VDC bus. The differential scheme was seen as the simplest way to implement sound protection without interfering with the input power source's (vehicle or ESU) own ground fault detection schemes. However, during integration testing, it has been seen that the 600VDC bus was not always balanced at certain times causing nuisance trips. These trips frequently happen when certain sources are joining the TVGM or when TVGMs are connecting with other TVGMs. Various types of solutions had to be devised and implemented to assuage these trips and allow the system to operate more robustly.

SAE J1772 Combo Connectors

A requirement from TARDEC was the use of SAE J1772 Combo connectors to connect input power sources and create the 600VDC bus linking TVGM to TVGM. While this scheme allows for quick connect and disconnect of the 600VDC bus as well as future compatibility with other vehicle power sources, it does come with unique challenges for a tactical power system. In addition to transmitting power, the J1772 connections incorporate communications and control to sense when a connection is made and to lock that connection in place whenever voltage is present.

The most prevalent challenge affecting the TVGM was the implementation of the locking pin on the J1772 inlet. Once a connection to a TVGM inlet port is made the connector is locked in place to ensure the connection is safe from inadvertent disconnects once power begins to flow.

The first challenge involved an underpowered drive circuit for the locking pin motor. Increasing the motor drive power made for an easy remedy.

The second challenge involved a few locking pin motors that did not make contact with their internal status switch when the locking pin was deployed. The result was that there was no feedback signal for the locking pin. These motors had to be modified such that when the locking pin was deployed the switch was made and the feedback signal sent back to the controller indicating that the port was indeed locked and ready for power

ENERGY STORAGE UNIT (ESU)

The Energy Storage Unit (ESU) is a major component for the V2G.. The unit has an energy storage capacity of approximately 22.8kWh. The ESU interfaces with one TVGM as part of a grid component family which consists of one (1) OBVP, one (1) TVGM, and the ESU.

Functional Description

The 22.8kWh ESU serves as a bidirectional power source charging from the grid power along with providing power allowing for HV 600Vdc power bus stability and meeting MIL-PRF-GCS600A power standards. It has the capability to serve as an upper and/or lower "guardrail" to aid in the stability of the HV 600VDC power bus. These values can be programmed into the ESU by the onboard VCM. The values allow for the ESU to either provide power (lower threshold) or store power (upper threshold) if the applicable threshold is exceeded. The ESU also allows for the supplementing of power in support of system functions such as minimizing the number of generators needed and the impact of power transients due to the addition / removal of various power loads. This includes the removal of OBVP power sources when the vehicles are needed to deploy for missions or the introduction of OBVP power sources when the vehicles return. Various power transients on the 600VDC power bus can be caused by the Environmental Control Units (ECU) and/or HVAC systems with high inductive motor surges during engagement when they are enabled or disengaged. The ESU works to provide suppression of these transients by either absorbing the energy by storing it or providing power to supplement the main sources during inductive motor engagements. This operational feature also lends well for the use of high energy, burst weapons utilizing power from the grid. In addition, the use of energy storage allows for silent operations where the OBVP power sources can be turned off when power demand is low enough or commanded by the users contributing to reduced fuel consumption. The ESU is designed to be mounted onto either an M1152 HMMWV mounted Amerdeck skid or M1102 trailer with its associated TVGM. The ESU is designed to meet both MIL-STD-461E for EMI requirements and MIL-STD-810G Environmental for Blowing Rain. Figure 11 illustrates the ESU mounted on the M1152 HMMWV Amerideck skid and the M1102 trailer.

Figure 11: ESU Mounted on either the M1152 (left) or the M1102 Trailer (right)

Detailed Design

The ESU is comprised of individual subsystems as part of the detailed design that allow for the system component to meet functional requirements. The internal subsystems include the following:

1. Low Voltage (LV) Control Power
2. High Voltage (HV) Power
3. ESU Control
4. ESU Internal Thermal Management
5. User Control/External Power Interfaces

The ESU internal controls require the use of both 28VDC and 14VDC power. This power is derived from one of three LV power sources. The primary source of LV power is from the HV 600VDC power by the use of two separate DC/DC converters; one for 600VDC-to-28VDC and one for 28VDC-to-14VDC conversions. The secondary LV power sources include energy storage provided by a 6T form factor, Li-Ion based battery and an externally mounted NATO port on the ESU. The 6T LV battery allows for internal controls operation without the presence of 600VDC and NATO power at the external port for up to 1 hour. If the NATO power is provided to the ESU, then the runtime of the internal control power can be extended along with the charging of the LV battery.

The ESU provides the energy storage for the HV 600VDC power with a capacity of 22.8kWh and can deliver up to 60kW of output power. This is accomplished by the use of a DC/DC converter power stage up front interfaced to a Li-Ion battery core pack provided by A123. The DC/DC converter is bidirectional and can convert the 600VDC down to ~400VDC and vice versa. The HV power system also provides interlocks for user safety on all access panels and HV connectors. In the event any one of the interlocks is broken, the HV power bus is disconnected and discharged to <40VDC within 2 secs. This is to prevent hazardous voltages being present when the user is performing maintenance inside the ESU and to prevent arcing with connecting/disconnecting HV cables. Along with the interlocks, the ESU is equipped with Ground Fault Protection as well that will disable all HV outputs and discharge in a similar fashion when any imbalanced currents of more than 6mA are detected.

The ESU control is primarily performed by a single centralized controller that manages the operational modes to perform while monitoring the status of the safety mechanisms along with performing a controlled startup/shutdown. The controller is the primary interface to the local VCM and provides various status parameters such as Voltage, Current, State of Charge (SoC), pack and power electronics temperatures, control voltage, etc. The controller is also responsible for handling and reacting to any faults detected or any safety related interlock/protection events.

The ESU includes active thermal management of the internal battery corepack and power electronics. This was required in order to allow for ESU operations in ambient temperature range of -40 degC to +50degC. The thermal management is performed by a combination of liquid water glycol and an active chiller unit. The cooling systems are powered from the HV 600VDC and/or LV 24/28VDC power. The cooling system is sized to reject at least 4.4 kW of power generated heat at a 65 degC ambient temperature.

The ESU provides a main user control panel that includes external connectors for the HV and LV power along with (2) two manual disconnects for 600VDC power bus when the unit is shutdown and not in use. The HV 600VDC interface utilizes a SAE standard J1772 combo connector and the LV 24/28VDC power utilizes a standard NATO power port. Along with the power connector interfaces, the unit provides a Master Power switch that when disabled, ensures all internal components and power are disabled and an external data communications port. Figure 12 below shows the user control panel.

