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Electrical and Power Quality Performance Evaluation of a SiC Based 500kW High Temperature and High Power-Density Inverter

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ABSTRACT

In pursuit of future high-power capabilities for U.S. military ground vehicles, the transition towards vehicle electrification has been heavily adopted. High power-density and high temperature inverters play a key role in progressing vehicle electrification adoption across the U.S. military. This paper presents experimental results to evaluate the power quality performance of the developed high power-density and high temperature inverter, Enercycle™ DC-1000 Inverter based on silicon carbide (SiC). The DC-1000 inverter is a bi-directional inverter with a power density of 11.4 kW/L, which is capable of operating at 600 Vdc and delivering 500kW continuous output power and transient output power up to 640 kW, enable ground vehicle electrification. The experimental results to evaluate the power quality aspects such as distortion factor, ac voltage ripple, and voltage transient due to step load are presented in this paper. Moreover, challenges and next steps for further improvement of design have been discussed.

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1. INTRODUCTION

Ground vehicle electrification has been advancing to improve operational performance, energy efficiency, and long term sustainability across both commercial and defense applications [1]-[4]. Early progress has centered on lighter-duty platforms, but broader adoption will require integrating hybrid and fully electric powertrains into tactical wheeled and tracked programs [5]-[7]. Achieving this transition depends on developing high performance power electronics and energy systems capable of delivering the substantial power levels these vehicles demand—ranging from roughly 100 kW to well above 1 MW for the most power intensive platforms. Electrified drivetrains offer significant advantages, including increased low speed torque, quieter operation, reduced maintenance needs, and decreased reliance on conventional fuels [7]-[9]. Despite these benefits, the stringent operational environments and high-power requirements introduce numerous technical challenges that must be addressed to enable widespread adoption.

Figure 1: Enercycle DC-1000 Inverter

2. ENERCYCLE DC-1000 INVERTER OVERVIEW

The Enercycle DC-1000 Inverter (

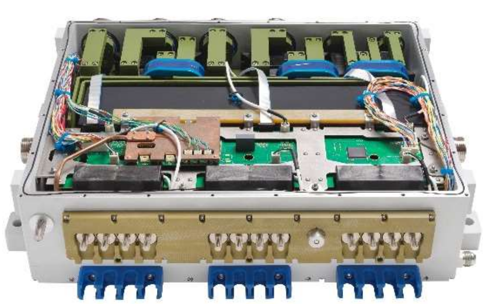

Figure **1**) was developed to deliver a compact, high-power, high temperature operating bi-directional inverter capable of supporting advanced hybrid-electric propulsion and onboard power generation.

The Enercycle DC-1000 Inverter has the following key features:

- Universal bi-directional ac/dc inverter for automatic motoring and generating mode operation,
- High-frequency Silicon Carbide (SiC) power switching devices,
- Continuous output power up to 500 kW and transient output power up to 640 kW at nominal 600 Vdc and coolant temperatures of up to 105 °C,
- High-voltage dc and ac safety interlock,
- DSP (Digital Signal Processor) based high-speed sensored and sensorless control algorithms,
- Supports parallelization and modularity of inverters for increased power capacity,
- Designed to meet vehicle vibration standards,
- Total volume of 44 L.

2.1. System Architecture

The DC-1000 Inverter can interface directly with the high voltage dc bus, traction motor/generator, and ancillary loads. It is capable of bi-directional operation, converting dc to ac (motoring mode) to drive electric motors and ac to dc (generating mode) to recharge batteries or connect with other dc loads. The dc interfaces consist of dc connectors and SiC static switch modules. The static switch modules were uniquely developed to enable multiple dc power distribution interfaces while each port/interface can be individually controlled by dedicated static switch. An exploded internal view of the DC-1000 Inverter is shown in Figure 2.

