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

Wesley G. Zanardelli, Ph.D.
Advanced Propulsion Team
US Army TARDEC

CPT John Kelly
ARSC, DET 8
US ARMY RDECOM-TARDEC

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Presentation Overview

- Objectives
- Background
- Experimental Setup
- Characterization and Power Quality Test Procedures
- Experimental Results
- Modeling
- Simulation Results
- Modeling Parameter Variation
- Conclusions
- Future work

Objectives

- Component level compliance with MIL-PRF-GCS600A(ARMY)
- Identification of parameters on power generation components
- Electrical machine characterization
- Modeling
- System level power quality compliance
- Optimization of high-voltage bus capacitance

Background

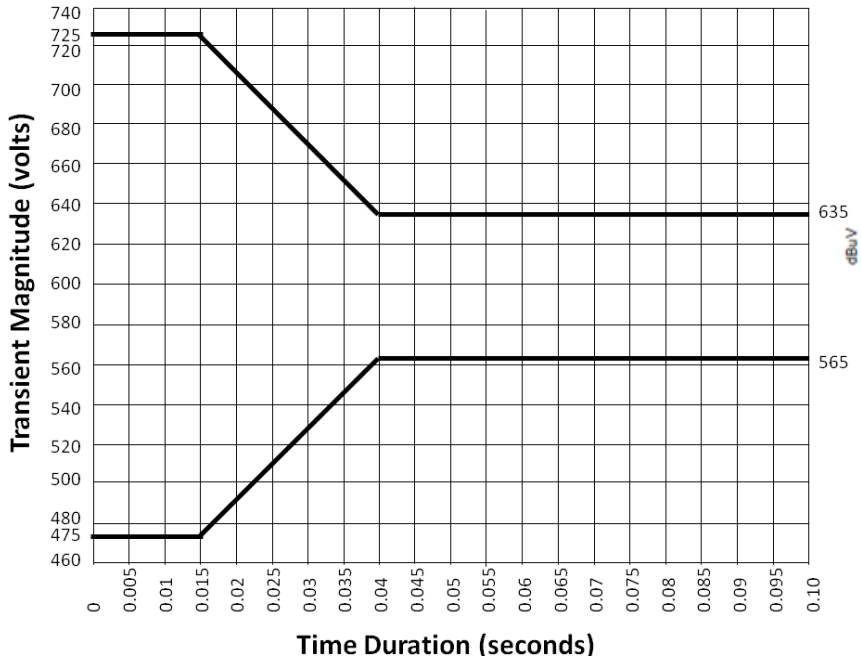
Background
MIL-PRF-GCS600A(ARMY)

- 3.1.3 Electrical Characteristics

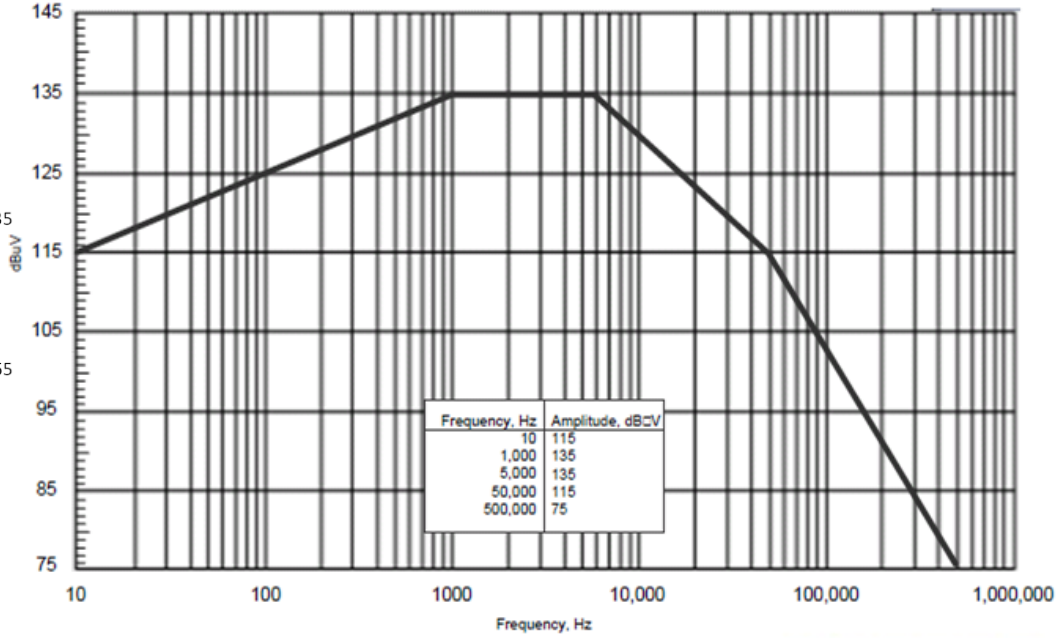
Steady-state Voltage	565V – 635V (600V ± 35V)
Ripple Amplitude	9V
Distortion Factor	0.015

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

- Normal Transients: 475V – 725V for 15ms

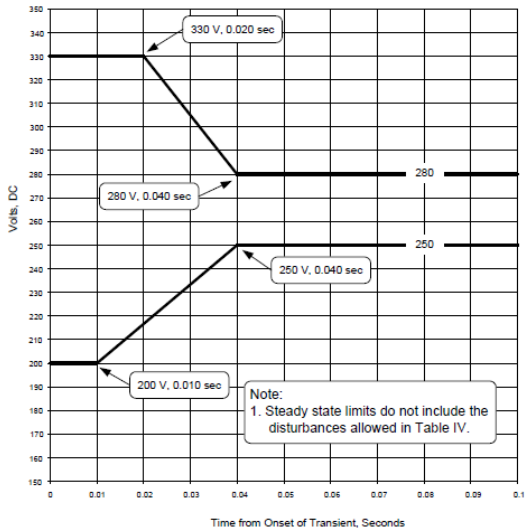


- Distortion Spectrum

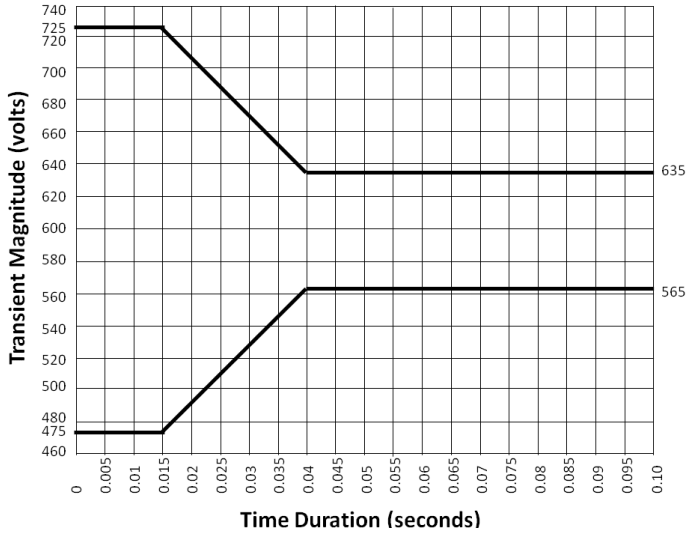


Background MIL-STD-704F vs. MIL-PRF-GCS600A(ARMY)