Figure 12: View of the ESU User Control Panel with and without cables attached

Development Lessons Learned / Data Obtained

The performance of system testing at Ft. Devens, MA yielded positive results as to the use of the ESU in this type of application in that the use of guardrails supported the stability of the HV power bus. This feature did not allow the voltage to rise or droop below the tight threshold limits that were desired even when significant power loads such as the various ECUs or the 30kW laundry dryer were utilized.

In every initial development, various technical challenges and issues are present. With the ESU, one technical issue that was observed, was the need to a balanced precharge of both the +300VDC and -300VDC power rails on the HV power bus. Differences in the control circuitry due to tolerance extremes can cause imbalanced currents to be sensed as the HV bus precharges and as a result Ground Fault Protection monitoring in the system the HV sense reacts to this imbalance by disabling the detecting components HV outputs. This proved to be a challenge during the initial system integration efforts. As a result, it was determined that future consideration needs to be taken to ensure a tighter tolerance of selected components is implemented.

OVERVIEW OF THE VCM “SYSTEM BRAIN”

The hardware to run control system for the project consists of 12 vehicle communication modules (VCMs) that communicate with their respective components and with each other. A topology of the system is shown in Figure 13.

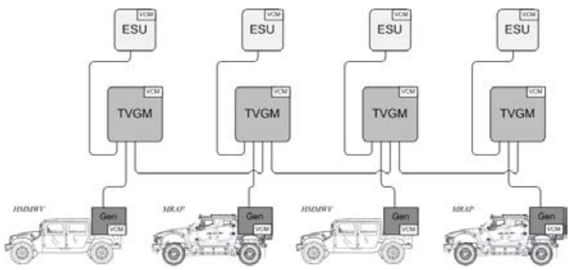

Figure 13: Overall layout of grid components

Hardware and software VCM development

The development of the Vehicle Control Module (VCM) presented several challenges and required these features:

- The board must provide sufficient computing capacity in a relatively small volume that is subject to a hostile environment related to temperature, vibration, and moisture.
- The system needs to utilize power line carrier (PLC) to avoid running extra Ethernet cables around the network and to avoid potential signal corruption from wireless technologies.
- Each VCM has 4 PLC channels to determine which port components are connected to.
- The VCM must route traffic between the four channels to provide a network for the computers to communicate over.
- The system has to communicate with the different end devices over CAN-bus.
- Provide a graphic user interface (GUI) for control and view of the system. This is provided via an Ethernet connection to a web server hosted on the computer.

The VCM is shown in Figure 14. There are four power-line carrier (PLC) channels on the PLC board (left) with a single-board computer (SBC) mounted on top. On the right is the power supply for the VCM, compliant with MIL-STD-1275E and supplies a 3.3 V power from a 24 V Source.

The single-board computer (SBC) is based on the form factor and component design of the BeagleBone computer running a 1 GHz ARM A8 CPU. The board was redesigned by IPERC with components that are able to withstand an extended ambient temperature range of -40 to 85°C. These boards have headers for serial, Ethernet, CAN-bus and SPI interfaces. These headers are used both to communicate with the locally attached equipment and to communicate with a cortex M4 processor on the PLC board, which routes Ethernet traffic between the VCMs via PLC.

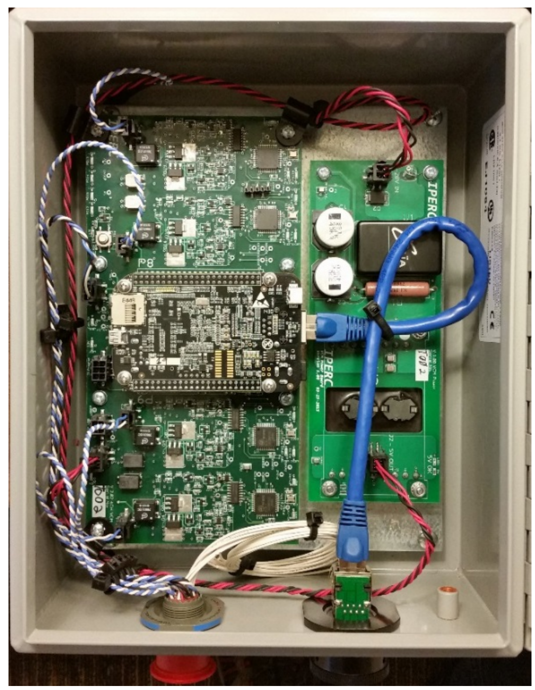

Figure 14: VCM containing PLC and SBC (left) and power supply (right)

Twelve VCMs were assembled and tested at the IPERC facility in Colorado prior to installation in the actual vehicles, ESU, and TVGMs. This testing included temperature, PLC communication speed, and CAN-bus communication to test VCMs for functionality and reliability and to debug issues related to operation.

Each VCM runs a suite of software developed by IPERC that manages communication with the grid components as well as for making the control decisions used to stabilize the microgrid. The control actions are broken out into several different categories: Vehicle management, ESU management, TVGM management, contingency handling and web interface.

Vehicle management

The vehicles are one of the energy sources that can be connected to the TVGMs. The vehicle and the TVGM must be configured to safely and reliably step though the connection process, setting voltages and checking for faults inside components. Control sequences are in place for connecting both running and non-running vehicles to the grid, as well as connecting a powered vehicle to both a de-energized and an energized TVGM.

There are also algorithms in place for dispatching a vehicle that is currently off and connected to the grid. This is automatically done as the loads increase and there is a need for additional power sources. Similarly, a separate algorithm handles the curtailing of vehicles when the loads are low to reduce fuel usage.

Control sequences also had to be implemented to treat the cases where a vehicle must be disconnected from the grid (as would happen when it is required for normal transportation purposes). Before disconnecting, the amount of power is checked on the grid to prevent the voltage from collapsing under too much load. Similar to the permutations for connecting vehicles, the disconnect sequences consider disconnecting a running and non-running vehicle from an energized and de-energized TVGM.

ESU management

The energy storage units are treated similarly to the vehicles when connecting or disconnecting, however, there is a significant difference in the function of the ESUs, specifically when they have to act as “guard rails” on the grid.