2.2. Enercycle DC-1000 Inverter Specifications

Top-level performance specifications for the Enercycle DC-1000 Inverter are as follows:

- DC Interfaces: Qty 3
- Inverter output current: 800 Arms continuous and 1000 Arms transient.
- Coolant inlet temperature: 105 °C maximum.
- Coolant flow rate: 0.6 L/s minimum.
- Coolant type: 60/40 or 50/50 EGW
- Ambient operating temperature: −40 °C to 121 °C.
- Dimensions: 22.8 in. (L) ×18.3 in. (W) × 6.5 in. (H)
- Weight: 240 lb.
- 98.9% analytically calculated efficiency at 800 Arms with dc link voltage of 600 Vdc and 105 °C coolant temperature.

3. POWER QUALITY PERFORMANCE EVALUATION

The Enercycle DC-1000 Inverter is capable of bi-directional power flow operation (motoring or generating mode), to support a scalable, modular approach to power management. The DC-1000 Inverter can be paired with an Electric Generator (GEN) to supply the high voltage dc bus or to a motor to deliver torque.

In generating mode, variable high frequency ac power that is generated from the motor is converted to 600 Vdc power through active rectification process by the inverter. The dc power is then filtered and stabilized by the dc link capacitor. In motoring (motor drive) mode, the energy from the 600 Vdc vehicle bus is converted by the inverter to three-phase variable-voltage-variable-frequency ac power to drive the machine to the desired speed used to deliver torque to the drive motor(s).

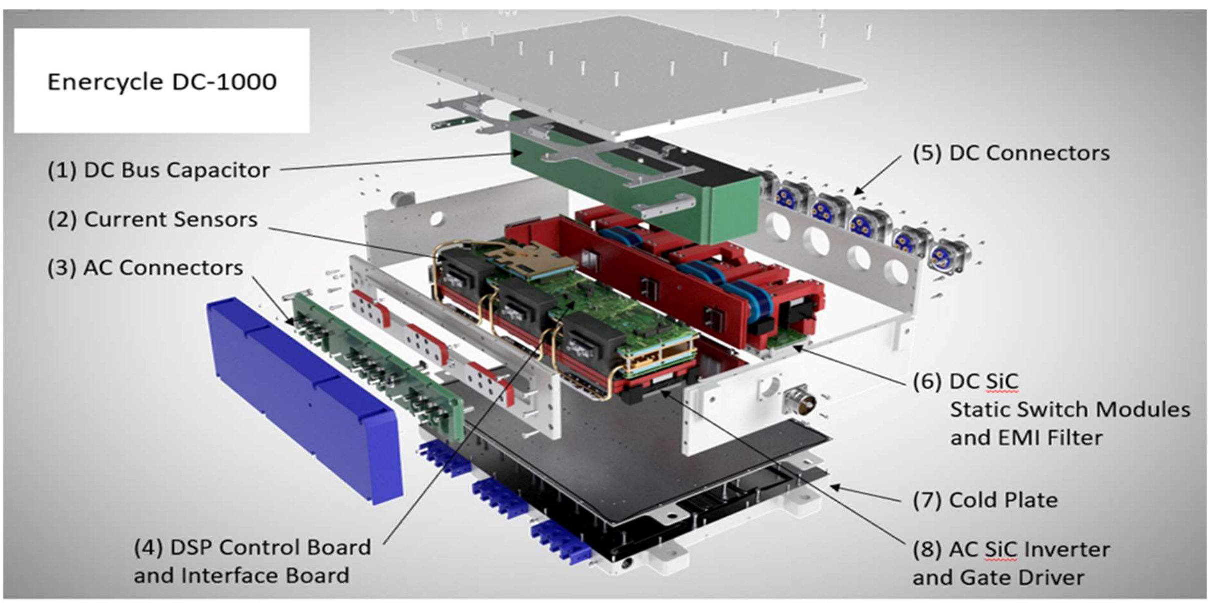

Figure 2: An exploded view of the Enercycle DC-1000 Inverter. (1) DC Bus Capacitor. (2) Current sensors. (3) AC Connectors. (4) DSP Control Board and Interface Board. (5) DC Connectors. (6) DC SiC Static Modules. (7) Cold Plate. (8) SiC MOSFET Devices and Gate Drivers.

