EVALUATING VOLTAGE REGULATION COMPLIANCE OF MIL-PRF-GCS600A(ARMY) FOR VEHICLE ON-BOARD GENERATORS AND ASSESSING OVERALL VEHICLE BUS COMPLIANCE.

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ABSTRACT

For the latest military vehicles being developed with high-voltage, on-board power generation systems, compliance with MIL-PRF-GCS600A(ARMY) is a prerequisite for vehicle bus stability. The primary component responsible for stability is the generator/controller. As part of MIL-PRF-GCS600A, the voltage regulation requirements for the generator sub-system can be validated in the laboratory. However, determining overall vehicle electrical system compliance before prototype integration is more difficult. The individual loads on the bus may not be available for laboratory integration and testing. Likewise, the vehicle prime mover, an internal combustion engine (ICE), may not be available. Assessing compliance to MIL-PRF-GCS600A during the sub-system development phase, prior to vehicle build, can aid in optimization of the electrical system, i.e. vehicle bus capacitance sizing and allocation. Vehicle electrical system compliance can be assessed using high fidelity generator/controller models together with ICE and load models. Various load duty cycles and fault conditions can be simulated and evaluated with respect to MIL-PRF-GCS600A.

With its two world class laboratories, the Motor Testing Laboratory and the new Ground Systems Power and Energy Laboratory (GSPEL), the US Army Tank Automotive Research, Development and Engineering Center (TARDEC) is uniquely equipped to perform characterization and testing of high-voltage vehicle generator systems. Generator testing to MIL-PRF-GCS600A is part of TARDEC's standard electrical machine testing and characterization procedures. From testing and characterization results, high fidelity models are developed and validated.

INTRODUCTION

The US Army Tank Automotive Research, Development and Engineering Center (TARDEC) Motor Test Laboratory is equipped to evaluate electrical machine and drive systems for military and civilian applications. Typical applications include power generation, propulsion, servo-mechanical and power conversion. Performance specifications, fault tolerance, integration practicability, Technology Readiness Level (TRL), reliability and controllability can be evaluated.

The focus of this paper is the compliance assessment of a vehicle on-board electrical power generation systems with respect to military performance specification MIL-PRF-GCS600A(ARMY). The first objective is sub-system level bench testing of a prototype generator system using a power supply as a load. Results of voltage regulation under steady state operation and during transient step loading are presented.

Vehicle level testing and fully operational electrical power characterization testing are planned for late FY13. Vehicle compliance, however, can be assessed from the development of a high level generator system model and its placement into a vehicle electrical system model; the generator system performance can simulated with respect to typical vehicle load impedances and duty cycles.

The second objective of this paper is to develop a model of a prototype vehicle power generation system. As part of an ongoing effort to increase on-board vehicle power, TARDEC is in the process of evaluating this system. A standard set of tests are performed to characterize the machine (only the rated power vs. speed curve was provided by the developer). From the characterization data, a model of

the generator and power converter is developed. This model, coupled with the dynamometer dynamic model is experimentally validated. With the validated model, overall vehicle electrical bus responsiveness is evaluated with respect to various load disturbances at different speeds, as well as various amounts of bus capacitance. The dynamometer model is replaced with a diesel engine model. When the prototype generator is integrated into a fully operational vehicle, these results can be verified. If successful, vehicle compliance with MIL-PRF-GCS600A can be assessed from laboratory testing. Deficiencies and design opportunities, e.g. capacitance optimization, can be determined and addressed prior to vehicle integration, saving time and money.

The next section details MIL-PRF-GCS600A and addresses the factors that affect compliance. The following section describes the electrical machine testing facilities and capabilities of TARDEC and the experimental setup. Results are presented and discussed. In the final section, the generator model is developed. The model is coupled with a basic diesel engine model and typical overall vehicle capacitance is added to simulate performance of the power generation system connected to a vehicle DC bus.

MIL-PRF-GCS600A(ARMY)

In 1955, MIL-STD-704 [2] was developed to provide an electrical specification for military aircraft. Requirements for AC and DC power systems as well as utilization equipment are defined. In 2010, MIL-PRF-GCS600A was developed to provide electrical specifications for military ground vehicles, outlining requirements for the 600VDC bus and utilization equipment. Similar to MIL-STD-704, five characteristics of the electrical system are described: (1) Steady state voltage range, (2) voltage transients, (3) ripple amplitude, (4) distortion factor, and (5) distortion spectrum. All five requirements are described in section 3.1.3.