The power supplies in the batteries are not capable of droop control and are therefore operated in one of three modes: a lower “guard-ring,” an upper “guard-ring,” or a constant charge. In the lower guard-ring concept, the ESU is instructed to run in voltage mode with a voltage setpoint toward the lower end of the droop curve. An upper guard-ring is instructed to run in voltage mode with a voltage setpoint toward the upper end of the droop curve.

Figure 15 shows the system response when there is a single 80 kW vehicle and a 20 kW battery. The vehicle is operating in droop mode and the ESU is configured as a *lower guard rail* with a voltage setting of 585 V. The ESU is configured for positive current (supplying the bus) and no negative current (drawing from the bus). The vehicle supplies the entire load on the system from 0 to 70 kW. The bus voltage goes down as the load increases due to the droop control responding to the load change. When the system load increases above 70 kW, the ESU now regulates the bus voltage to the setpoint of 585 V and the bus voltage is constant until the ESU has been fully utilized. When the battery reaches its maximum output of 20 kW, the ESU will output 20 kW constant and the vehicle will control the bus voltage again until the vehicle reaches its maximum output of 80 kW.

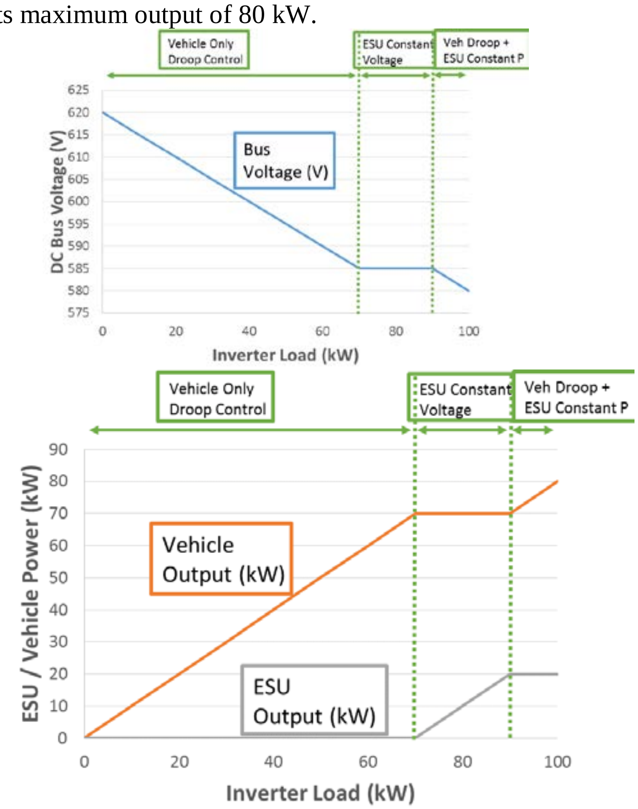

Figure 15: Bus voltage (top) and ESU/vehicle power (bottom) response with ESU as lower guard rail.

An example of an upper guard-ring is shown in Figure 16 with the same vehicle and ESU as before, but now the ESU is configured to operate in voltage mode with a setpoint of 615V. The settings for the ESU would be configured for negative current (drawing from the bus) and no positive current (supplying the bus). The vehicle supplies the entire load on the system from 10 to 80 kW. The bus voltage goes down as the load increases due to the droop control responding to the load change. When the system load goes below 10 kW, the ESU regulates the bus voltage to the setpoint of 615 V and the bus voltage is constant until the ESU has been fully utilized. When the battery reaches its maximum input of 20 kW, it remains constant at that value and the vehicle will control the bus voltage again until the vehicle reaches its minimum output of 0 kW. This configuration is used to protect the bus against surges when loads are turned off suddenly. When this happens, the brief excess power on the bus is absorbed by the ESU configured as an upper guard-ring.

In addition to the guard-rings, the ESUs is also configured in a mode to charge only and not regulate the bus voltage. In this mode, the voltage setpoint is set toward the lower end of the droop range (in this example 585 V), and the power settings for the ESU are configured for negative current (drawing from the bus) and no positive current (supplying the bus). The bus voltage should always be above this setpoint, so the ESU will just absorb a constant amount of power from the bus and increase in charge. The bus voltage is determined only by the vehicles in droop mode and the ESUs configured as guard-rings. The voltage should be configured below the lowest guard-ring but above the maximum output of the vehicles. Therefore, if the system approaches maximum load, the charging battery will reduce the amount of power absorbed to keep the bus energized.

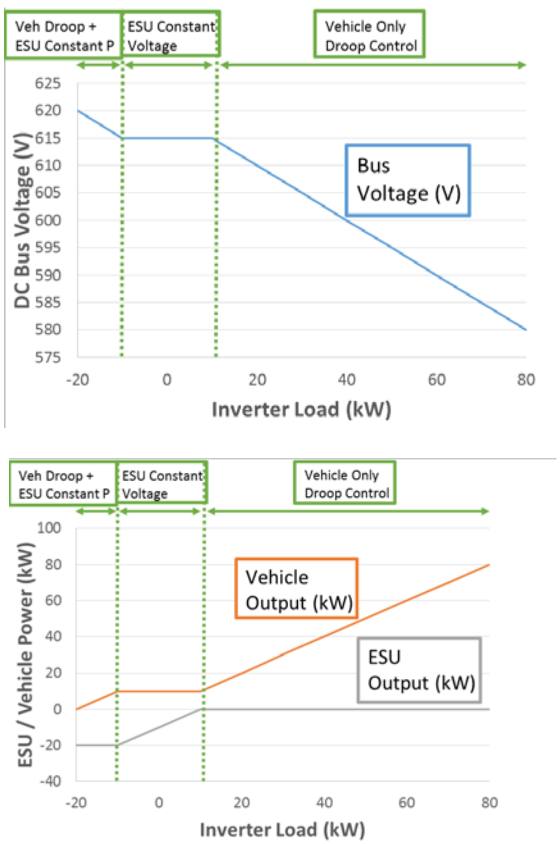

Figure 16: Bus voltage (top) and ESU/vehicle power (bottom) response with ECU as upper guard-ring.

An example of this operation is shown in Figure 17 for an 80 kW vehicle and a 20 kW ESU. Notice that below an inverter load of 50 kW, the ESU draws a constant 20 kW charge and the voltage on the bus is regulated by the vehicle. When the bus voltage reaches the ESU setpoint of 585 V, the ESU regulates the voltage and reduces the charging power from 20 to 0 kW. After the ESU is no longer charging the bus voltage continues to droop because of the vehicle to the 80 kW maximum output of the vehicle.