3.1. Test Requirements

The inverter shall measure and verify electrical performance for steps loads applied at dc link. **Table 1** shows the electrical characteristics for 600 V system, based on MIL-PRF-GCS600A requirement 3.1.3.

The nominal voltage is 600 Vdc. The equipment on the bus must be able to operate continuously at dc voltages ± 35 V from nominal and ac voltage ripple of 9 V peak. In addition, the equipment must be designed to sustain voltage transients between 475-725 V for 15 ms as shown in Figure 4.

Table 1. Electrical Characteristics for 600 V System

Parameters	**Value**
Steady-State Voltage	565 V – 635 V (600V ±35 V)
Normal Transients	475 V – 725 V (see Figure 3)
Ripple Amplitude	9 V
Distortion Factor	0.015
Distortion Spectrum	See Figure 3

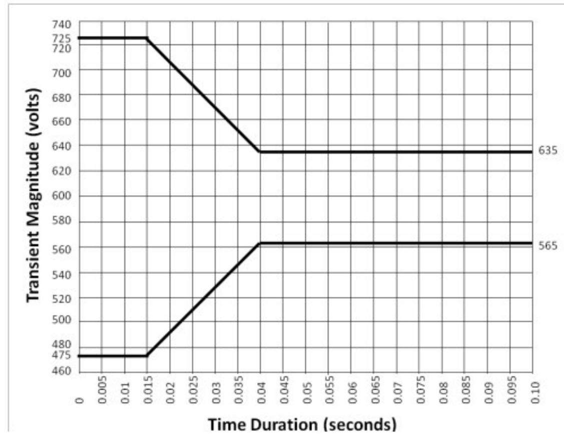

Figure 4. Envelope of normal transients for 600 Vdc system based on MIL-PRF-GCS600A.

Figure 3 is the Distortion Spectrum of MIL-PRF-GCS600A. The distortion spectrum and distortion factor are power quality attributes of the dc bus voltage.

The distortion spectrum is the frequency content of the bus voltage with an upper limit defined in MIL-PRF-GCS600A. The distortion factor (DF) is defined as the ratio of the root mean square (rms) dc voltage

