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DEMONSTRATION OF A 75 kW SILICON-CARBIDE BASED GENERATOR CONTROLLER FOR POWER DENSE APPLICATIONS

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ABSTRACT

The latest military vehicles have been developed with on-board high voltage (600Vdc) power generation systems. The generator controller is an essential part of such a power generation system. It interfaces and converts generator 3-phase ac voltages into vehicle dc bus voltage and is the primary component responsible for vehicle bus stability. Compliance of the controller's output dc voltage with MIL-PRF-GCS600A(ARMY) is a prerequisite for stability. This paper presents the design, and test results of a 75kW continuous operation power converter achieving a volumetric power density above 7kW/liter at an 85^{o}C coolant temperature. Details regarding power quality and thermal management are discussed. Performance results will be provided, including assessment of the voltage regulation requirements as part of MIL-PRF-GCS600A, efficiency (97%), and temperature results.

INTRODUCTION

The latest US Army military vehicles have been developed with on-board high-voltage (600Vdc) power generation systems requiring generator controllers to interface and convert generator 3-phase ac voltages into vehicle dc bus voltage. A prerequisite for vehicle bus stability is compliance with MIL-PRF-GCS600A(ARMY) and therefore generator controller's output dc voltage must meet stringent voltage regulation requirements.

In response to US Army needs, ESI Motion has developed and tested a line of liquid cooled Silicon Carbide (SiC) based high power generator controllers suitable for military vehicle 600Vdc power generation system. They offer high temperature operation (as high as 105^{o}C ambient temperature) and volumetric power density in excess of 7kW/liter. The focus of this paper is to present the design, and test results of a 75kW continuous operation power converter, including power quality, EMI emissions and thermal management.

SYSTEM REQUIREMENTS

In general, the generator controller is required to convert variable 3-phase ac voltages into 600Vdc and must be tuned to work over a range of input frequencies. The summary of basic design requirements is as follow:

- Output: 75kW of continuous power on the 600Vdc voltage side per the design characteristics of MIL-PRF-GCS600A;
- Temperature: coolant temperature range of -46^{o}C to 86^{o}C with a maximum ambient operating temperature of 105^{o}C;
- EMI: compliant with the emissions and susceptibility requirements of MIL-STD-461G (CE102, CS101, CS114, CS115, CS116, RE102, RS103, and RS105;

- Motoring mode: torque and speed control of a 75kW, 3-phase permanent magnet machine for the speed range of 1200rpm to 7000rpm;
- Environmental: basic shock conditions consist of imposing shock half sine impulse of 50g, relative humidity exposure up to 100%.

GENERATOR CONTROLLER DESIGN

A functional block diagram for the generator controller is shown in Figure 1. Power stage consists of a solid-state input/output contactor equipped with a pre-charge function (required for motoring operation), an EMI filter, SiC based voltage source inverter with ceramic DC link capacitors, galvanically isolated gate drivers and necessary current and voltage sensors.

Control stage includes DSP which executes control algorithm, analog and digital circuits providing fault detection and sensing and communication interfaces. Internal custom DC-DC converters, supplied by the external 28Vdc power provide isolated and non-isolated auxiliary power to the control and gate drive circuitry.

Interconnects are implemented through a busbar structure and all board-to-board connections are connectorized with minimum wiring needed only to route temperature sensors. Generator controller also includes a custom designed cold plate required for the liquid cooling loop.

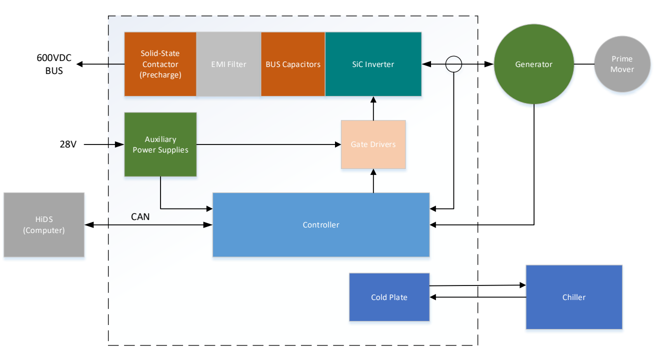

Figure 1: Generator Controller Functional Block Diagram

Generator controller implements ESI Motion's proprietary control architecture based on vector control algorithm to provide active rectification of generator ac voltages and near unity power factor at its input terminals. It is equipped with a convenient user-friendly PC interface that allows data monitoring (oscilloscope data capturing feature capable of 25μs time resolution) and adjustment of various power and control system variables simplifying testing and system level integration. It is controllable over CAN or USB data bus and is LabVIEW compatible. Figure 2 shows a screenshot of ESI motion's proprietary PC interface.