- Normal Transients



- MIL-STD-704F (270VDC)

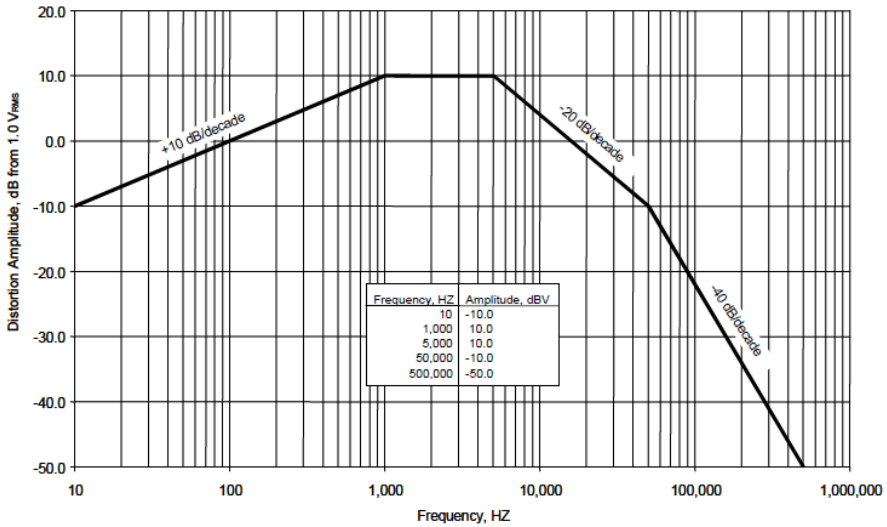


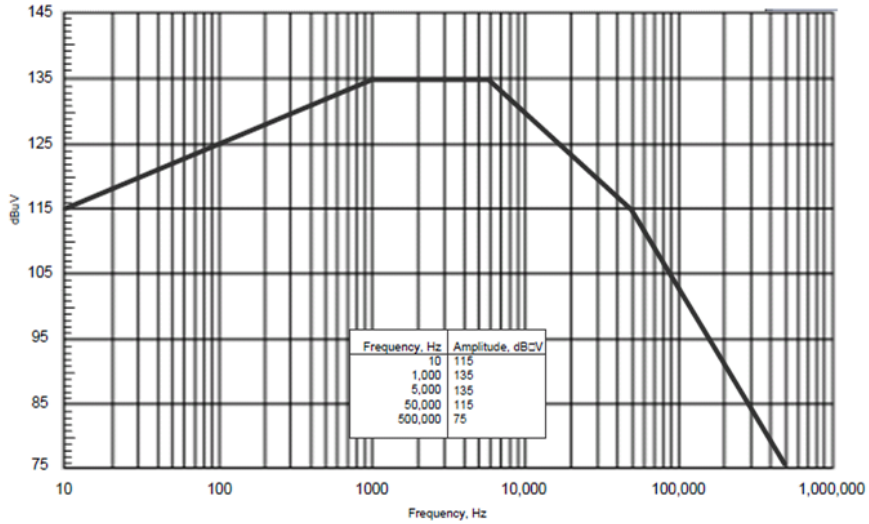
- MIL-PRF-GCS600A(ARMY) (600VDC)

Specification	MIL-STD-704F (270VDC)	% of Nominal	MIL-PRF-GCS600A(ARMY) (600VDC)	% of Nominal
Steady-State Voltage	250V - 280V (270V +10V / -20V)	11.1%	565V - 635V (600V ± 35V)	11.7%
Normal Transients	200V - 330V for 20ms (up) / 10ms (down), 40ms settling time	48.1%	475V - 725V for 15ms, 40ms settling time	41.7%
Ripple Amplitude	6V	2.2%	9V	1.5%

Background MIL-STD-704F vs. MIL-PRF-GCS600A(ARMY)

- Distortion Spectrum





- MIL-STD-704F (270VDC)
  - Distortion Factor: 0.015

Frequency	Amplitude, dBV	Amplitude, V	% of Nominal
10	-10	0.316	0.12%
1000	10	3.16	1.2%
5000	10	3.16	1.2%
50,000	-10	0.316	0.12%
500,000	-50	0.00316	0.0012%

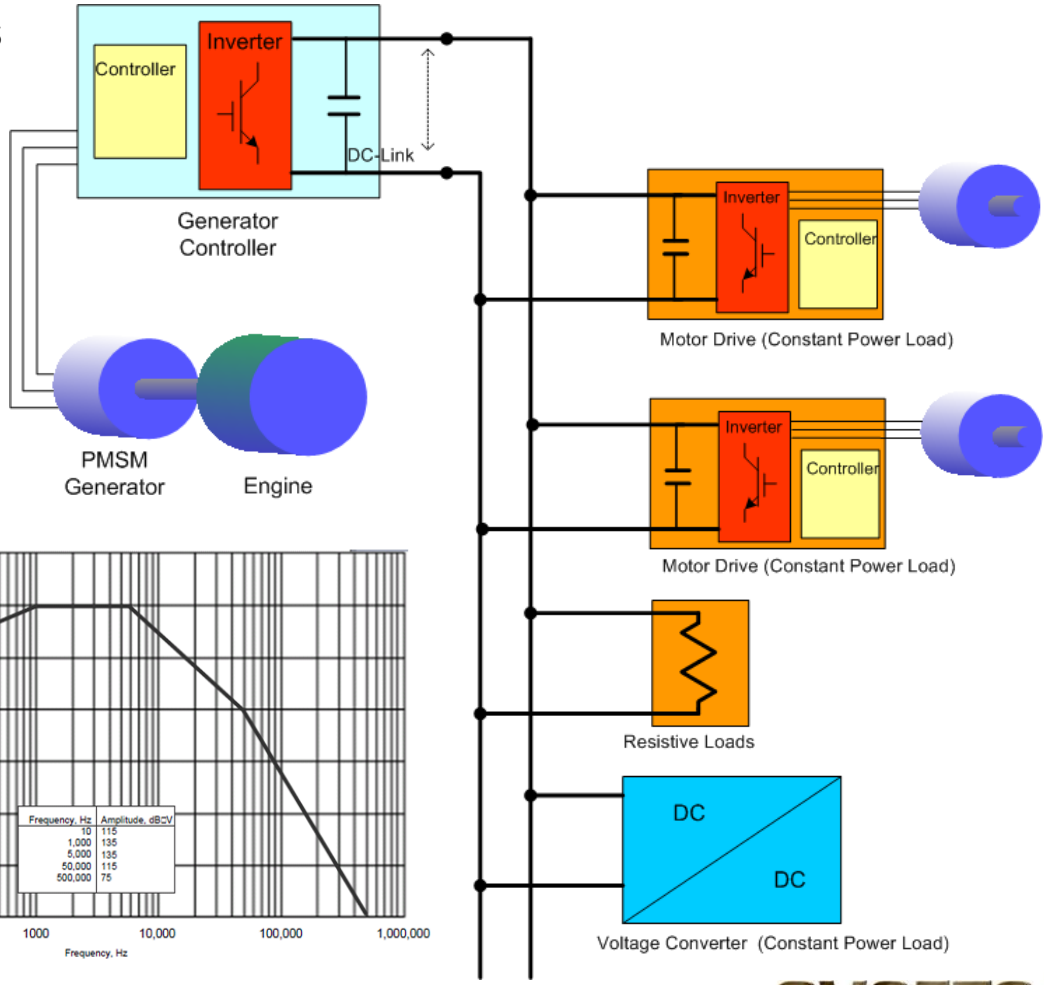
- MIL-PRF-GCS600A(ARMY) (600VDC)
  - Distortion Factor: 0.015