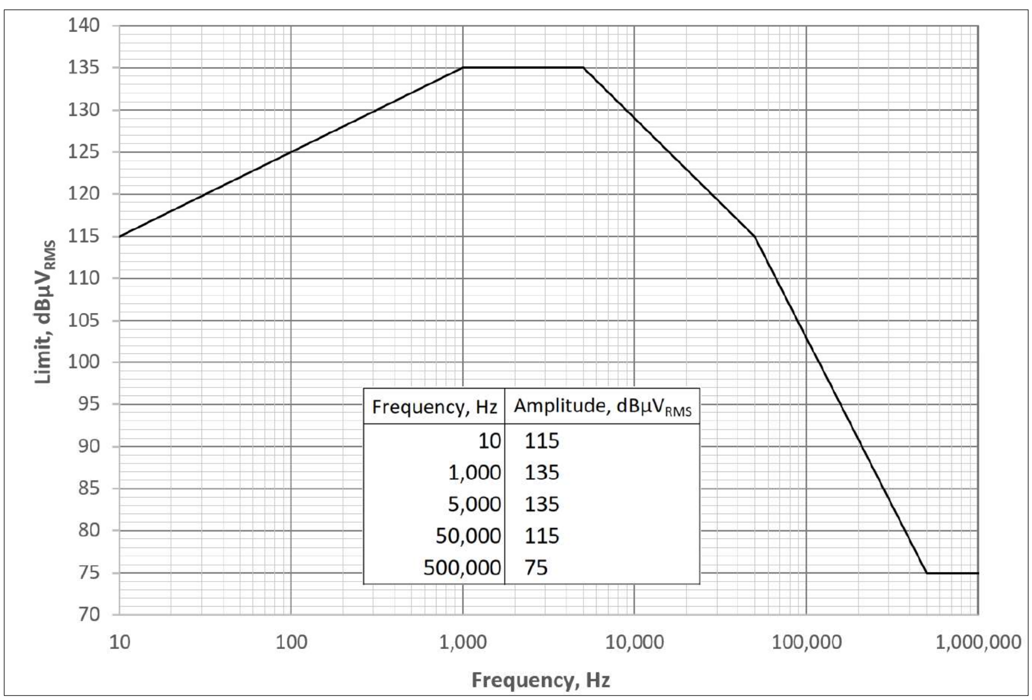

Figure 3. Maximum distortion spectrum for 600 Vdc system.

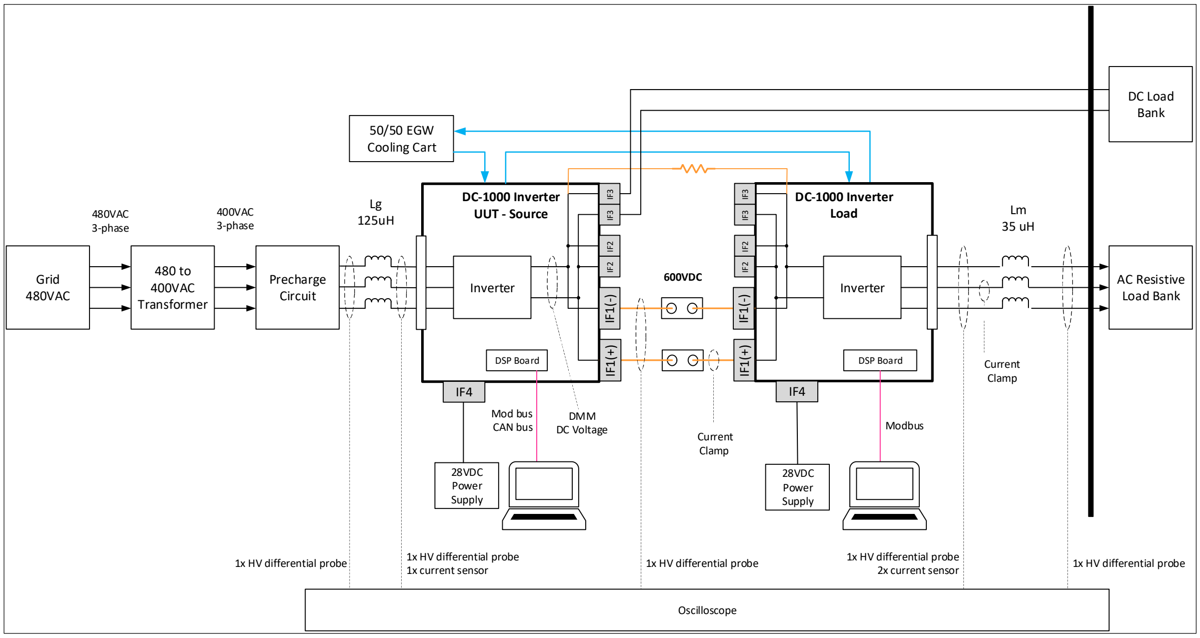

Figure 5. Test setup where EDU2 is generating 600 Vdc, and dc load as well as EDU1 are connected to 600 V dc link to function as a load for EDU2.

distortion (harmonics) to the dc steady state voltage according to eq(1). It represents the total harmonic distortion (THD) of the dc voltage waveform.

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

3.2. Test Setup

Figure 5 shows the test setup used for the creation of the test results in this report. The 3-phase output of the 380 Vac step down transformer is connected to the Unit Under Test (UUT). The 600 Vdc output from UUT is connected to a dc load bank as well as a similar inverter which supplies a 3-phase ac resistive load bank.

3.3. Test Results

Figure 6 shows the steady state dc link voltage of UUT operating at 350 kW and connected to 60 Hz grid and commanded to regulate dc link at 600 Vdc. The measured average voltage is 597.4 V which is -0.4% below reference value.

