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SiC POWER CONVERTERS FOR MILITARY MOBILE HYBRID POWER SYSTEMS

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ABSTRACT

Silicon carbide (SiC) semiconductor devices offer several advantages to power converter design when compared with silicon (Si). An increase in power density can be achieved with SiC thanks to the reduced conduction and switching losses and to the ability to withstand higher temperatures [1]. The main system level benefits of using SiC devices on mobile hybrid power systems include large reductions in the size, weight, and cooling of the power conditioning. In this paper, the authors describe the Wide-bandgap-enabled Advanced Versatile Energy System (WAVES) with a focus on the design and testing of a SiC prototype of a WAVES power inverter. The prototype is a 10 kW three-phase AC/DC inverter that is air-cooled, IP-67 rated, bi-directional, operates down to a power factor of 0.4, and designed to have overload capability up to 350% for up to 250µs of nominal rating. Because the inverter is bidirectional, it may be used as an AC input to DC output battery charger or as a DC input to AC output AC voltage supply meeting military power quality standards.

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1. INTRODUCTION

A key takeaway from combat operations in Iraq and Afghanistan is the growing need for electrical energy. Today, the main way to produce this electrical energy is by using generators. Generators introduce a variety of challenges. The primary drawback of a generator is its need for fuel. Fuel is expensive, heavy, and flammable. More fuel means more cost, more weight, and less safety.

Getting fuel out to remote military bases requires substantial logistical coordination and puts the lives of the men and women transporting the fuel at risk. The casualty factor for fuel resupplies in Afghanistan was 0.042 at its peak in 2010. This casualty factor equated to 1 casualty for every 24 fuel resupply convoys [2].

Generators require maintenance the more they are used. If they are loaded too lightly for too long, this can lead to increased need for maintenance and wet stacking, which is a significant reliability problem with tactical diesel generators deployed in the Army. Generator maintenance requires time, effort, a specific skill set, and potentially more life-risking transport of parts and/or people [3].

Generators are also loud. Depending upon how close the generator must be to the workstations, it may be necessary to wear hearing protection and, minimally, makes verbal communication difficult. This level of noise only serves to reduce situational awareness in hostile environments and can put a mission at risk by placing a mental strain on service men and women while making critical life-and-death decisions. Generator noise signatures also eliminate any opportunity for mission stealth.

Depending upon the power requirements and criticality of the system's weapons and other loads, it can be required to have two generators on site with one available as a spinning reserve. As noted, this is a worst-case scenario regarding maintenance and reliability, and it also compounds the noise exposure problem.

To address the issues of fuel cost, lives lost, complex logistics, generator maintenance and reliability, generator noise, the need for power source redundancy, and the increasingly high power and electrical energy demands of military loads the US Marine Corps started a program called MEHPS [4]. From the prototypes designed for this program, WAVES was developed with advanced features to improve upon each of the listed advantages.

WAVES is a scalable technology that is designed to optimize generator utilization. Rather than a generator running 24 hours per day WAVES uses smart electronics and battery storage to reduce generator runtime to 4-6 hours per day. WAVES scales from 5 kW to 10 kW. It delivers 208 VAC three-phase, 120 VAC single-phase, and 20-32 VDC.

WAVES stores energy in batteries. Loads are powered from the batteries through power converters until the batteries are drained. At that point, a generator is automatically started up and used to power the loads. The generator is run at full capacity. Any power not consumed by loads is used to charge batteries through some of the same converters. By running the generator at its most efficient operating point of full capacity, fuel efficiency is optimized, and generator run time is minimized. This in turn extends the life of the generator, increases the time between planned and unplanned maintenance, and improves the reliability of the critical power supply by avoiding wet stacking conditions.

Additionally, WAVES can be configured to collect solar energy to further reduce generator runtime. If the total load of the system is less than the amount of solar power available, then WAVES uses the surplus solar power to charge batteries. Field trials have revealed that this scenario is frequent and often results in the generator not starting up until well after the sun sets.

The rest of the paper is organized as follows. Section 2 introduces the importance of using wide bandgap devices in power converters. Section 3 describes the details of the main components on WAVES as well as the deployment environment. Section 4 shows testing results, including inverter efficiency and power quality, thermal results, and fuel consumption. Finally, conclusions are drawn in Section 5.