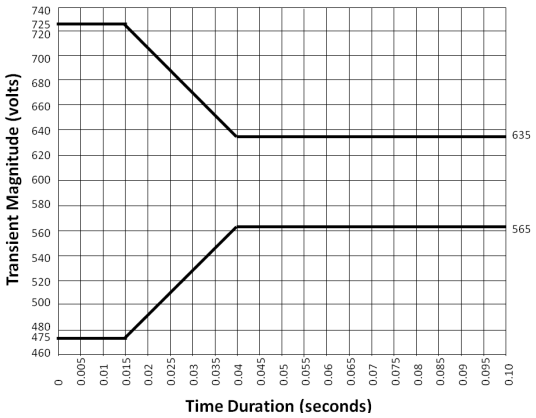
Frequency	Amplitude, dBµV	Amplitude, V	% of Nominal
10	115	0.562	0.09%
1000	135	5.62	0.9%
5000	135	5.62	0.9%
50,000	115	0.562	0.09%
500,000	75	0.00562	0.0009%

Background: Typical Vehicle Architecture

POWER AND MOBILITY

- Vehicle Loads
  - Motor Drives & Voltage Converters
    - Constant Power
    - Capacitive (dc-link)
    - Switching noise
  - Resistive Loads
  - Inductive Loads
    - EMI filters
    - Phase Margin Reduction

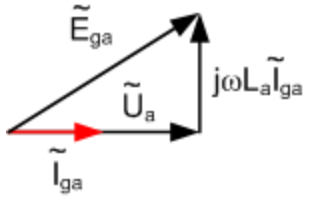




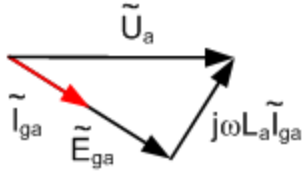
Background: Generator Control Theory

POWER AND MOBILITY

- Active Rectification
  - Inverter required for Voltage Control
  - Unity Power Factor is possible at terminals