3.1.3 Electrical Characteristics. The electrical characteristics, when measured at the terminals of the utilization equipment, shall be in accordance with Table 1.

Steady-state Voltage	565V – 635V (600V +/- 35V)
Normal Transients	475V – 725V for 15ms (See Figure 1)
Ripple Amplitude	9V
Distortion Factor	0.015
Distortion Spectrum	See Figure 2

Figure 1 shows the steady state voltage limits and normal voltage transient limits of MIL-PRF-GCS600A. The nominal voltage is 600VDC. The equipment on the bus must be able to operate continuously at DC voltages +/- 35V from nominal and AC voltage ripple of 9V_peak. In addition, the

equipment must be designed to sustain voltage transients between 475-725V for 15ms.

Variation in steady state voltage can result from exceeding power limits of the generator system or steady-state error in the voltage regulation control. Voltage ripple on the bus can be caused by engine torque pulsation (i.e. combustion ripple), instability in the generator system control loop, DC current harmonics from loads, and source/load impedance mismatch. DC bus voltage transients are typically a result of load disturbances.
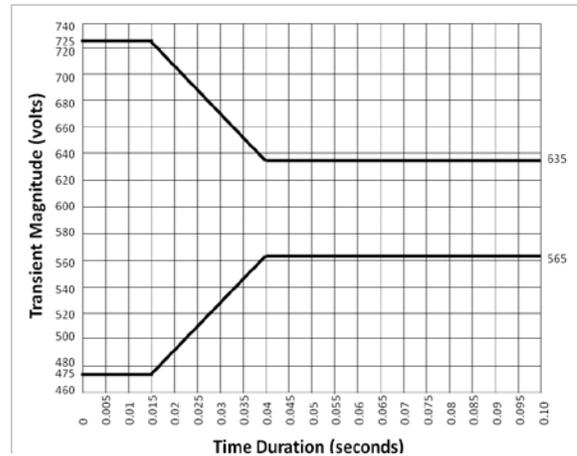
Figure 1: MIL-PRF-GCS60A bus voltage limits
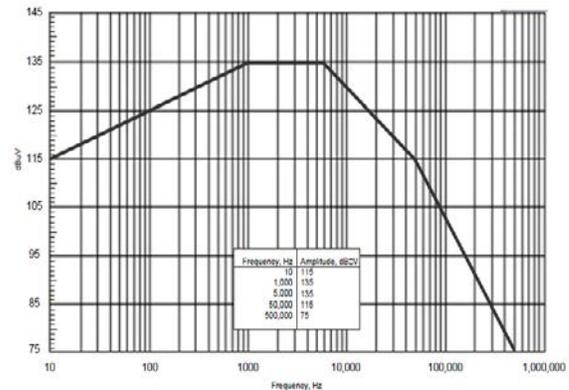
Figure 2: MIL-PRF-GCS60A bus Distortion Spectrum

The responsiveness of the generator system (and the prime-mover), the bus impedance, and the severity of the load change dictates the magnitude and duration of the voltage transient.

The generator system responsiveness is determined by several factors: (1) prime-mover responsiveness, (2) the generator electrical and mechanical time constants, (3) the current and voltage control loop bandwidth, and (4) the amount of capacitance of the generator's DC-link.

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The responsiveness of a generator can be evaluated with respect to the normal transient envelope by applying resistive step load. Section *4.2 Sub-System Level Bench Testing* of MIL-PRF-GCS600A states:

4.2.1 <u>Voltage Regulation to Step Load</u>. All power sources shall be bench tested with a simulated load profile (equivalent to the worst case operation of the system) to verify that electrical characteristics meet normal transient performance.

Figure 2 is the Distortion Spectrum of MIL-PRF-GCS600A. The distortion spectrum and distortion factor are power quality attributes of the DC bus voltage [1]. The distortion spectrum is the frequency content of the bus voltage with an upper limit defined in MIL-PRF-GCS600A(ARMY). The distortion factor (1) is defined as the ratio of the amplitude of the harmonics relative to the DC component in the signal [3]. It represents the Total Harmonic Distortion (THD) of the voltage waveform.

$$\text{Distortion Factor} \;=\; \frac{\sqrt{\sum_{h=1}^{\infty} V_h^2}}{V_{DC}} \qquad (1)$$

DYNAMOMETER VALIDATION RESULTS

TARDEC has two world class laboratories for electrical machine testing, the newest one is part of the Ground Systems Power and Energy Laboratory (GSPEL). Both laboratories are equipped with 4-quadrant dynamometers (267kW and 350kW induction machines) and high voltage, controllable power supplies (three 900V / 250kW and one 800V / 800kW unit). In addition, there is a controllable, resistive load bank available (Figure 3). It is liquid cooled and capable of 250kW. The resistor banks can be paralleled to achieve different power levels and can be switched under load in 5kW steps.