2. WIDE BANDGAP DEVICES FOR POWER CONVERTERS

The key components on any mobile hybrid power systems such as WAVES are the power converters. These are the devices in charge of power conditioning, which implies the electrical energy conversion between AC to DC (from generator to batteries), DC to AC (from batteries to loads), and DC to DC (from batteries to loads, solar to batteries, etc.). In turn, the main components of the power converters are the power electronic switches (i.e., MOSFETs). Up to now, most of these switches are made of Si. The growing need of electrical power and higher power density of existing and future military systems are pushing the Si-based power electronics systems to their operational limits [5].

To address future needs, wide bandgap devices such as SiC and GaN (Gallium Nitride) have been developed and now have achieved manufacturing readiness level as high as 10 for some applications, as referenced in [6], [7] and [8] systems. Thanks to the development and increasing maturity levels of wide band gap devices, specifically SiC, a great opportunity to further optimize WAVES is now available.

For the WAVES application in this paper UEC Electronics has chosen SiC devices for many of the MOSFETs in the various system power converters. In general, SiC offers the following advantages when compared to Si [9] [10]:

a) Higher critical electrical field that produces higher breakdown voltages from a smaller die thickness than Si and hence lowers the conduction resistance.

b) Higher thermal conductivity

c) Higher operation temperatures and/or less cooling requirements.

d) Higher current density of approximately 2 to 3 times that of Si.

e) Higher operating switching frequencies.

Therefore, due to the lower conduction and switching losses, in conjunction with higher thermal conductivity and operating temperatures, SiC devices can use smaller heatsinks to improve power density or provide greater power for the same size heatsink. Additionally, the potential for higher switching frequency operation reduces the size of several additional components such as inductors and capacitors needed for voltage and current conditioning, increasing the power density of the system.

3. WAVES DESCRIPTION

WAVES optimizes each type of power conversion to provide stable, conditioned 28 VDC, 120 VAC single-phase, and 208 VAC three-phase power. The system accepts and regulates power from a variety of scalable renewable energy sources, scavenge power sources, energy storage arrays, and auxiliary AC sources (see Figure 1).

WAVES intelligently and adaptively manages the power available from each source to minimize fuel consumption and generator maintenance regardless of load demand.

The 10 kW WAVES includes a power inverter box, a DC PDU, Energy Storage Modules (ESM), solar arrays, a 5-15 kW generator, and the associated interface cables. The base configuration is palletized with features for securing it to the M1102 Light Tactical Trailer – Marine Corps Chassis (LTT-MCC) or the Joint Light Tactical Vehicle (JLTV) trailer. Except for the solar arrays, the system can be fully connected and operable while mounted on the trailer along with a single generator. While stationary, the system can have two generators connected for system reliability or for maintenance of the primary generator.

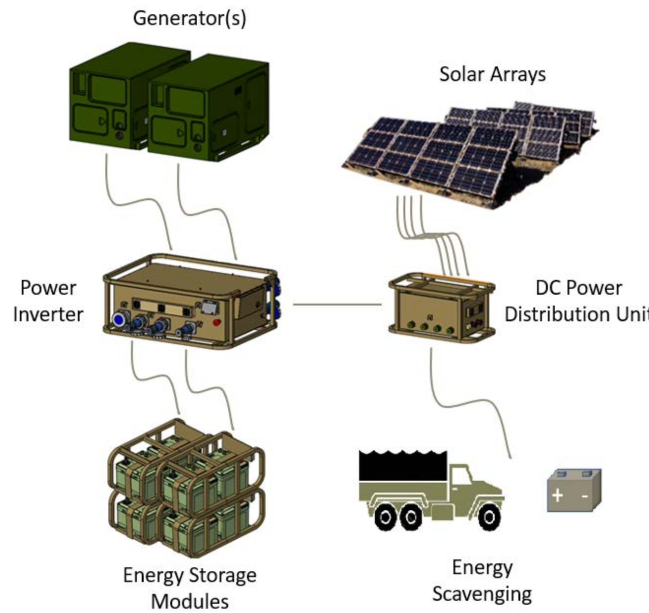

Figure 1. WAVES base system.