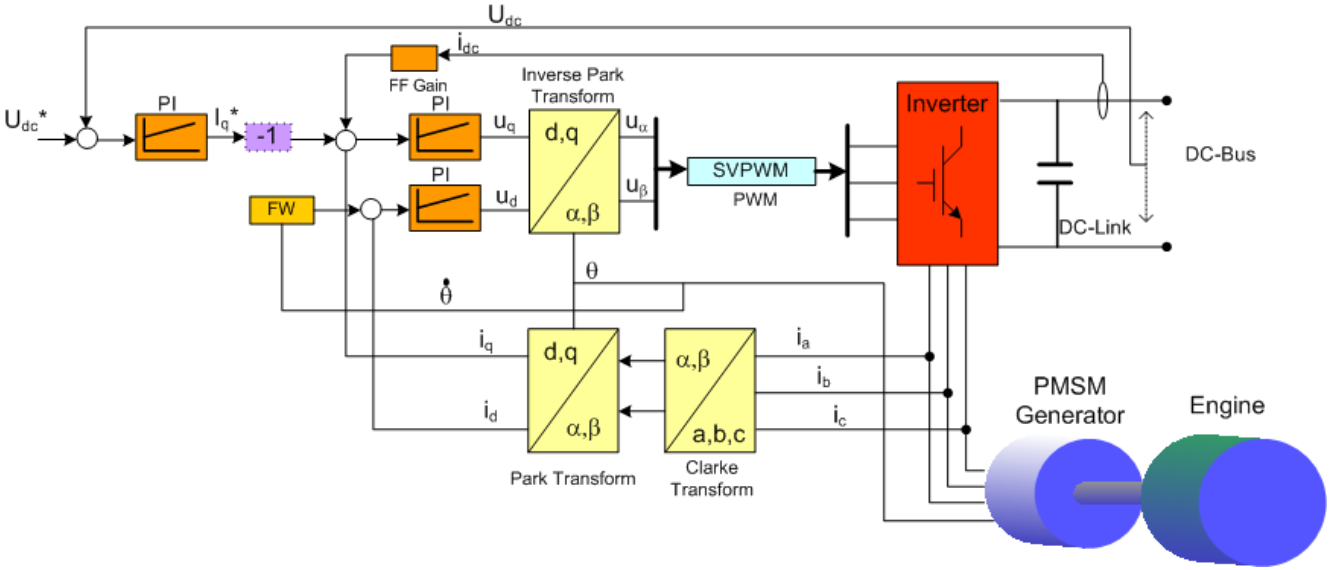


Generator Phasor Diagram



Motor Phasor Diagram

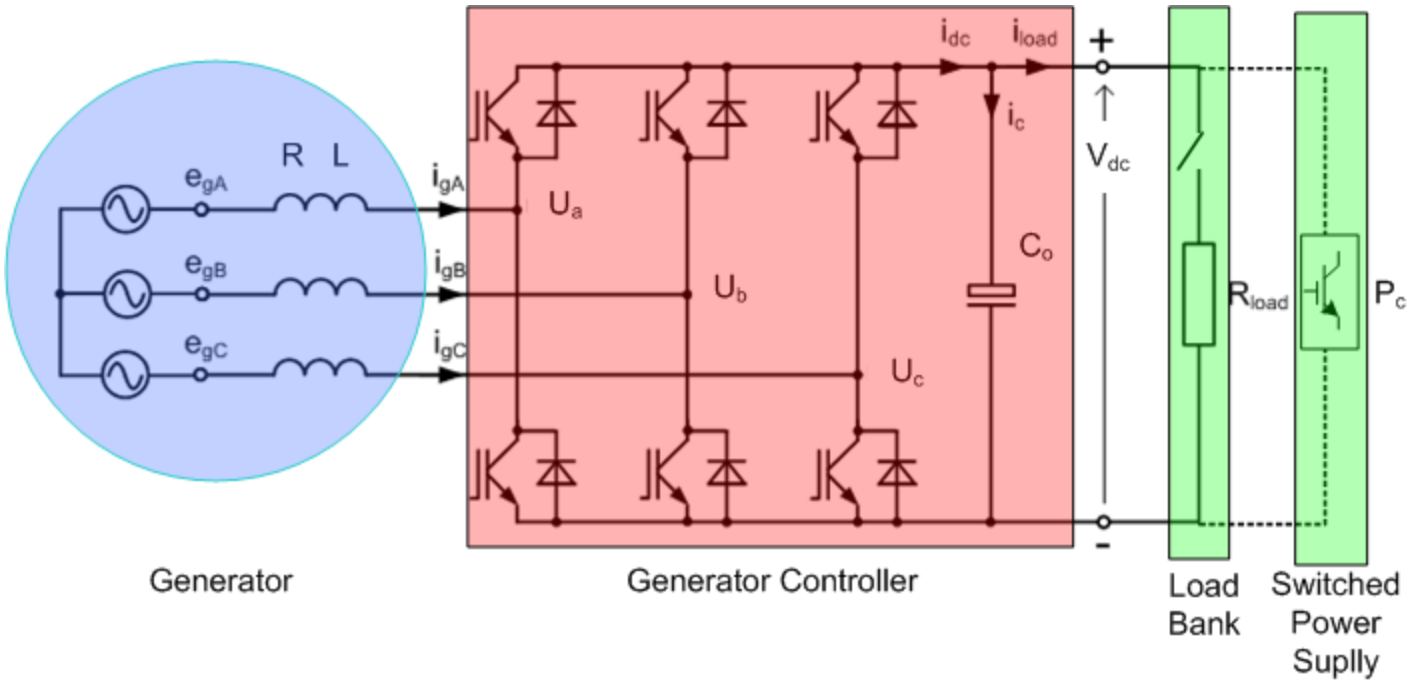
- Vector Control



Experimental Setup

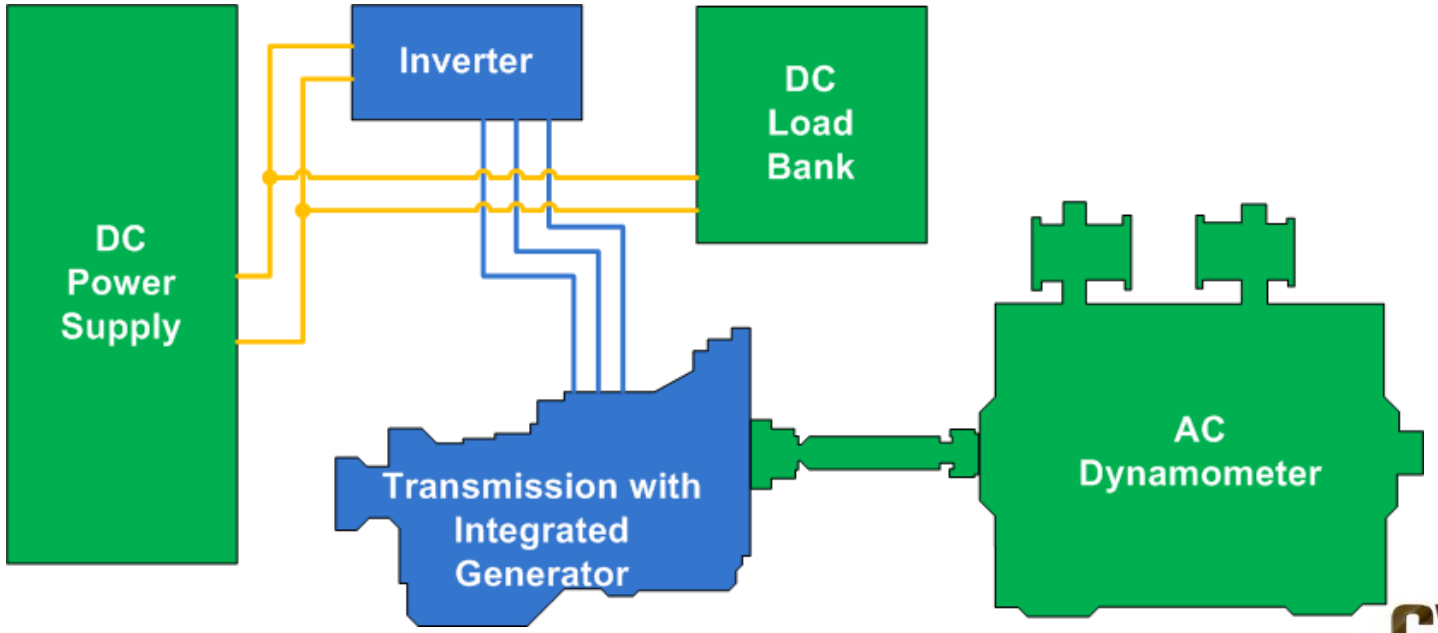
Electrical Diagram of Setup

- Generator, Inverter and Load Equivalent Circuit



Experimental Setup

- AC Dynamometer
  - Constant Torque: 1244N·m from 0-2,000rpm
  - Constant Power: 260kW from 2,000-10,000rpm
- DC Power Supply
  - 900V / 1000A / 250kW
- DC Load Bank
  - 250kW in 5kW Steps
- Temperature and Flow Regulated PGW cooling loops



Characterization and Power Quality Test Procedures

TARDEC's Standardized Tests and Evaluations

POWER AND MOBILITY

Traction Motor *Servo Motor* *Generator* *Alternator* *DC/DC Converter*

Machine Characterization

- Winding Resistance Characterization
- Inductance Characterization
- Back EMF Measurement and Characterization
- Rotor Inertia
- Spinning Losses (Iron Loss, Friction, Windage) – Spin Down Test

Drive Performance Validation/Determination

- Maximum Electrical Speed
- Maximum Starting (Stall) Torque
- Torque Ripple
- Speed / Torque (Current) Envelope Continuous
- Efficiency
- Speed vs. Power Envelope (Continuous)

Drive System Controllability

- Speed Regulation / Response
- Torque (Current) Response
- Voltage Regulation / Response

System Robustness

- Fault Tolerance
- Reliability Evaluation
- Conducted EMI Evaluation

Drive System Integration Practicability

- Safety Evaluation / Testing
- SWaP-C Evaluation
- Power Quality Compliance (MIL-PRF-GCS600A(ARMY) / MIL-STD 704/1275)
- Current Harmonics

Drive System Technology Readiness Level (TRL)

Power Quality Testing Scenarios

- 4.2.1 Voltage Regulation to Step Load.
  - *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.*
  - 19 → 88kW resistive load bank step, 1800rpm
  - 88 → 19kW resistive load bank step, 1800rpm
  - 0 → 50kW resistive load bank step + 19kW constant power (2700μF),1800rpm