When there are no vehicles present on the system, the modes of the batteries are still the same, although the settings only the lower guard-rings are required and the highest lower guard-ring should be configured slightly different. The constant charging mode is not required as there are no other power sources to charge the batteries from. There is still a need for upper guard rails to absorb power from inductive loads, however the highest lower guard can be configured to provide the upper protection at the same time. When no vehicles are present, ESUs currently in upper guard-rings and constant charge are reconfigured to be lower guard-rings.

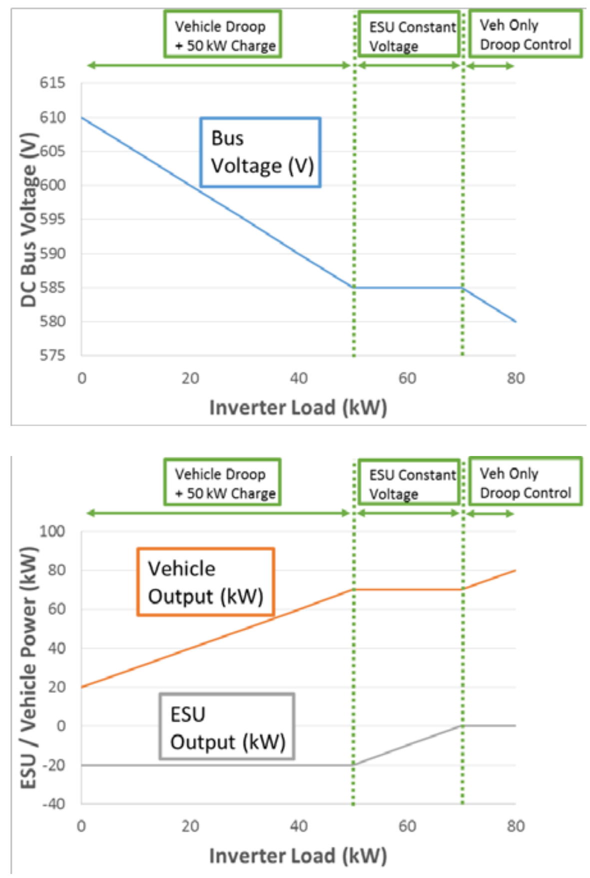

Figure 17: Bus voltage (top) and ESU/vehicle power (bottom) with battery configured for constant charge

When there are multiple ESUs on the grid, they are set at least 5V apart from each other as DC power supplies have issues regulating the same bus simultaneously. There is only one upper guard rail and the remainder are setup for lower guard rails. Any constant charging ESUs will be setup below the lower guard rail ESUs.

The mode of the ESU depends on several system parameters including number of vehicles, the number of ESUs, the SoC of the batteries, the power capability of the system and the current load on the system. There are triggers that determine how to choose the ESU mode:

- If the ESU's state of charge is below the allowable minimum (20%), that battery will either be put into a constant charge mode or disabled based on the amount of load on the system.
- If the number of ESUs available for guard rail protection change, the configuration of the ESUs in guard rail mode need to be adjusted.
- If a battery in charging or upper guard-ring mode nears the maximum allowable state of charge (90%), the mode is changed to prevent the battery from overcharging.
- If the grid goes from having vehicles to not having vehicles or vice versa, the ESUs are reconfigured based on the new configuration.

Similar to the vehicles, there are also a number of sequences defined to handle the connection and disconnection of ESUs from the grid. Additionally, there are also algorithms in place to "rotate" the ESUs between lower and upper guard rail roles as a function of their state of charge.

TVGM management

The TVGMs are the major connection point between the various microgrid components. They serve as the junction between the vehicles, the batteries, and each other, and consequently are subject to a number of unique control sequences.

Connecting two TVGMs together effectively combines two minigrids together into a single microgrid. There are several variations for this scenario:

1. In the case where one of the TVGMs is powered and one is not, a new TVGM without any connected sources will be connecting to an established, powered grid. This would be the case used when one TVGM has been powered and another TVGM is connected to expand the grid. After this sequence, both TVGMs will be powered.
2. In the case where both TVGMs are powered and establishing a ring-bus configuration, there are multiple TVGMs that will be forming a ring-bus configuration. Electrically, the buses on both TVGMs are already joined through the other connections and the additional ring-bus connection is creating a duplicate path. Therefore, the voltage across the contactor is minimal and the contactors can be closed.
3. In the case where both TVGMs are powered but not establishing a ring-bus configuration, there are two completely isolated microgrids that need to be joined. Since the voltages on the bus are not the same and can't be aligned before the connection, this type of join is prevented.

There are also several control sequences that are issued to the TVGMs while they are connected, including enabling the inverter loads after the TVGM is powered, and then disabling the inverter outputs when shutting down the system.

A TVGM has no internal power source contributing to the grid, so the majority of the disconnect sequences for the TVGMs are driven by the connected equipment. For instance, if the line between the TVGM and the vehicle is disconnected, the TVGM must wait for the vehicle to adjust its output current to zero before opening the contactor. At that point, the TVGM can open the contactor and remove voltage from the cable. There are five different cases for the TVGM disconnects: (1) an ESU or vehicle is disconnected and there are other power sources, (2) an ESU / vehicle / TVGM is disconnected and is the only power source, (3) a TVGM connection is disconnected and there are other power sources on the TVGM and there is no ring-bus, (4) a TVGM connection is disconnected and there are other power sources on the TVGM and there is a ring-bus, and (5) a connection is disconnected and there are no power sources.

Contingency handling

The final set of instructions for the grid control consider the various contingencies that can be handled. These include non-responding contactors on the vehicles, TVGMs, and ESU and the loss of communication between the VCMs and the equipment to which they are connected. In addition, the contingency algorithms must deal with fault messages received from any of the equipment as well as erroneous data received over both the CAN networks and the PLC networks.

Web Interface

Each VCM runs a version of the web server used to view the GUI. This was to allow the GUI to be accessed on any component in the system and display information from all connected VCMs. An example of the GUI is shown Figure Here the top row represents the detected ESUs, the middle row the TVGMs, and the bottom row the detected vehicles. This GUI shows the TVGMs in a ring-bus configuration, with the left-most and right-most TVGMs connected together through their "outer" ports.