3.1. Power Inverter Box

The power inverter box is the chassis that contains most of the equipment used to convert AC power to DC power and vice versa. The inverter is a 12.5 kVA, 0.8 pf, bidirectional, two-stage, three-phase, galvanically isolated, 25.6 VDC from/to 120/208VAC, and air-cooled (see Figure 2).

The two stages are a DC-DC stage and an AC-DC stage. Both stages of the inverter solution are bidirectional. A dual active bridge (DAB) DC-DC stage interfaces on a “low voltage (LV)” side with a nominal 28 VDC connection, which is typically an energy storage module (ESM). The DC-DC uses Si MOSFETs on the LV side and SiC MOSFETs on the high voltage (HV) side.

The AC-DC stage interfaces with the AC loads and/or the grid/generator at a nominal 120 VAC per phase (line to neutral). The AC-DC inverter uses SiC MOSFETs. Between the two stages is a nominal high voltage DC link. This solution set provides a scalable and modular architecture that provides opportunity for improvements and additions, such as higher DC bus voltages (e.g., 48V LV, 300V HV) or more output power as the need arises.

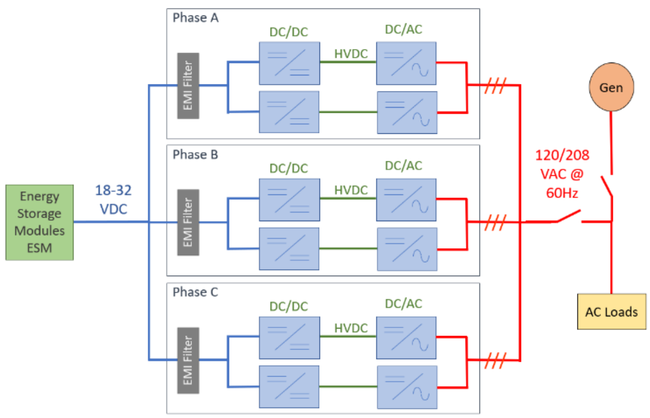

Figure 2. Power inverter box - one-line diagram.

The DC-DC converter consists of three assemblies: two circuit cards (one each for LV and HV) and one high frequency (HF) transformer-inductor assembly. The AC-DC is a single circuit card but requires a separate sinus filter circuit card. Each stage must also have its own controller card.

The DC-DC, AC-DC, and sinus filter circuit cards are mounted to a hollowed out rectangular prism heatsink with fans on either side. When installed in the mechanical enclosure a seal is created around the heatsink and the inside of the heatsink is capable of being exposed to rain or weather of any type.

Figure 3 is an image of a manufactured inverter box. Efficiency and critical power quality and load support features of the inverter are described in Section 4.

Figure 3. Power inverter picture.

3.2. DC Power Distribution Unit (PDU)

The DC PDU contains four 1 kW inputs for solar, one 4 kW input for scavenge power, and one 2 kW DC output.

The solar input accepts 20 VDC to 100 VDC, allowing connection to a solar array with open circuit voltage of 80 V with 25% overhead. When solar panels are connected, a maximum power point tracking (MPPT) algorithm is used to maximize the input power. The solar chargers are optimized for performance, manufacturability, and reduced EMI emissions.

The scavenge power DC input ports accept MIL-STD-1275E DC power from a fixed source. This feature allows the user to charge the battery bank from a vehicle, other batteries or any other compliant source of DC power that may be available now or in the future. To charge from a fixed source, the user configures the system through the front panel switches.

The DC output lugs provide 2 kW of MIL-STD-1275 quality 28 VDC output power. This regulated output has a configurable output voltage range (18-32 VDC) and current limit, if desired.

3.3. Energy Storage Modules (ESM)

The ESM is comprised of two MIL-PRF-32565B compliant batteries wired in parallel and a custom interface box. The interface box enables advanced features not required of the battery by the MIL-PRF-32565B. The interface box provides a 5-segment State of Charge (SOC) indicator and a push button to allow the operator to interrogate the ESM health and state of charge. Mechanically, the ESM box is designed to stack up to four high with an alignment mechanism for storage and shipping.