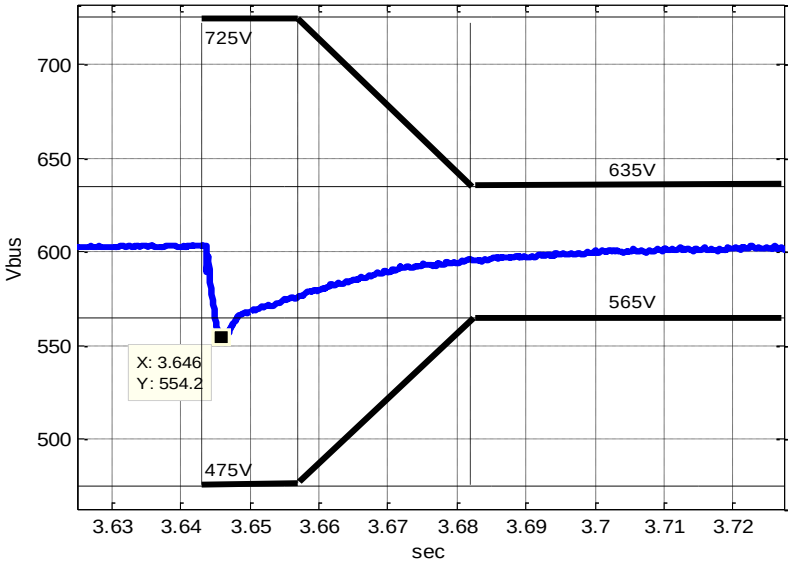
- 3.1.1.11 Distortion Spectrum.
  - *The distortion spectrum is defined as the maximum allowable limit of distortion expressed in decibels above 1 microvolt as a function of frequency.*

- 3.1.1.12 Distortion Factor.
  - *The distortion factor is defined as the ratio of distortion to the steady state voltage.*
  - 19kW resistive load bank, 1800rpm
  - 88kW resistive load bank, 1800rpm
  - 50kW resistive load bank + 19kW constant power (2700μF), 1800rpm

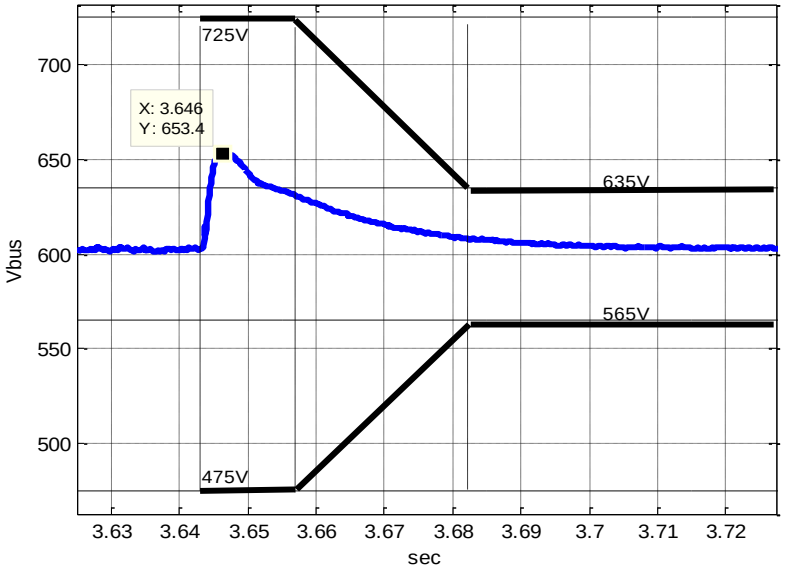
Experimental Results

Experimental Results – Voltage Transient Response

4.2.1 Voltage Regulation to Step Load

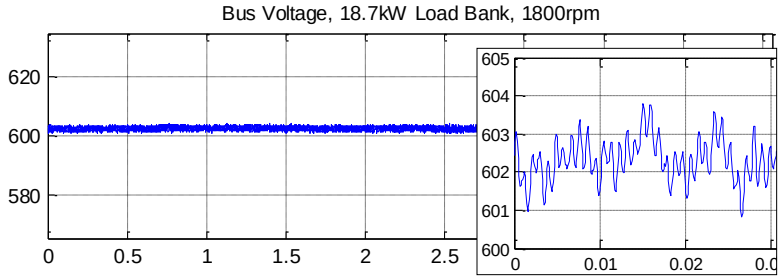


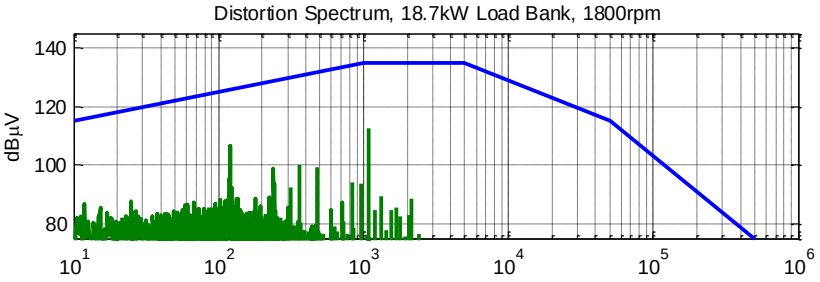
19 → 87kW resistive load bank step, 1800rpm

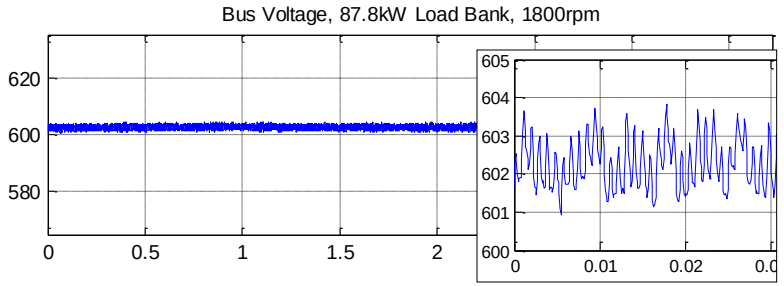


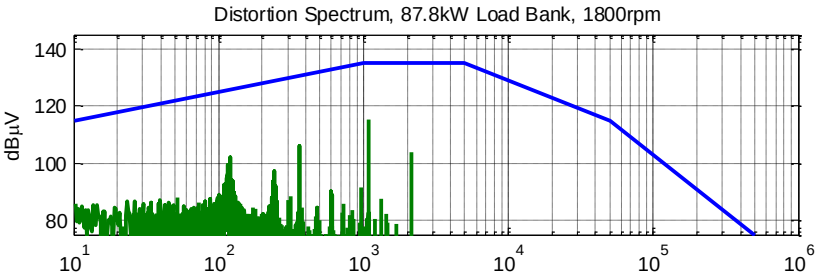
87 → 19kW resistive load bank step, 1800rpm