The Distortion Spectrum of MIL-PRF-GCS600A is shown in Figure 3. The distortion spectrum and distortion factor are power quality attributes of the dc bus voltage. The distortion spectrum is the frequency content of the bus voltage with an upper limit defined in MIL-PRF-GCS600A.

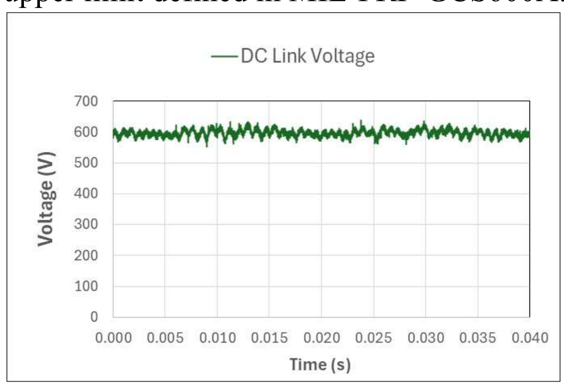

Figure 6. DC Link Voltage – Steady State at 350 kW load.

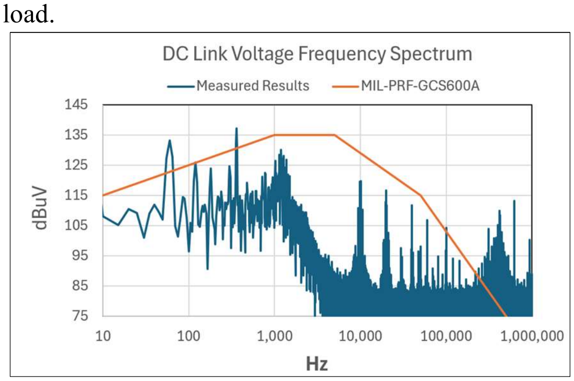

Figure 7. DC Link Voltage Frequency Spectrum at 350 kW load.

To evaluate the UUT against this requirement, the frequency spectrum of the dc link voltage of UUT at steady state operation while providing 350 kW is measured and plotted against the limit MIL-PRF-GCS600A as shown in Figure 7. The measured spectrum is beyond the limit at two frequency ranges:

1) in the range above 250 kHz which is mainly due to the fact that EMI filter is not in the circuit to attenuate the noise in that range.
2) below 500 Hz, more specifically only at 60 Hz and 360 Hz which is likely related to the control algorithm. Further tuning of the control algorithm may help to reduce the ripple.

Based on the measured voltage spectrum shown in Figure 7, the DF from 0 Hz to 1 MHz frequency range is 0.029 while the requirement is 0.015. However, it is worth nothing that DF of the measured voltage spectrum from 1.23 kHz to 1 MHz is 0.014 meeting the requirements. This confirms that better tuning (Kp and Ki parameters) of both outer voltage control loop and inner current control loop to reduce the low frequency ripple, especially at 60 Hz and 360 Hz, could help to reduce the DF to meet the requirements. Even though sampling rate or processing delay could play a role in the observed distortion, however, due to 10kHz sampling rate and processing the data by the processor with the same rate, those would be less likely the cause of distortion.

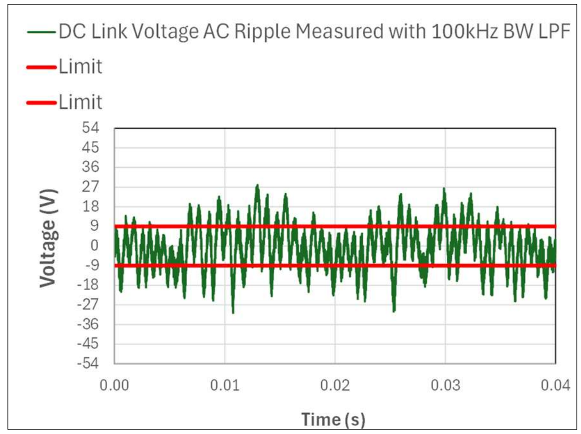

Figure 8. DC link voltage steady state ac ripple measured with 100 kHz BW LPF at 350 kW load.