The two MIL-PRF-32565B compliant batteries in an ESM must be of the same type (A: 55 Ah, B: 90 Ah, see MIL-PRF-32565B for details), but otherwise can be comprised of any vendor battery that meets the standard. As few as two ESMs can be connected for low load operation with a 5 kW generator. ESMs configured with batteries capable of providing 650 Ah total at 20-28 VDC will allow the system to meet most customer requirements for generator cycling, silent watch, and life expectancy in the 10 kW generator configuration. This also provides the optimal capacity with the lowest total weight.

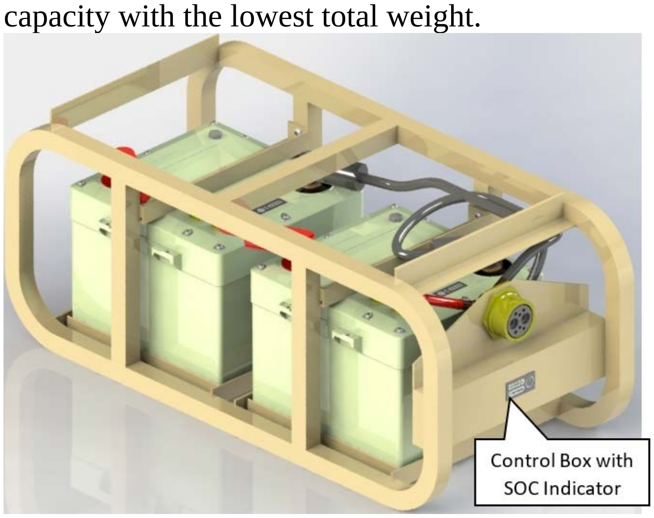

Figure 4. Energy Storage Module

Each ESM is connected to the power inverter box by a single interface cable, limiting the total number of system cables. The power inverter box can accommodate up to six ESMs for situations requiring extended silent watch or when generator cycling needs to be minimized.

The standard battery bank capacity of 650 Ah was chosen to include a reserve energy capacity. With a load of 5 kW and the battery voltage at nominal 24 VDC, 650 Ah will ensure that the system does not experience more than 6 full discharge-charge cycles in a 24 hour period. Thus, the generator does not turn on more than 6 times a day.

The ESM and the system are designed such that the ESM can be replaced while the system is in operation.

3.4. Solar Arrays

Each solar array is approximately 54 inches by 43 inches by 3 inches thick, weighs 60 pounds, and is capable of up to 470 W. The standard WAVES offering includes eight solar arrays to provide over 3.76 kW nominal power. The solar arrays will utilize an integrated “kick stand” to minimize weight and will tri-fold to allow the arrays to be setup extremely quickly and stored compactly. Arrays will be connected in parallel to maximize the power input on each channel.

3.5. Generator

WAVES can work with a variety of 120/208 VAC military generator types. WAVES is compatible with 5-15 kW Advanced Medium Mobile Power Source (AMMPS) generators and a few varieties of 3-5 kW Tactical Quiet Generator (TQG) sets.

If a generator has an auto-start capability, WAVES software can utilize it. If not, UEC has designed and implemented custom auto-start kits for these generators and can do so for most generators. Auto-start capability is not mandatory but enables autonomous power system operation for maximum fuel savings with minimum human interaction.

3.6. Deployment Environment

WAVES is designed for deployment versatility. The system components may be transported, dropped off, and then quickly set up on the ground as shown in Figure 5. Note that WAVES does not require the solar arrays, but solar collection sustainably reduces generator fuel consumption.

Figure 5. WAVES deployed on the ground.

As shown in Figure 6 WAVES is also designed to fit compactly on a standard M1102 Light Tactical Trailer – Marine Corps Chassis (LTT-MCC), or on the Joint Light Tactical Vehicle (JLTV) trailer. Except for the solar arrays, the system can be fully connected and operable while mounted on the trailer.

Figure 6. WAVES prototype on LTT-MCC.

WAVES is designed to be modular and versatile enough to support distributed deployment of the various system components for other mobile applications as well. The batteries and inverter do not have to be directly next to each other. Another example of a relevant application being considered by the Army is the potential integration of the inverter into a variety of vehicles as shown in Figure 7.