Figure 2: Generator Controller PC Interface Screenshot

Figure 3 shows a final completed ~~demonstration~~ unit implementing liquid cooling. Generator controller ~~Demonstration hardware~~ hardware was designed and built to meet the system design specification as listed in Section 2, and to provide the steady-state voltage within 565 V – 635 V (600 V ± 35 V), having ripple amplitude and distortion factor below 9 V and 0.015 respectively, and for the permanent magnet generator speed range of 1200 rpm to 7000rpm.

Further, this power converter is capable of operating in motoring mode by controlling torque and speed of a 75kW, 3-phase permanent magnet machine making it suitable for use in Integrated Starter Generator (ISG) applications.

Figure 3: 75 kW SiC Based Generator Controller Hardware

TEST RESULTS

Testing was performed in several stages. After component and system level integration testing, the assembled unit without enclosure was subject to a series of thermal tests to verify temperature rise of all electrical and mechanical components in the package. The coolant loop was attached and coolant temperature was varied while generator controller was operating at a maximum power level of 75kW until thermal equilibrium was reached (approximate 45 minutes operation).

Figure 4 shows a thermal image of the hardware unit at a coolant temperature of 75ºC. As can be seen, no hardware component exhibited temperature rise of more than 10ºC. After component with the highest temperature rise have been identified, the temperature sensors were installed and tests were repeated for fully enclosed hardware unit and at a maximum coolant temperature of 85ºC and a maximum ambient temperature of 105ºC while temperature was monitored through a PC interface. After 80 hours of endurance testing, it was determined that no component inside the package exceeds maximum temperature of 125ºC while operating at a maximum power level.

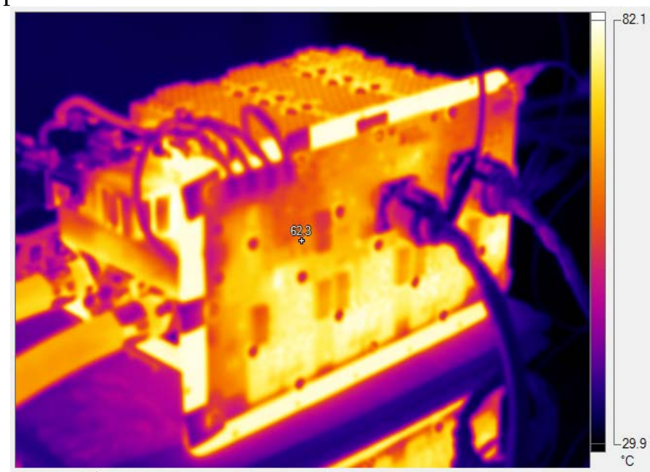

Figure 4: 75 kW SiC Based Generator Controller Hardware

After the thermal testing confirmed that completed hardware unit satisfies system requirements from Section 2, power quality and EMI tests were performed.

Figures 5 and 6 show the generator controller output dc voltage transients (blue trace) overlaid with the steady-state and normal transient limits of MIL-PRF-GCS600A (green trace). The resistive load bank was configured for a 40kW resistive step-load and the machine speed was set to 7000rpm.

As can be noted, the voltage transients are within the limits of MIL-PRF-GCS600A. When the load is applied the voltage sags to 560V and returns to 600V within 25ms. When the load is removed the voltage rises to 650V and returns to 600V within 25ms.