The right side of the GUI screen includes a number of buttons that the operator can use to command the system. These include enabling or disabling the control system, connecting all components in the grid to TVGMs, disconnecting all components from the TVGMs, and stopping the system from performing actions.

Results from Implementation

The VCMs have been program and tested along with the rest of the physical equipment in the microgrid. An auto detection method is used so that each VCM can automatically determine what equipment it is connected to as well as which port on the VCM. This is necessary for safely joining and disconnecting the various grid components. This is done via the packets sent over the PLC because the four PLC channels are isolated from each other and can determine the connection.

The program architecture was updated so that all process models are run on a single computer instead of distributed among the computers. This places the most stress on the CPU running the model manager but prevents the model transmissions from sending over the powerline carrier network, thereby relaxing the burden placed on that communication.

The power-line carrier communication network operates at a very limited transmission rate, leading to reducing the size of the messages conveyed between VCMs and also to a need to streamline the communication mechanism. Data is limited to absolutely required items to reduce the traffic on the network.

A total of approximately 800 different data streams are used in this control system with 12 connected components, of which about 25 percent are calculated and used for system variables. The data are transmitted every couple of seconds between the hosts.

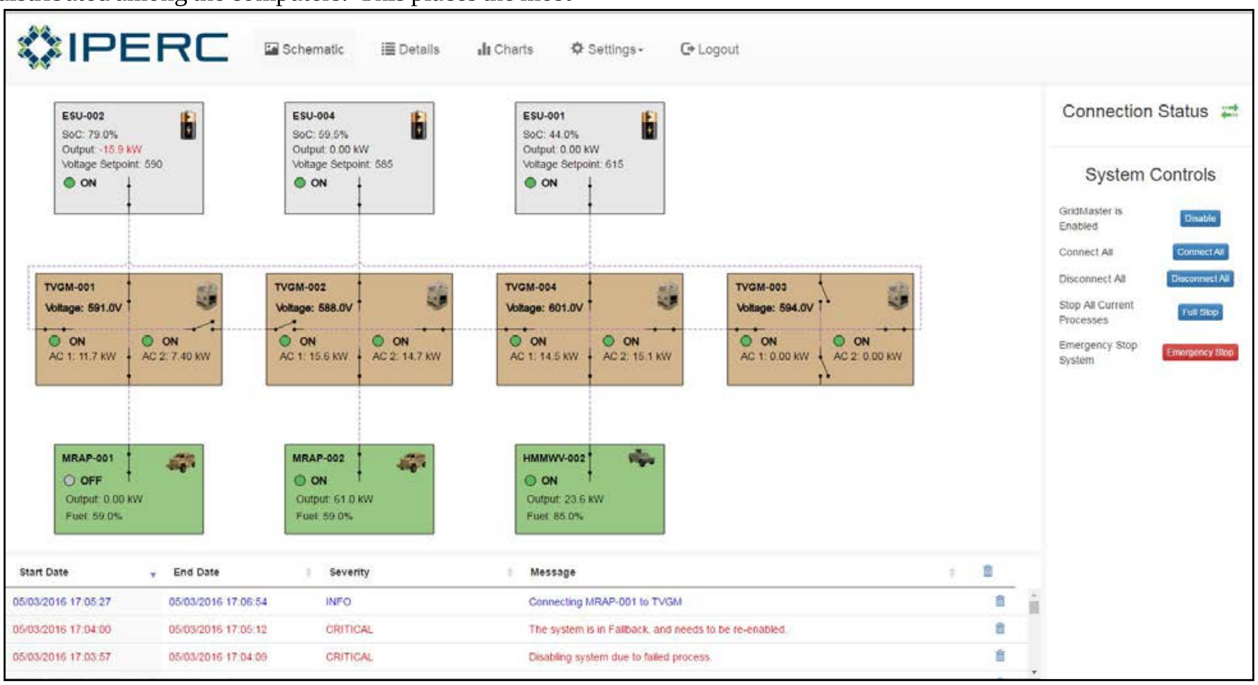

Figure 18: Example GUI image

Process testing

A number of procedures have been successfully tested both in a controlled laboratory environment and with the actual equipment in field tests at TARDEC and Fort Devens. The successful tests incorporate the following processes:

All communications have been put in place between the VCMs and their associated equipment, including the MRAPs, HMMWVs, ESUs, and TVGMs. This involved defining, testing, and validating two-way communications over CAN-bus and averaging about 50 control and data acquisition points from each piece of equipment.

Both MRAPS and HMMWVs have been joined and removed from their respective TVGMS, and all TVGMs have been joined and split from their adjacent TVGMs, including those that complete a ring-bus architecture.

The guard rail operation of the ESUs has been successfully implemented and tested in all modes with up to 4 ESUs. In addition, the “rotation” of the ESUs from lower to upper guard rail – as a function of the state of charge – has been shown to work as designed.

The dispatch and curtailing of vehicle generators was tested and shows the expected response to a decrease or increase of loads. The curtailment of unneeded generation results in fuel savings, directly in the generator that has been turned off but also in the remaining active generators that then operate at a higher part load ratio and consequently a higher efficiency.

The emergency stop function of the GUI has been successfully tested during times of unexpected contingencies in the microgrid.

Dozens of alert messages have been added to the GUI to warn the operator when there are any issues with the grid components, and also as informational commentary on what the control system is doing at any given time. These messages shows issues with the sub-components as well.

In addition, it has been shown that the GUI is available through any of the VCMs, regardless of where it is in the microgrid, and from any VCM to be able to view and control the entire microgrid. Multiple GUIs can be access simultaneously and through a remote access point connected to this network it has been demonstrated that the system can be monitored and controlled from any point on the planet (assuming the operator has the appropriate credentials to log in to the system).

Challenges and Technology Advancements

During the execution of this project, a number of technological challenges were encountered and overcome. One of the main concerns was the need to have the VCMs work reliably in harsh environments. Most single-board computers have a limited operating temperature range, and those that are rated for higher temperatures tend to have CPU speeds much lower than that required to properly run the control programs. This problem was solved by developing and building a dedicated single board computer based on the BeagleBone architecture. The custom-built computers use components with an extended temperature range of -40 to +85°C and were subjected to numerous thermal stress tests before mounting into the VCM enclosures.