Figure 3: Dynamometer and Programmable Resistive Load bank

In the test setup, the generator was driven by the IM dynamometer. The output of the generator controller was connected the load bank. In some of the tests, the 250kW laboratory power supply was also connected to the bus, adding an additional 2700µF capacitance. The dynamometer/generator speed and torque were recorded along with the load bank voltage and current.

Resistive Step Loading (MIL-PRF-GCS600A 4.2.1)

The resistive load bank was configured for a steady-state 19kW load. The dynamometer was set to regulate speed at 1800rpm. Figure 4 shows the generator voltage and current for a 70kW resistive step load. When the load is applied the voltage sags to 554V and then returns to 600V in 60ms. The dc current goes from 32 to 148amps.

Figure 5 shows the speed and voltage of the generator. The speed of the dynamometer drops by 44rpm (2.4%) when the generator responds to the applied load step. Within 570ms the dynamometer returns to 1800rpm. Figure 6 shows that the voltage transient is within the limits of MIL-PRF-GCS600A. Figure 7 shows the voltage transient when the 70kW load is removed.
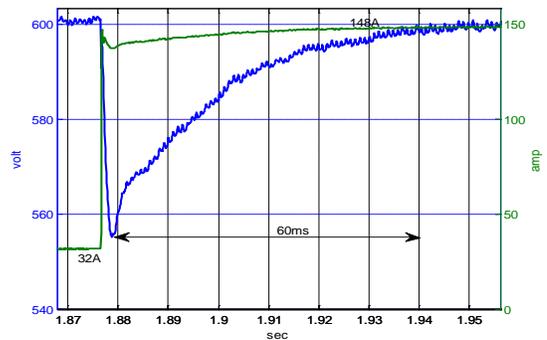
Figure 4: Generator voltage and current during step-load transient
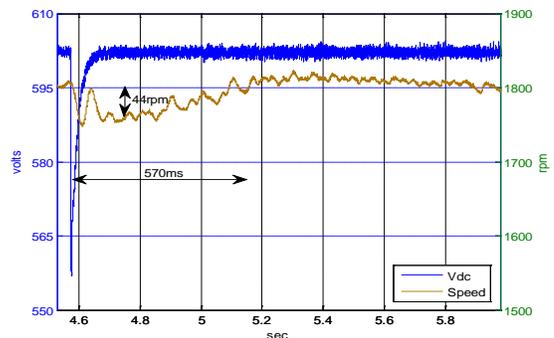
Figure 5: Generator voltage and speed during step-load transient

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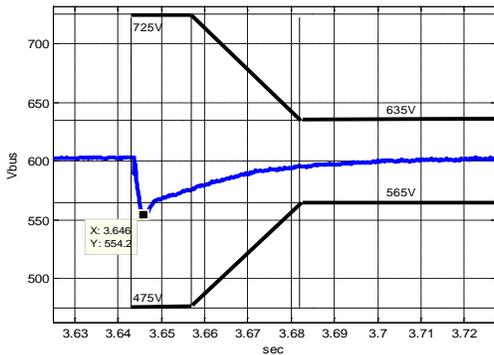
Figure 6: Generator voltage and MIL-PRF-GCS600A limits for 70kW step-load transient
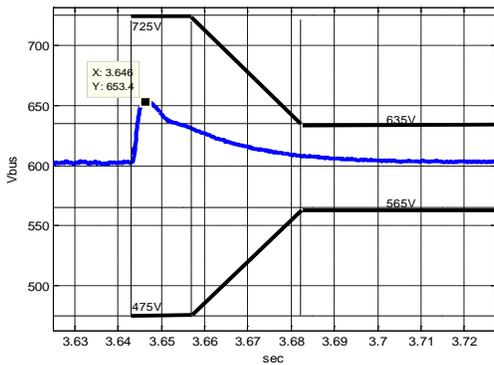
Figure 7: Generator voltage and MIL-PRF-GCS600A limits for 70kW load drop transient