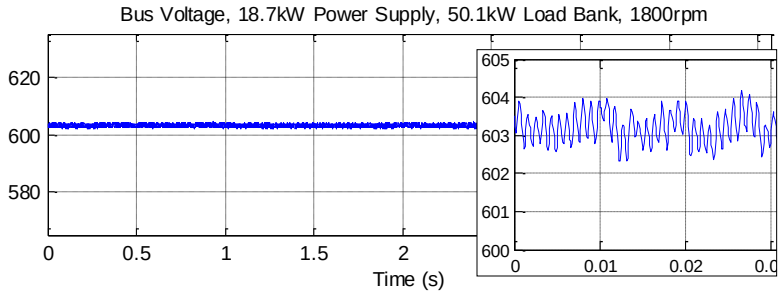
Experimental Results - Steady State

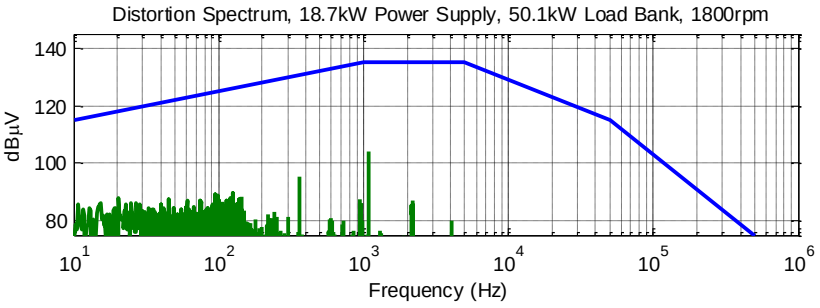








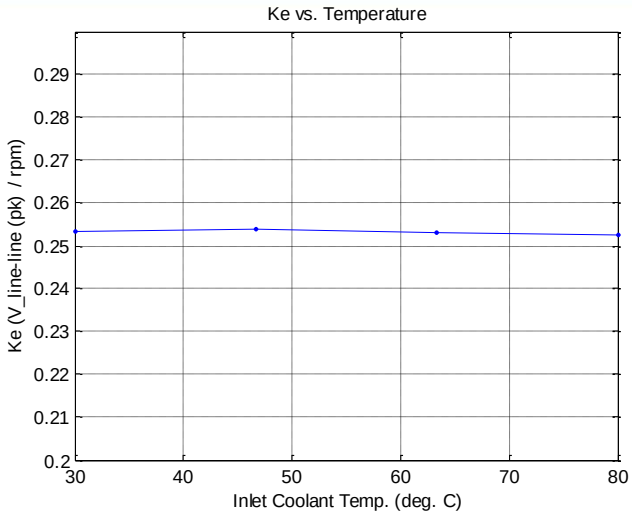


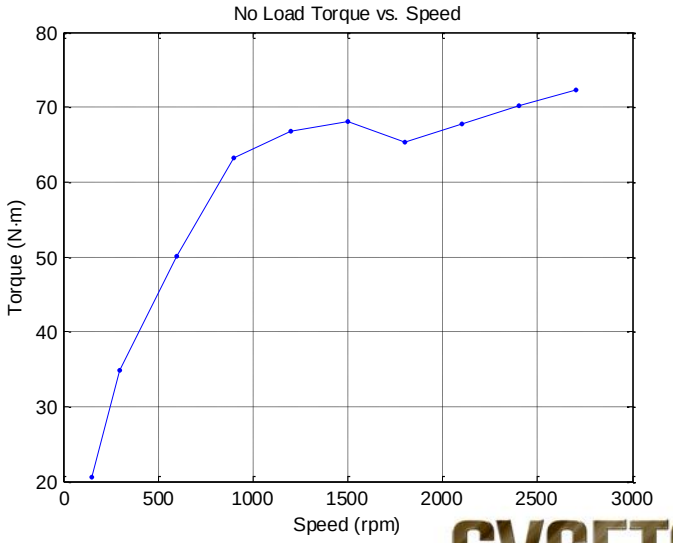


Distortion Factor
0.0012
0.0015
0.0010

Machine Characterization

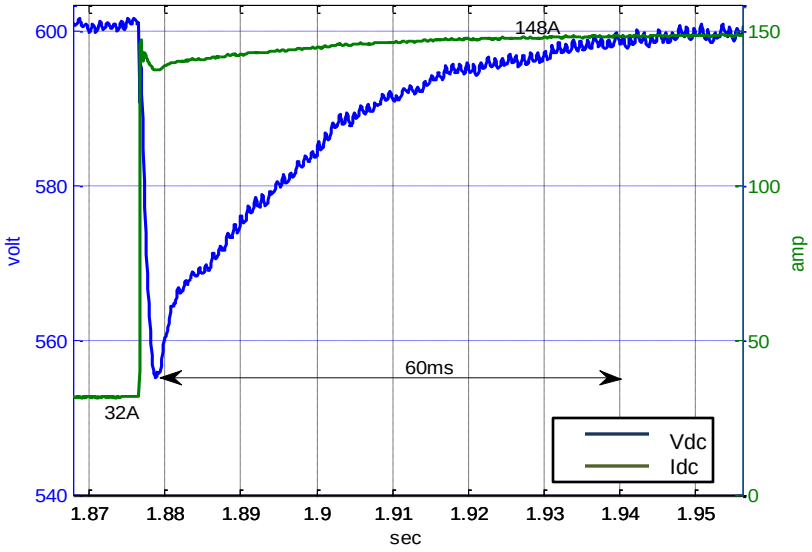
- Voltage Constant K_e = 0.253 $V_{ll(pk)}$ / rpm
  - Negligible variation across speed (150rpm - 2700rpm) and temperature (30C, 46.7C, 63.3C, 80C)
- Phase resistance R_s = 10.7 mΩ
- Friction (combined Coulomb (static) and viscous (dynamic))



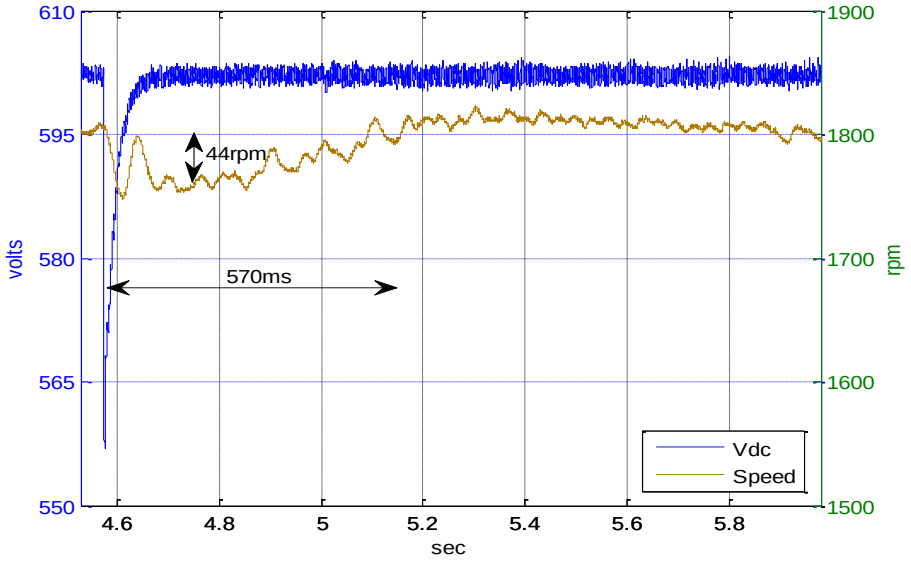


Electrical and Mechanical Response Estimation

19 → 87kW resistive load bank step, 1800rpm



Voltage Transient: ΔV 48V and 60 msec



Speed Transient: Δ 44rpm and 570 msec

Modeling

Modeling Effort

Objectives:

1) Evaluate the required amount of bus capacitance need for bus stability
2) Assess the total vehicle electrical system's compliance to MIL-PRF-GCS600A(ARMY)