To verify the ac ripple at dc voltage, the average dc voltage is subtracted from the measured dc voltage and the remaining part is considered as the ac ripple which is then plotted against the requirement and illustrated in **Figure 8**. It should be noted that ac ripple is plotted with 100 kHz bandwidth (BW) low pass filter (LPF) to filter out the high frequency ripples since an EMI board was not present during the test. Furthermore, the ac ripple is plotted with 1 kHz and 300 Hz BW LPF in **Figure 9** and **Figure 10**, respectively, which confirms that considerable part of ac ripple is at lower frequency matching results illustrated in Figure 7. It should be noted that addition of EMI filter might have broader impact on system performance, specifically EMI's interaction with inverter's control loop and affecting the stability of the inverter.

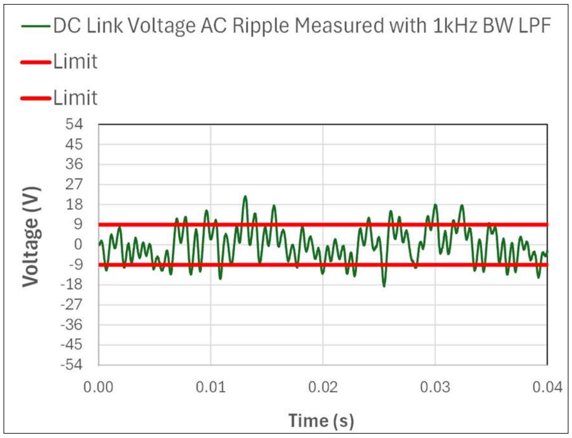

Figure 9. DC link voltage steady state ac ripple measured with 1 kHz BW LPF at 350 kW load.

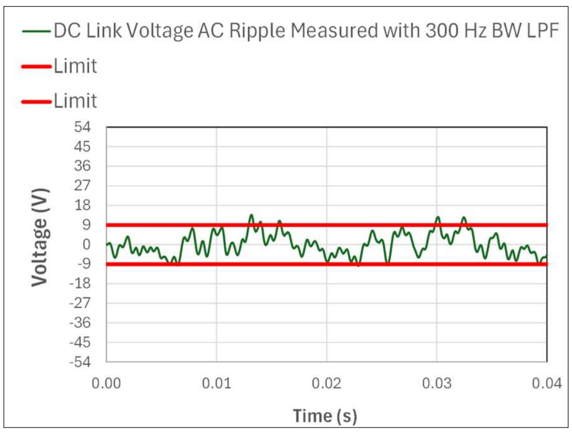

Figure 10. DC link voltage steady state ac ripple measured with 300 Hz BW LPF at 350 kW load.

3.4. Transient Performance

For transient performance testing, a 125 kW step load was directly applied at dc link of the DC-1000 Inverter to verify the transient response of the inverter and the result is shown in **Figure 11Error! Reference source not found.** compared to the limit requirements per MIL-PRF-GCS600A. Based on the figure it can be seen that the inverter is capable of regulating the dc voltage back to its reference value at 600 V within 15 ms after 125 kW step load is applied at dc link. However, its over- and under-shoot response needs further tuning (Kp and Ki parameters) of the outer voltage control loop to response faster to load transients and keep the dc link voltage within the requirements limit.

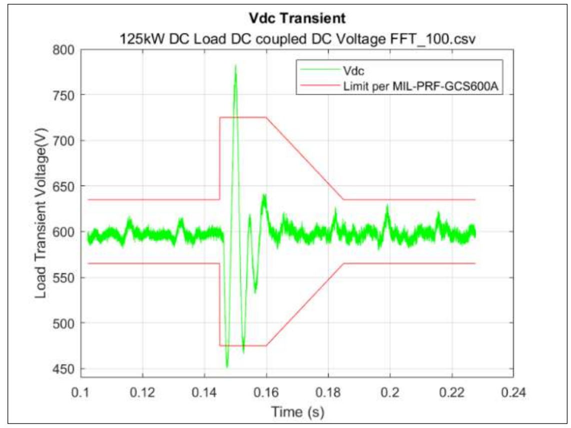

Figure 11. DC link voltage transient response with 125 kW dc step load.