Along with resistive loads, constant power loads are also on the vehicle electrical bus. Constant power loads, such as motor drives, draw more current as the voltage decreases to maintain the same power. These motor drives have capacitive DC-links for decoupling line inductance. The additional capacitance affects the stability of the bus. The 250kW laboratory power supply is used to emulate a constant load. Figure 8 shows the test setup with both the power supply and resistive load bank connected in parallel with the generator.
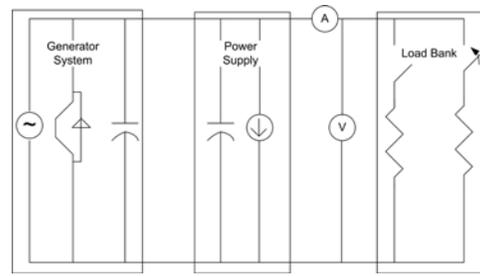
Figure 8: Generator and load lab configuration

MIL-PRF-GCS600A Section 4.2.1 requires voltage regulation compliance during a worst case step load event. For the target application, the worst case step load was determined to be 70kW. To validate this, the laboratory power supply is configured for power regulation of 19kW, replacing the static 19kW resistive load. Then, a resistive load of 70kW is switched on. Figure 9 compares the generator voltage response to both cases: (1) static 19kW resistive load + 70kW dynamic resistive load and (2) static 19kW constant power load + 70kW dynamic resistive load. There is approximately 10V difference between the voltage transient. The additional capacitance of the power supply reduces the voltage sag.
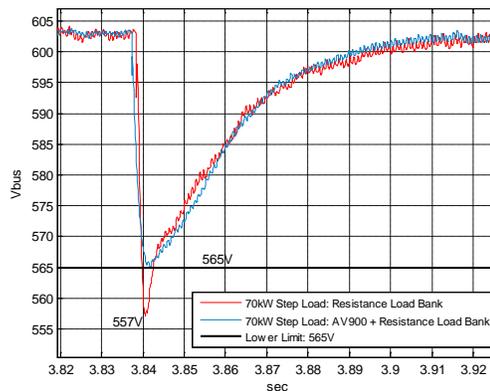
Figure 9: DC bus voltage transient comparison

Distortion Evaluation

The distortion spectra for three steady-state operating points are shown in Figure 10 with the blue lines representing the upper limits defined in MIL-PRF-GCS600A(ARMY). The first plot shows the distortion spectrum of the generator DC bus voltage with an 18.7kW resistive load at 1800rpm. The second plot was the result of an increased resistive load of 87.8kW. The third plot included a 50.1kW resistive load and an additional 18.7kW

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load from the laboratory power supply, which added 2700µF capacitance to the bus.

Figure 10: Distortion spectra for steady-state operation

The distortion factors for the three plots in Figure 10 are 0.0012, 0.0015, and 0.0010 respectively. MIL-PRF-GCS600A permits a maximum distortion factor of 0.015. Although compliance is required at the vehicle level, the component level distortion spectra and factors are below the maximum allowable.

MODELING THE GENERATOR RESPONSE

MIL-PRF-GCS600A requires Electrical Characterization Testing be performed on a fully operational electrical power system integrated into an Army ground vehicle during routine operation. However, assessing compliance prior to full integration is a worthwhile effort. In its prototype development phase the generator's size and impedance can be optimized with respect to estimated vehicle loads and duty cycles. Of particular interest is the sizing of the overall bus capacitance which is the sum of the generator and load DC-links. Greater capacitance increases bus stability, however increases the weight and size of the generator controller.

Modeling and simulation is a means to assess compliance to MIL-PRF-GCS600A without a fully operational vehicle electrical power system (integrated or standalone). A generator model was developed and validated. Simulation analysis was conducted on DC-link capacitance optimization.

Generator System Model

The generator system tested was a Permanent Magnet Synchronous Machine (PMSM). PMSM generators are being used for vehicle on-board electrical power generation because of their high power density. The engine provides the input torque to the generator. The resulting AC winding voltages are converted to DC voltage via an inverter. This method of conversion is called active rectification and is realized using field-oriented control. [4]