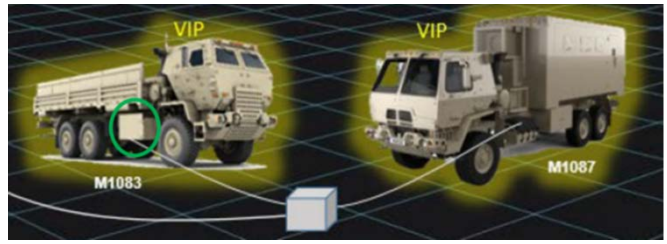

Figure 7. Notional Army-related vehicle applications of the WAVES inverter. [11]

Each component in WAVES is designed to be rugged and rated for IP-67 to survive austere environmental conditions common to military applications.

4. SYSTEM TESTING

This section presents the test results obtained with the WAVES prototype with a focus on the power inverter box. The test results include the efficiency, AC power quality and thermal management of the power inverter box. Additionally, the fuel consumption of the MEPHS system is shown.

4.1. Inverter Efficiency

The most direct way to increase fuel efficiency is to reduce the losses in converting power between DC and AC. To minimize losses and maximize fuel efficiency, special attention has been paid to each stage.

Inverter loss is affected by the choice of semiconductor devices and transformer design. The power loss, and therefore the efficiency, of an inverter at any given operating point is affected by temperature, switching frequency, DC-link voltage, modulation depth, power factor, and the operating current. At high power levels, the losses are dominated by the switching and conduction losses in semiconductor devices as well as copper losses in the transformer which increase approximately linearly with load current and result in a flatter efficiency at higher power.

The MOSFETs of the AC/DC inverter stage and the high voltage side of the DC-DC converter are SiC devices. The SiC MOSFETs have lower switching losses while maintaining low conduction losses which produces notably lower total converter losses.

Figure 8 shows a comparison of the MOSFET efficiency between Si and SiC devices in the HV stage of one phase of the DC-DC portion of the power inverter. In this graph the switching frequency was set to 100 kHz. Below 500 W a hard switching control was used, while above 500 W a zero-current control algorithm was implemented. During lower power loads <500 W, an 8% to 10% efficiency improvement can be obtained by using SiC devices. This is a significant advantage for a typical WAVES application because that is the power range where WAVES operates most of the time.

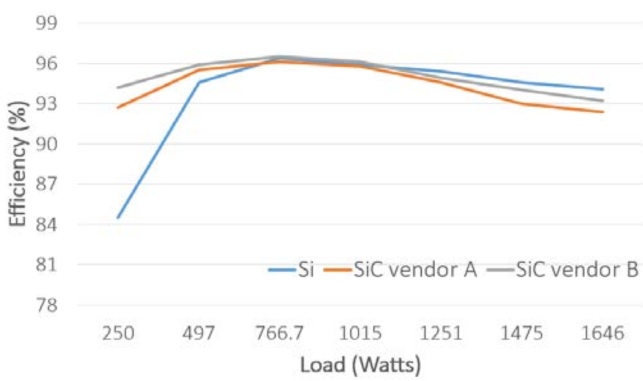

Figure 8. MOSFET Efficiency Comparison – Silicon vs. Silicon Carbide

It is important to mention that by using more advanced switching control algorithms and scaling back the cooling load, a higher efficiency could be obtained. At higher loads (1000W and above) the conduction losses dominate and at the time of testing the on-resistance of commercially available SiC components had not yet exceeded the Silicon market.

4.2. Inverter AC Power Quality

The power inverter output power quality meets MIL-STD-1332B Class B or better. Each inverter module is digitally controlled with component tolerances tight enough to ensure that voltage and frequency regulation is maintained within 3%. When configured as a three-phase inverter, a critical feature of the connections to the source and the load and can support 100% load imbalance. Any phase is capable of continuously supporting a 4.16 kVA load with no load on any other phase while maintaining an output voltage on all phases that is compliant with MIL-STD-1332B.

Figure 11 shows the response of the 12.5 kVA inverter prototype to a full load 10 kW 0.8pf load step relative to the requirements of MIL-STD-1332B. The response does not violate any transient limit and requires less than 70 ms to recover to within the steady-state limits.