One noted issue with the single board computer is that the processor speed of 1 GHz is at the lower range required to accommodate the demands of all running programs. This includes the data acquisition, the control algorithms, the web server, and the communication routing. Since there is no guarantee of which computers will be on a given microgrid, all of the VCMs had to execute the full set of programs. Consequently, the functional code had to be greatly streamlined and optimized so that it could run on the relatively slow processors.

There are also a couple of other manifestations of the slower speeds: the control system takes about 60 seconds to boot and begin running the control algorithms, and the web server takes about 6 to 8 minutes before it is fully up and available for browsing, especially as the model manager communicates with the other VCMs and builds models to represent the entire system. This limits the operator's ability to view the system immediately upon startup.

In addition, limited update rate impacts the setup of the entire system such that fully joining all families of grid components can take about 10 to 12 minutes. Most of this time is used to verify the state of the various breakers, perform ground fault checks, setup power supplies and wait for vehicles to start. Increasing the update rate of the system would decrease this time as would a more powerful processor. Another possible solution would be to optimize the division of tasks between the various subcomponents and system controller. This would also improve the response of the system when handling fast transient tasks. It is expected that these alternative methods will be investigated in future phases of this work.

Additional challenges were noted with the power line carrier. Homeplug Green-Fi is a new standard and no chips were available for purchase for implementation in this system, so PLC technology used in the SPIDERS microgrid project was used in this project. This led to a system with significantly limited bandwidth. Additionally, power line carrier signals are very sensitive to the component wiring and the internal electronics of the components. IPERC vetted the PLC technology utilized in the VCMs in the lab environment, but additional issues crept up when implementing the signals in the actual equipment.

MODELING AND SIMULATION (M&S)

The electric power system is an enabling infrastructure that supports the continuous operation related to different mission critical facilities, both at the component level and the system level. There is a need to build an extensive library of V2G/V2V components in the simulation environment. This includes the development of adequate models for simulation of a variety of distributed generators and short term storage, including the corresponding control and power electronic interface. Without M&S, a piece of a complex system, when integrated, may not perform as anticipated, which will require rework to portions of the systems. A generic model is preferable to enable the integration of control strategies. Dynamic loads are modeled as well as constant electrical loads. The MATLAB/Simulink models each components of the system and is able to describe their steady-state and dynamic behaviors. The transient responses are analyzed as well.

In order to study Figure 19 system architecture, a Matlab-Simulink implementation of the system was done. The model describes steady-state behavior of the components.

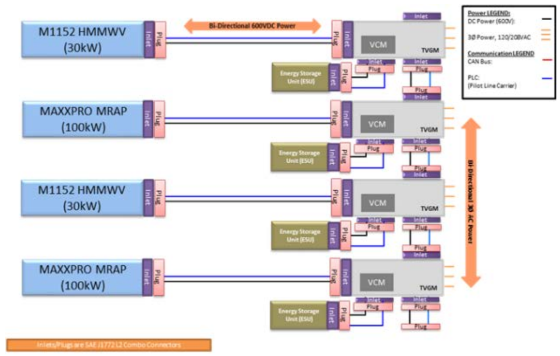

Figure 19: V2G Set-up

The top level diagram of the Matlab-Simulink system is shown in Figure 20. In Figure 20 the top left and right corners are for HMMWVs and bottom left and right corners are for MRAPs.

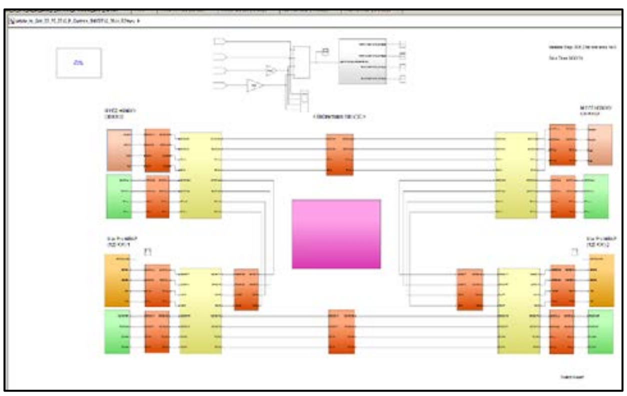

Figure 20: V2G Set-up

A couple of graphs from the simulation run showing the engine rpm and total power requirement are given Figure 21.

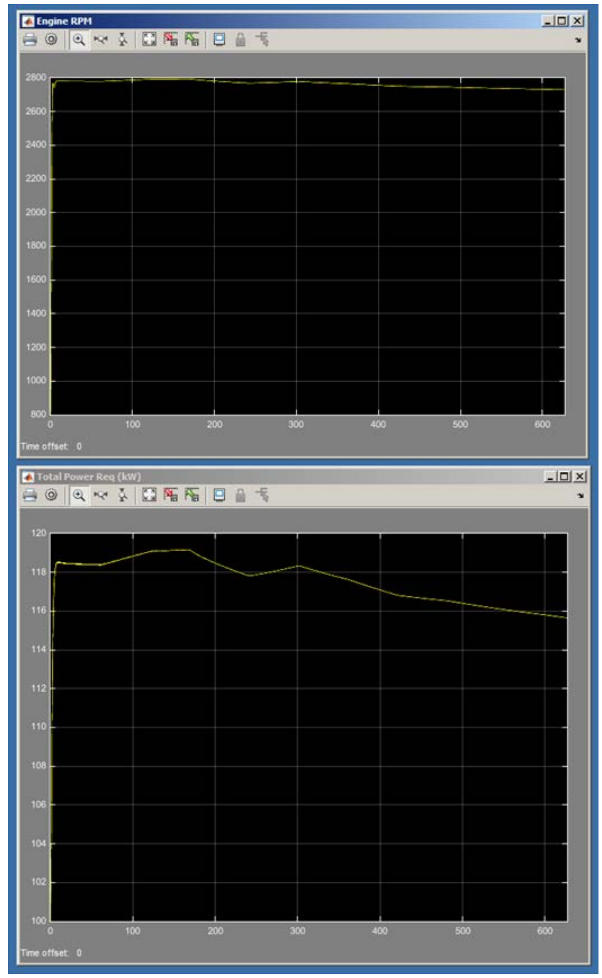

Figure 21: Simulation Run

The modeling and simulation portion of this work involves a modeled system of the V2G/V2V using the SimPowerSystems toolbox in the MATLAB/Simulink environment. The model will be utilized to understand the system performance and control based on three layered architecture control loops –current, impedance and voltage. The V2G/V2V model will be utilized to understand the system performance and control. The model will use a Direct Current (DC) three level Hierarchical control loops approach - current, impedance and voltage, similar to the DC microgrid. The primary loop uses an impedance feedback loop to control the power percentage for each electrical source so that each source carries its share of the electrical load. The secondary control handles differences in voltage to the microgrid. The tertiary control, controls power from the microgrid to the electrical distribution system. In addition, the model will be used to develop and design energy efficient vehicle coordination control system. This simulation will track two main parameters to characterize the resultant behavior over the simulated time period: fuel consumption.