The generator parameters were experimentally determined in the TARDEC Motor Test Laboratory as part of a larger effort to fully characterize the generator. The controller response was estimated from the step loading testing of the previous sections. Figure 11 is the block diagram of the modeled generator and controller. Also shown are the dynamic models for the dynamometer and laboratory loads.
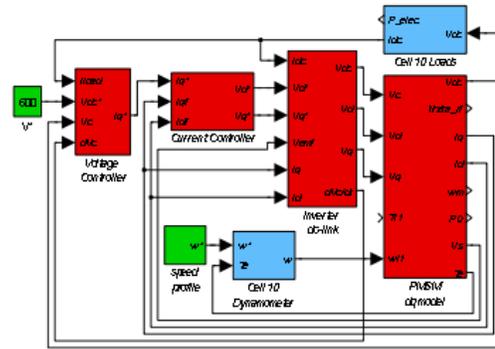
Figure 11: Model of generator, controller, and load

For model validation the 70kW resistive load and the power supply constant power load were simulated (2).

$$\frac{dV_c}{dt} = \frac{1}{c}\left[Iq - \left(\frac{P}{V_c}\right) - \left(\frac{V_c}{R(t)}\right) \right] \qquad (2)$$

Where: Vc = dc-link voltage
Iq = Quadrature axis current
C = DC-link (+Power Supply) capacitance
P = kW of constant power load
R = Resistive load

Model Validation

The generator, dynamometer, and load models were experimentally validated. Figure 12 shows the comparison

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between the experimental voltage response and the simulated voltage response to step load and constant power load. In addition, the generator model was also validated with respect to various speeds, including low speeds resulting in current limiting and speed transients similar to transmission shifts.
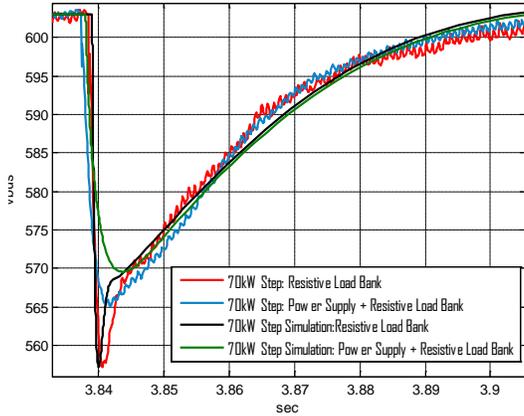
Figure 12: Simulated vs. experimental results

50% Reduction in DC-Link Capacitance

Figure 13 shows the voltage response when the generator DC-link capacitance is reduced by 50%. When the 2700μF from the laboratory power supply is on the bus, there is less than 4V difference in voltage sag. However, without the laboratory power supply capacitance, there is 20V difference in voltage response.
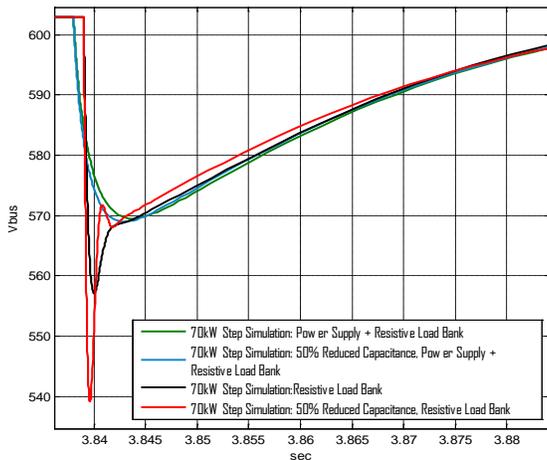
Figure 13: Voltage response comparison with different bus capacitance

CONCLUSION

This work has developed modeling and simulation tools for power generation system analysis and optimization and established the laboratory capability to validate the results.

Methods to characterize a black-box power generation system without a published set of parameters, build models, and verify compliance with the voltage regulation requirements of MIL-PRF-GCS600A(ARMY) have been developed. The power generation system model created can be combined with models of an engine and high-voltage bus architecture to assess power quality at the vehicle level. System response can be evaluated for varying DC-link capacitance values and EMI filter parameters, controller gains, and driveline inertia.

This work supports optimization (minimization) of the bus capacitance for power generation systems. Although greater levels of capacitance can increase bus stability, there are implications related to cost, weight, size, and cooling of the power electronics. Finally, the optimization methods can be expanded to help a vehicle integrator allocate capacitance across all LRUs in high-voltage bus architecture for ground vehicle applications while maintaining voltage regulation compliance.

ACKNOWLEDGMENTS

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[3] IEEE Standard 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, April 12, 1993

[4] R. Burgos, E. Wiechmann, J. Holtz, " Complex State-Space Modeling and Nonlinear Control of Active Front-End Converters," IEEE Trans. Ind. Appl., vol. 52, No. 2, April 2005 pp. 363-377

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