4.3. Thermal Results

The WAVES design integrates all inverters into one package and the cooling is achieved by forcing air into an extruded heatsink per phase. Various design iterations and a Finite Element Analysis (FEA) evaluation of the heat removal characteristics of a variety of heatsinks for inside the enclosure were performed as part of the design and prototype of WAVES.

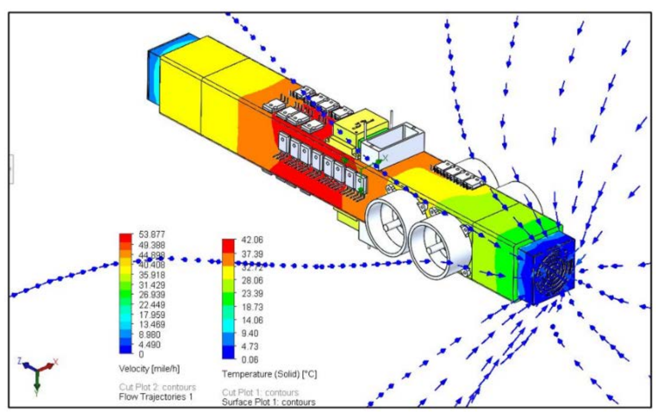

Figure 9. Power Converter Thermal Results.

This analysis led to an extruded heatsink which enables effective regulation of the internal electronics temperature while maintaining a water-tight seal in a cost-affordable, mechanical apparatus.

4.4. Fuel Consumption

As described during the introduction, fuel is expensive, heavy, and flammable. More fuel means more cost, more weight, and less safety. WAVES is designed to intelligently manage the power available from each source to minimize fuel consumption regardless of load demand. The system only starts the generator when the power stored in the ESM array is low, therefore running the generator at or near peak generation capacity to maximize efficiency and minimize run-time, thereby reducing fuel consumption (see Figure 10).

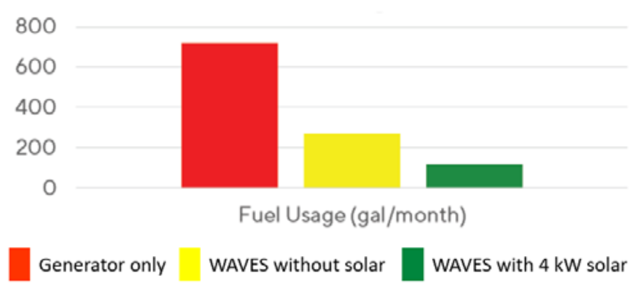

Figure 10. Monthly Fuel Usage[1]

Figure 10 shows that WAVES without solar power reduces fuel consumption by more than 50%. Adding a full complement of solar input power gives another 50% gain.

Additionally, the choice of inverter technology can have a large impact on the WAVES operational effectiveness, particularly the system fuel consumption for two reasons: a) Inverter weight reduction can help WAVES increase the amount of solar and energy storage available on the WAVES trailer, and b) Losses in the inverter transformer are often the main cause of the low inverter efficiency that leads to lower fuel efficiency.

[1] WAVES numbers are based on 24-hour test; and generator numbers are based on analysis.

4.5. Government Facility Testing

UEC's WAVES solution has been evaluated by the Platform Integrity Department of the Naval Surface Warfare Center Carderock Division and by the Power Systems and Electronics Branch of the U.S. Army Aberdeen Test Center Support. In addition to government testing, UEC's WAVES solution participated in the US Army's 72 hour Technical Support and Operational Analysis (TSOA) and 3-week Maneuver Support, Sustainment and Protection Integration Experiments (MSSPIX) programs. Each field exercise matched UEC's WAVES technology with soldiers in the field and worked to integrate our technology into multiple battlefield scenarios. Participation in these U.S. Army events allowed UEC to further define and refine the design of the WAVES production solution to meet the warfighter's needs.

5. CONCLUSION

This paper presented a 10 kW WAVES prototype and the advantages of using wide bandgap devices such as SiC in the AC/DC power inverter. During the introduction, the paper addresses the importance of generating electrical energy in remote locations, and the fact that today this is mostly achieved by using generators. Therefore, fuel consumption is critical. The most direct way to increase fuel efficiency is to reduce the losses in converting power between DC and AC, hence increasing the power converter efficiency.