The main objective is to model and simulate the system and to evaluate, and analyze the energy efficiency and fuel consumption for various scenarios. The results will be compared to a system performance supported by Tactical Quiet Generators (TQG).

Basically this M&S includes a load profile for the microgrid. It includes mathematical models for the vehicle engines (HMMWV and MRAP), the battery, converter and inverters, microgrid which basically connects the vehicle power system. In addition, there is a protocol which allows allocating one or more vehicles in the system depending on the average power demand. The M&S work is currently ongoing and additional information are implemented at this time. However, based on the experimental engine fuel economy information for the vehicles, a comparison has been made between the vehicle based micro-grid, against the TQG which is currently used in the microgrid system. This study clearly demonstrates the fuel economy benefits of using V2V based system. This is depicted in Figure 22 which shows total fuel consumption in gallons/per hour. In general it appears that V2G system is more efficient in terms of fuel economy compared to TQG, except at very low power output of 5kW. The benefits can be enhanced if complete throttle control which allows wide variation of speed can be implemented in both HMMWV and MRAP. Similarly, if the TQG was allowed to run over a wide speed range instead of the fixed speed of 1800, it may be possible to improve its fuel economy as well.

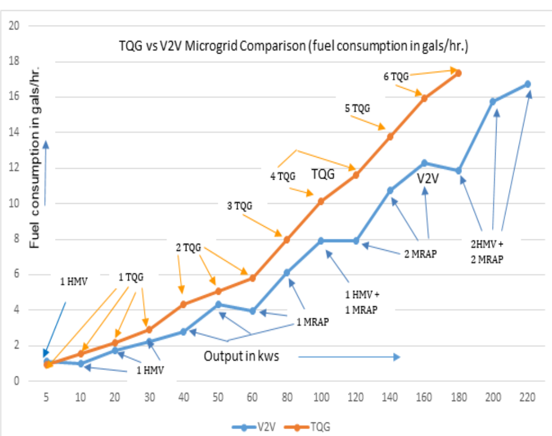

Figure 22: Total Fuel Consumption TQG vs V2G

However, having several vehicles in the V2V system allows logistical benefits in terms of avoiding carrying extra equipment i.e. TQG, and also corresponding cost of fuel ensuing due to that. Another advantage of the V2V system is that it will have batteries as well. Since battery has high efficiency, it is advisable to use batteries at very low load power demand (if the battery SOC permits that). It seems that it is advisable to keep some reserve space in the batteries, so that generators can be run at higher load than the minimum, which can realize better efficiency from the engines. Usage of the batteries notwithstanding, the real fuel economy will be mostly due to the engine efficiency and correct allocation of the vehicles, and operating those at the best possible point in the engine fuel map.

Testing

TVGM Three-phase (3Ø) Inverter

Component-level testing took place at TARDEC's Ground Systems Power & Energy Labs (GSPEL) test sites. TVGM1 (first of four TVGMs) was delivered to Test Cell 104 for high-power testing of the three-phase (3Ø) inverter with an AC Load bank. Test article was connected to an AV900 bi-directional DC power supply set to 600V. Connection to the input was via an SAE-J1772 Cable. AC output from the 3Ø inverter was routed through a 100A MIL-C-22992 Class-L to Cam-Lok adapter cable to a Simplex dynaMITE 400 3Ø AC resistive load bank. Post-SLB-STO/D Demo testing will employ load banks with switchable inductance & capacitance and the ability to unbalance the phases to reflect real-world load profiles.

Test Results

Testing started out with running the inverter through a series of load-steps from 5kW to the full 60kW. Test data revealed that inverter efficiency increased with load. Next line of testing involved running the Inverter at steady-state loads at different levels (5kW, 10kW etc.) for six-hour periods. Peak inverter efficiency was measured at 95% at full 60kW output.

System Integration Testing

System Integration Testing of the complete system was conducted at TARDEC. Testing began with HMMWV2 and MRAP2 alternating as the power source. Both were connected via J1772 cables to TVGM2 and ESU1. The inverter in TVGM showed a 95% efficiency, consistent with the data from TVGM1 tested at TARDEC. The ESU's DC-DC converter, required for making the current-source battery to appear as a voltage source, ran at an incredible 99%, with 30.3kW input and exactly 30,000W out.

As more components arrived, the system was slowly built. First tests involved manually stepping through the connect- and disconnect- sequences, followed by running them in automated mode. Performance revealed, while the system could run in automatic mode, Supervised mode was the best, as we could watch the system as it stepped through the sequences while still being able to intervene if/where necessary.

Notable system challenges included stability of the operating system, an HVAC unit failure in ESU2, 600VDC Active Rectifier failure unit in MRAP1, coolant spillage inside TVGM 2, failure and replacement of a DC-DC converter in ESU 3, and repeated Ground-Fault Detection (GFD) system trips. The GFD issues (expanded upon later in this paper) were mitigated by several solutions– running separate earth-ground cables to isolated patches of earth for proper, yet isolated grounding, and other solutions covered in the BCIL Demonstration section.

Maximum load pushed at TARDEC was 204kW into three load banks (the dynaMITE 400, and two PowerStar 100s), as well as two DRS HG-1240 Improved Environmental Control Units (I-ECUs) with soft-start and variable-frequency drive for the main compressor motor. Figure 23 shows the System under test at TARDEC.

Figure 23: Testing at TARDEC

FT. DEVENS BCIL DEMONSTRATION

The system arrived at the Base Camp Integration Lab (BCIL) on the South Range of Ft. Devens, MA on 15 MAY 16 in preparation for participation in the FY16 Sustainability Logistics Basing, Science & Technology Objective /Demonstration (SLB-STO/D). The STO's goals were to demonstrate reductions in water consumption by 75%, Waste back-haul by 50%, and fuel consumption of 25%

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The system assets were quickly situated and inter-component connections made. Eight 100A Class-L cables were run across the ring road surrounding the BCIL, and on to P-DISE boxes where switchover and switchback would take place. Figure 24 shows the approximate location of system components relative to the BCIL proper. Assigned loads were the billeting shelters buildings 25-32, latrine buildings 41 & 41, shower buildings 43 & 44, north laundry building 47, and kitchen tent building 46 lighting & cooling.