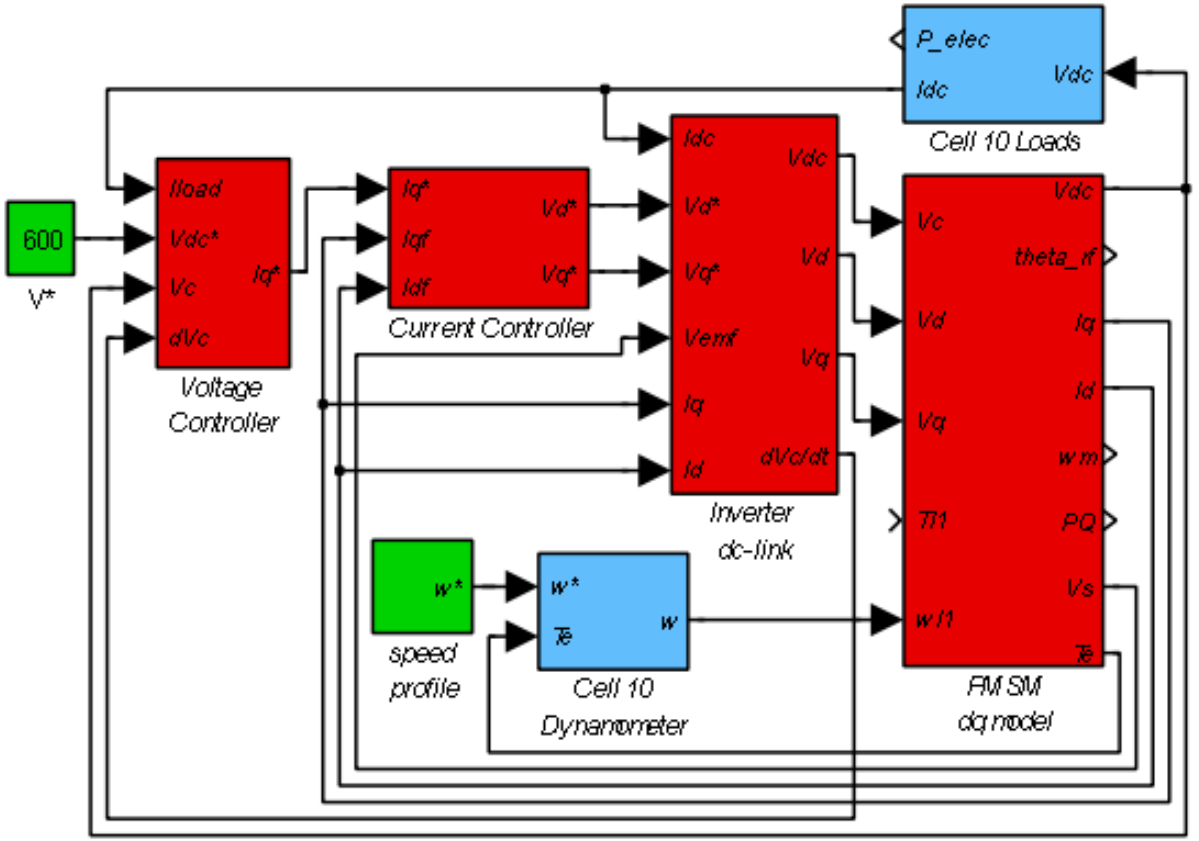
Procedure:

1) From test data develop a model of the generator/controller system
2) Compare simulation results with experimental results to validate the model
3) Adjust generator/controller model's dc-link and apply load transients
4) Incorporate the generator/controller model into a vehicle electrical system model

Modeling: Experimental Setup

Models:

- Generator Controller
  - Voltage
  - Current
- Power Stage
  - Inverter
  - Dc-link
- Generator
  - dq frame of reference
  - Speed input
- Loads
  - Switchable Resistance
  - Constant Power
- Dynamometer
  - Speed Command
  - Torque response