The authors demonstrated that their SiC power inverter design resulted in a more efficient power converter when compared to a converter based on Si devices. The more efficient power converter takes advantage of the advanced SiC MOSFET characteristics such as reduced conduction and switching losses as well as the ability to withstand higher temperatures.

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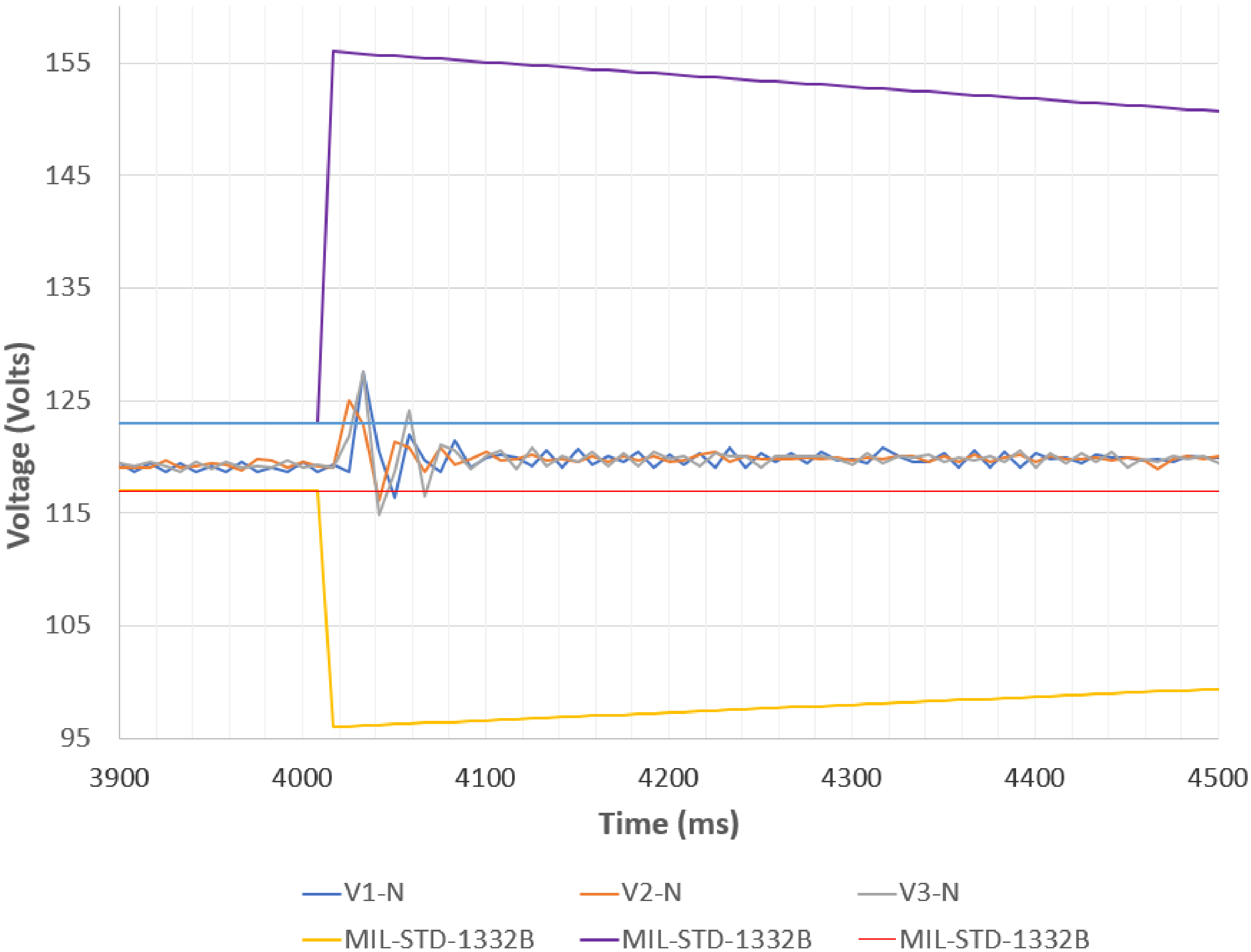

Figure 11. Balanced 10 kW 0.8 pf Load Step Response