Figure 24: BCIL Location

Setup, Test and Preparation

The SLB-STO/D Schedule built in 2 ½ weeks (16 MAY to 03 JUN) for system setup, testing, and preparation for the Demonstration, which ran from 06-17 JUN 16. System issues similar to those from the testing at TARDEC started to appear. The TARDEC Team, diagnosed and resolved system issues, including the repeated nuisance trips of the GFD circuit. Ultimately, the decision was made to deactivate the action function of the GFDs at the TVGMs while retaining their advisory function. The GFD functionality at the vehicles and ESUs remained in place. This was also based on the fact that the baseline MEP-series Tactical Quiet Generators (TQGs) do not include ground-fault detection, so neither should the TVGMs. To test the system without powering any BCIL loads, the AC load banks from TARDEC were used. Each TVGM was connected to a load bank and loaded down until it over-current tripped. A peak load of 193kW was supported during testing at the BCIL.

Figure 25: Set-up at the BCIL

Demo Record Runs

The actual demo ran from 06-10 JUN and resumed 13-17 JUN, to include a day for visit by the Assistant Secretary of the Army for Installations, Environment & Energy (ASA-IEE), Ms. Katherine Hammack, on 15 JUN.

Days 1 & 2 were marred by repeated GFD Trips, when the circuits were finally disabled. On Day 3, while powering all assigned loads, the theory of two ground cables contacting each other resulting in a system-wide crash was tested. Two ground cables were deliberately touched together. This caused a cross-conducting ground current, which resulted in a GFD trip. Part of the system crashed, resulting in an earlier-than-planned switch-back from system-power to shore-power for the latrines, showers, laundry, and kitchen tent for the remainder of 08 JUN. It was discovered that insulating the ground wires until just before they reached their respective grounding spikes provided additional protection against nuisance trips.

Day 4 was spent verifying the system did not suffer any damage from the previous day's trip. Only the billeting shelters (Bldgs 25-32) were powered by the system. Load banks took the place of the remaining assigned loads.

Day 5 marked the first full day of powering all assigned loads. Peak power demand was 193kW for approximately 45 minutes. The laundry's dryer had a 30kW load-step by itself. TVGM 3, assigned to power this load as well as the two showers, handled this load-step without incident. Week 2 (Days 6-10) saw the cumulative production of ~2.5MWh of energy to all assigned loads.

Soldier Training & Focus Groups

Soldiers from elements of the 542nd Quartermaster Co. and 804th Medical brigade performed a two-week exercise at the BCIL, concurrent with the STO's Demo. Soldiers with the Military Occupation Specialty (MOS) for Generator repair, installation & operation (91D), and Heavy truck mechanic (91L) were trained on the theory of operation, actual operation of the system from an automotive perspective, and switch-over/switch-back of the loads from shore-power to system-power. A total of eleven loads were switched dailybetween 0800-0830hrs and switched back between 1430-1445hrs, yielding at least six hours of runtime per day. Soldiers liked the overall concept of the system, identifying various scenarios in which the System would be used. Valuable focus-group feedback enabled us to identify opportunities for improvement. Comments ranged from: "wish we had this in-theater", to "I like the mobile nature of the system and the ease and speed with how it sets up". Leadership's feedback centered around how much they liked the fuel savings.

Army Leadership Day

On Wed, 15 JUN, the aforementioned ASA-IEE toured the BCIL facility to see the various technologies being demonstrated and displayed. The Tac V2G/V2V system was fully operational at that time. Ms. Hammack was singularly impressed with the System, and remarked that the V2G/V2V system was a serious step-up from the previously demonstrated OBVP-TVGM system at the FY14 BCIL Demo.

Several US Marine Commanders, as well as representatives with the British (UK) Army expressed interest in further developing the capabilities demonstrated by the V2G/V2V system to suit their respective mission requirements.

Bottom-Line Results: Preliminary data indicates that a typical baseline 30kW MEP-805B TQG will produce ~7kWh for every gallon it consumes (7kWh/gal). The Tactical V2G/V2V Demo System developed by TARDEC averaged 10 kWh/gal for an equivalent resistive load, when considering the 0.8 pf (power factor) of 3Ø AC loads.

FUTURE ACTIVITIES

TARDEC has already identified several opportunities for both collaboration with other agencies & service branches, as well as improvement of the overall system. TVGMs and ESUs were overweight for this exercise. The TVGMs' weight and size can be reduced to about 1/3 their present values, to be more suited to the military ground-vehicle operating environment. The ESUs were approximately 32% over their specified weight, and could be reduced to about ½ to 1/3 their present size and weight, making them, along with the TVGMs, much more manageable to move and maneuver.

Combat Vehicle-to-Grid Module (CVGM)

One component not mentioned in this paper was the CVGM. Originally specified to weigh no more than 150lbs and be two-man portable, it was tabled from this stage of system development, due to funding constraints. It remains on the table as an opportunity-item for further development.

Acknowledgements

TARDEC would like to acknowledge those individuals that at one point or another participated in, and made up the Tactical V2G/V2V Demo Team:

- **TARDEC:** Ronald Genter, Allison Hester, John Monroe, Tomas Pesys, Kenneth Ratcliff, Denise Rizzo, Ph.D., Joseph Stempnik
- **Coritech:** John Gregory and Ali Alrikabi
- **DCS**: David Larabee
- **DRS**: Mark Byron, Scotty Hughes, Terry Stifflemire, Stan Smith, and Ray Willis
- **IPERC**: Ben Garrison, (Island) Bob Harwig, Tony Maggio, Mike Miller, Stephanie Pine, Scott Roberts, and Chris Rowland
- **LexTM3 Systems**: Russ Ristau, CTO
- **Navitas**: Nicole Bennett, Thomas Drake, Kevin Foldvary, Chad Hartzog, David Hayman, Kathryn Hill, Zachariah Jerrim, Neil M. Johnson, Richard Miller, Greg Skofronick, Ben Sinsheimer

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