Table 2. Electrical Characteristics for 600 V System (MIL-PRF-GCS600A).

Parameters	**Requirements**	**Obtained Results**
Normal Transients	475 V – 725 V (upper and lower limits as shown in Figure 4**Error! Reference source not found.**)	Tested only at 125 kW. The dc voltage is regulated back to the reference value (i.e., 600 Vdc) withing the required time. However, transient over-/under-shoot is out of the required range (see Figure 11**Error! Reference source not found.**)
Ripple Amplitude	9 V	27 V
Distortion Factor	0.015	0.029 (from 0 to 1 MHz) 0.014 (from 1.23 kHz to 1 MHz)
Distortion Spectrum	See Figure 3.	See Figure 7. It is above the limit at 60 Hz, 360 Hz, and at

Table 2 lists the summary of the requirements as well as the summary of obtained results from DC-1000 Inverter test. Even though the obtained results did not meet all the requirements in terms of DF, ac ripple, and frequency spectrum, taking the right corrective action such as adding EMI filter and further tunning of the control loop will improve the performance of DC-1000 Inverter.

4. CONCLUSIONS AND FUTURE WORK

As presented in this paper, the Enercycle DC-100 Inverter was designed to operate in bi-directional mode to generate the ac voltage for load as well as regulating the dc link voltage. The inverter needs to work in active front end rectification mode to regulate dc link voltage at 600 Vdc. To verify the inverter power quality performance, both steady state and transient tests were conducted based on MIL-PRF-GCS600A for 600 Vdc system. Even though the inverter is designed for 500 kW continuous operation, the tests were conducted at 350 kW steady state and 125 kW load transient due to equipment availability at the time of conducting the tests. Future testing of the DC-1000 Inverter (500kW continuous and 640kW transient) will encompass maximum loading of the inverter both at steady state and transient tests.

Experimental results confirmed that the DC-1000 Inverter is capable of regulating dc link voltage at 597.4 V (measured average voltage) which is -0.4% below reference value of 600 V. The obtained results revealed that further filtering needs to be implemented at dc link to attenuate the frequency range above 250 kHz which is beyond the control bandwidth to reduce the ripples. Moreover, the control algorithm needs to be further tuned to reduce the low frequency (below 500 Hz) voltage ripple, more specifically at 60 Hz and 360 Hz. In addition, the measured voltage spectrum has a DF of 0.029 which is beyond the requirement (=0.015). However, it is worth nothing that DF of the measured voltage spectrum from 1.23 kHz to 1 MHz is 0.014 meeting the requirements. This confirms that better tuning (Kp and Ki parameters) of both outer voltage control loop and inner current control loop to reduce the low frequency ripple, especially at 60 Hz and 360 Hz, could help to reduce the DF to meet the requirements.

Based on the captured results during step load, it was confirmed that the inverter is capable of regulating the dc voltage back to its reference value at 600 V within 15 ms after 125 kW step load is applied at dc link. However, its over- and under-shoot response needs further tuning (Kp and Ki parameters) of the outer voltage control loop to response faster to load transients and keep the dc link voltage within the requirements limit.

CONTACT INFORMATION

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ACRONYMS

AC	Alternating Current
DC	Direct Current
DF	Distortion Factor
DSP	Digital Signal Processor
EGW	Ethylene-Glycol and Water
LPM	Liters Per Minute
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
PWM	Pulse Width Modulation
RMS	Root Mean Square
SiC	Silicon Carbide
UUT	Unit Under Test
Vds	Drain to Source Voltage