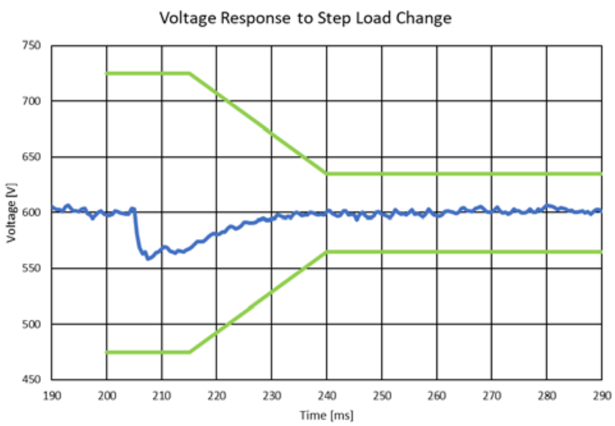

Figure 5: Generator Controller Voltage for 40 kW Step-Load Transient

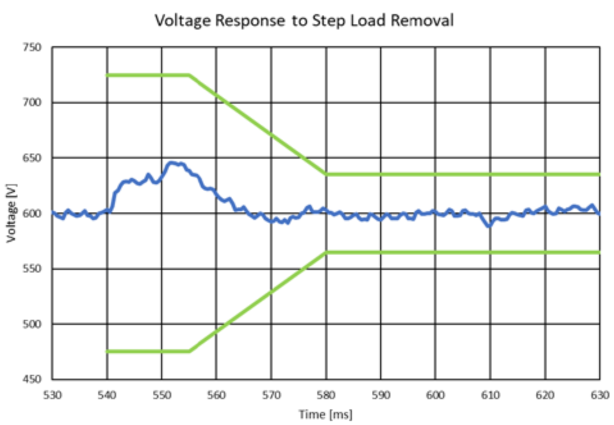

Figure 6: Generator Controller Voltage for 40 kW Load Drop Transient

Figures 7 and 8 show the voltage ripple and the distortion spectrum of the generator controller output dc voltage (blue trace) overlaid with the upper and lower steady-state ripple amplitude limits defined in MIL-STD-GCS600A (Figure 7) and the upper distortion limit as defined in MIL-STD-GCS600A (Figure 8, red trace). The resistive load bank was configured for a 50kW continuous resistive load and the machine speed was set to 7000rpm.

As can be noted, although compliance is required at the vehicle level, the component level voltage ripple and distortion spectrum are below maximum allowable per MIL-PRF-GCS600A.

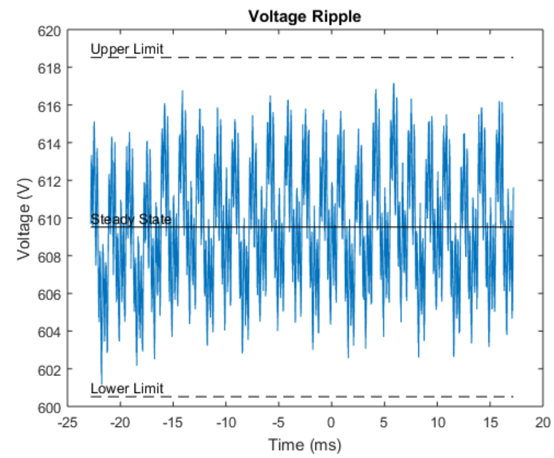

Figure 7: Generator Controller Output DC Voltage Ripple

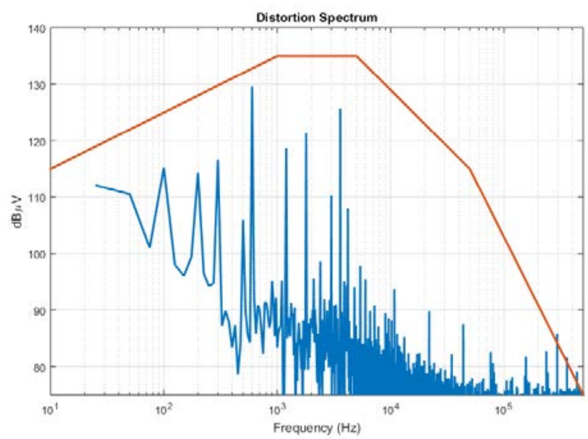

Figure 8: Generator Controller Output DC Voltage Distortion Spectrum

CONCLUSION

ESI Motion has developed a line of liquid cooled Silicon Carbide (SiC) based high power generator controllers suitable for military vehicle 600Vdc power generation system. This paper presented a hardware design and associated test results of a 75kW continuous operation power generator controller developed in response to increased US Army needs.

A liquid cooled hardware solution rated for continuous operation at 105°C ambient temperature and offering volumetric power density in excess of 7kW/liter was built and tested with favorable results. Test results show compliance with MIL-PRF-GCS600A on the component level while providing 75kW continuous operation power and verified that these new hardware solutions are ready to meet the new and stringent performance and reliability goals of the latest US Army military vehicles.

ACKNOWLEDGMENTS

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