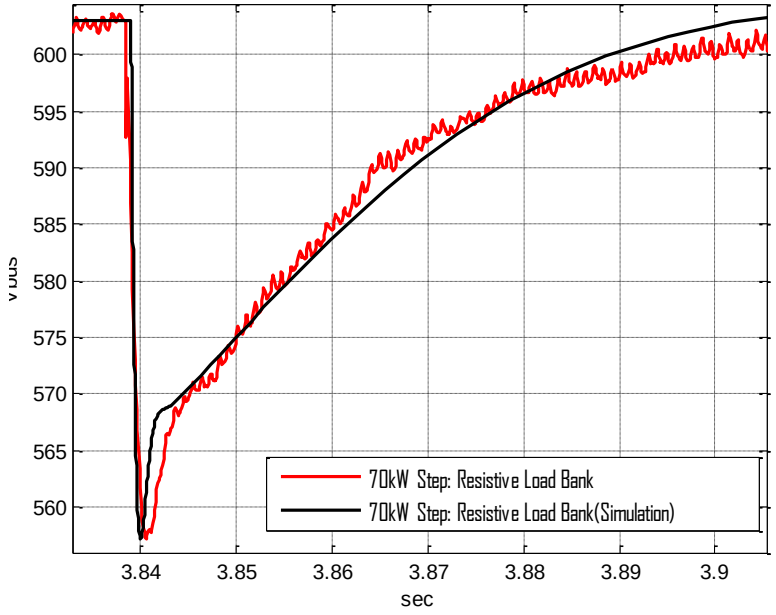


Simulation Results and Modeling Parameter Variation

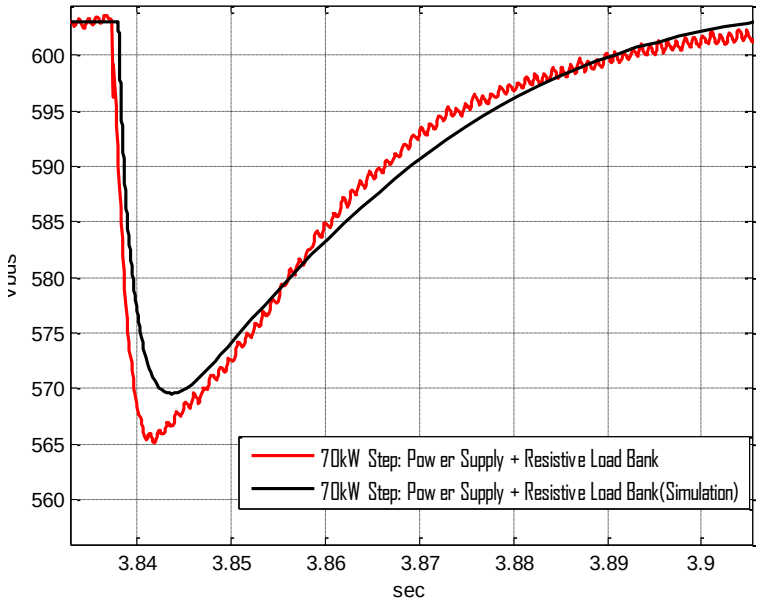
Modeling: Experimental Validation

Comparison between Experimental and Simulation Results: Voltage Transient

70kW Resistive Step Load



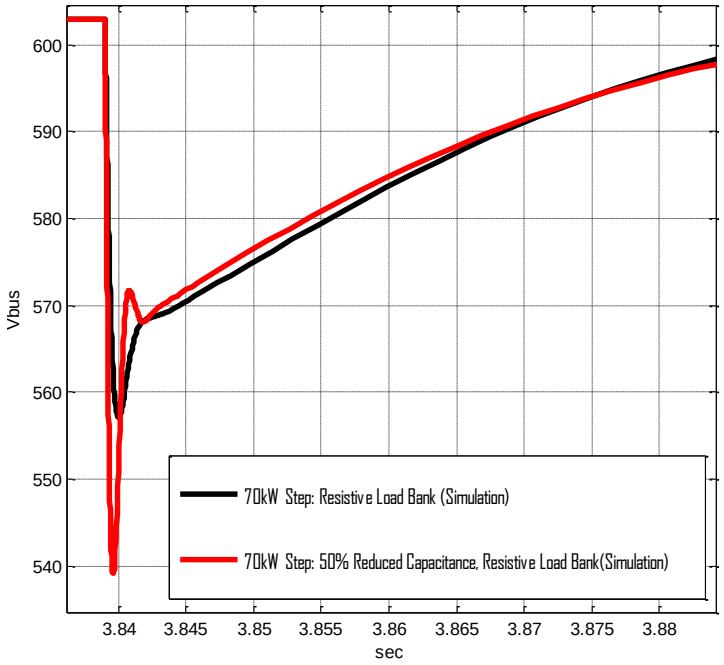
70kW Resistive Step Load +Constant Power Load (Lab Power Supply)



Modeling: Evaluation of Generator/Controller Capacitance

Comparison between 100% and 50% dc-link capacitance: Voltage Transient

70kW Resistive Step Load



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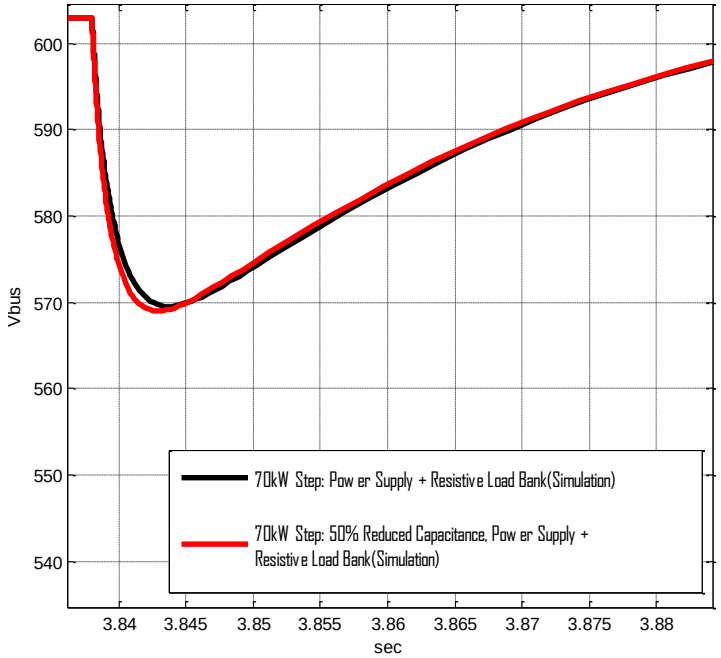
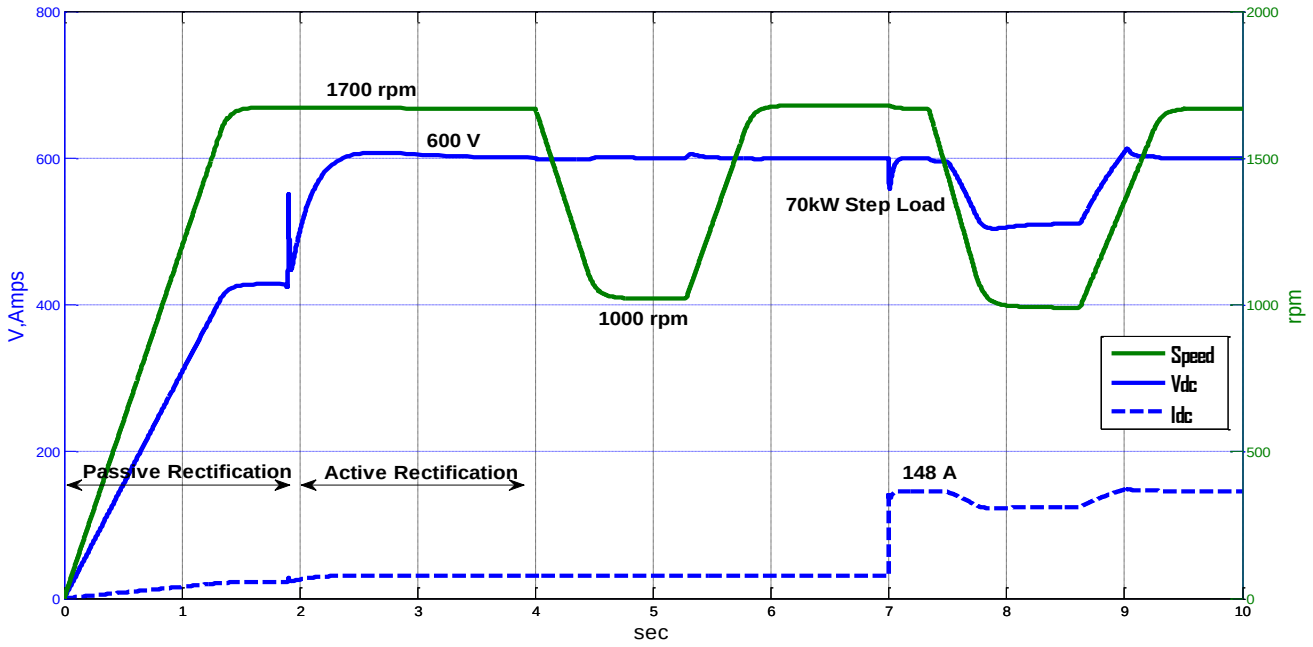


Modeling: Simulating a Vehicle Load Cycle

Simulation of a Vehicle's Electrical System

- Generator Startup
- Transition between Passive and Active Rectification
- Voltage and Speed Transients
- Generator Controller Current Limits



Conclusions and Future Work

Conclusions

- Compliance verification with MIL-PRF-GCS600A(ARMY)
  - Established the laboratory capability to validate the results
- M&S tools for power generation system analysis and optimization
  - Characterization of a black-box power generation system, and model development
  - Evaluation of system response with varying DC-link capacitance values and EMI filter parameters, controller gains, and driveline inertia

Future Work

- Combine component models with those of an engine and high-voltage bus architecture to assess power quality at the vehicle level
- FY13 power generation system SIL and vehicle integration
- Optimization of the bus capacitance for power generation systems
- Vehicle high-voltage bus capacitance allocation