

# A Bi-Directional DC-DC Converter with Minimum Energy Storage Elements

Leon M. Tolbert<sup>1,3</sup>, William A. Peterson<sup>2</sup>, Cliff P. White<sup>3</sup>, Timothy J. Theiss<sup>3</sup>, Matthew B. Scudiere<sup>3</sup>

<sup>1</sup>The University of Tennessee  
Electrical and Computer Engineering  
Knoxville, TN 37996-2100  
Tel: (865) 974-2881  
FAX: (865) 974-5483  
e-mail: [tolbert@utk.edu](mailto:tolbert@utk.edu)

<sup>2</sup>E&M Power  
6 Emma Street  
Binghamton, NY 13905  
Tel: (607) 766-9625  
Fax: (607) 766-9622  
[peterston@EandMpower.com](mailto:peterston@EandMpower.com)

<sup>3</sup>Oak Ridge National Laboratory  
National Transportation Research Center  
2360 Cherahala Blvd.  
Knoxville, TN 37922  
Tel: (865) 946-1328  
Fax: (865) 946-1262

**Abstract** — A proof-of-concept military advanced mobile generator set has been developed. The military generator set uses an internal combustion diesel engine to drive a radial-gap permanent magnet alternator at variable speed. The speed of the engine is determined from a user selectable interface that for a given load and ambient thermal conditions controls the engine to run at its most efficient operating point.

The variable frequency, variable voltage produced by the permanent magnet alternator is diode-rectified to a high voltage (~400 V) dc link, and an inverter is used to produce selectable frequency, controllable ac voltage. As part of the power electronics for this unit, a 7 kW bi-directional dc-dc converter has also been developed. The converter can charge 24V batteries that are used to start the internal combustion engine and to power auxiliary low voltage dc loads. Additionally, the bi-directional converter can also draw power from the batteries to help maintain the high voltage dc link during severe load transients. Because of stringent weight and volume requirements for this application, the minimum in energy storage elements (high frequency transformers, capacitors, and inductors) was used. This paper presents a description and experimental analysis of this novel dc-dc converter design.

## I. INTRODUCTION

The U.S. Department of Defense has initiated a program to upgrade and develop enhanced tactical power systems to provide reliable electrical power in the battlefield. One aspect of this program is for the development of advanced mobile generator sets in the medium power (5-60kW) range. These future generator sets are to be portable, lightweight systems that are electronically controlled, signature suppressed, and capable of operating on DF-2/JP-8 fuels in extreme environmental conditions.

Existing military gen-sets in the medium power range have been designed to be extremely rugged, cost-effective sources of power. These units are significantly heavier than their industrial counterparts to meet the stringent ruggedness requirements of the military and because the units provide additional features and capabilities that are not available on industrial units. Military mobile electric generators are designed to operate in a temperature range from -45°C to 60°C and at altitudes ranging from sea level to 3000m.

Existing military gen-sets have a diesel combustion engine

that is governed to run at a fixed speed such that the directly coupled alternator driven by the engine produces a fixed frequency output of either 50 or 60 Hz in some units or 400 Hz in other units. Brushless synchronous machines are presently used to convert the mechanical power of the rotating shaft into three-phase electrical voltage at a preset frequency.

In order to reduce their logistics burdens, the DOD would like future gen-sets to be much lighter, smaller in volume, more fuel-efficient, quieter, and more reliable than the existing units. Fixed-speed engines are forced to run outside their optimum fuel consumption envelope when these units are not run near full load; therefore, running the engine at variable speed and using power electronics to convert the variable voltage and frequency to a fixed voltage and frequency can allow more efficient operation of the gen-set [1-7]. With advanced diesel engines and variable speed technology, goals for the program were to reduce weight by almost 50% and increase efficiency by up to 30.

## II. SYSTEM DESCRIPTION

A block diagram of the electronic power conversion system for the proof of concept generator set developed at the Oak Ridge National Laboratory (ORNL) is shown in Fig. 1 [1]. The military generator set uses an internal combustion diesel engine to drive a radial-gap permanent magnet alternator at variable speed. The speed of the engine is determined from a user selectable interface that for a given load and ambient thermal conditions allows the engine to run at its most efficient operating point.

The variable frequency, variable voltage produced by the permanent magnet alternator is diode-rectified to dc voltage, and an inverter is used to produce selectable frequency, controllable ac voltage. The user is allowed to select single-phase 120 V, dual-phase 120/240 V, or three-phase 120/208 V. Each of these voltage configurations can be generated at 50 Hz, 60 Hz, and 400 Hz such that the unit can be compatible with equipment produced from around the world or for aerospace applications.

The power conversion system also incorporates a bi-directional dc-dc converter that can charge 24V batteries that are used to start the IC engine and to power auxiliary loads, or

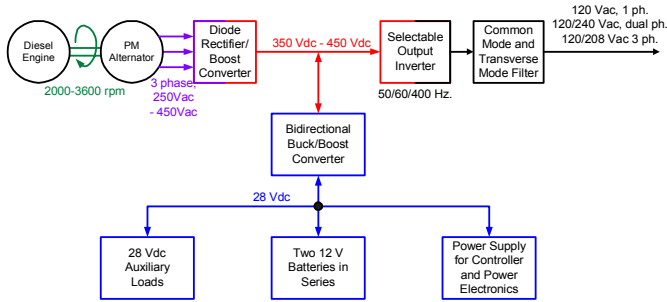


Fig. 1. Functional block diagram of power conversion components in generator set.

the converter can draw power from the batteries to help maintain the dc link during severe load transients.

The gen-set was designed such that the inverter can produce 120 Vrms line-neutral voltage for dc link voltages between 350 Vdc and 450 Vdc. During normal operation, the alternator line-line voltage is rectified by the three-phase, full-bridge rectifier with conventional six-pulse rectification. The minimum desired dc link voltage of 350 Vdc corresponds to an alternator speed of 2800 rpm. When the DC link voltage produced by this normal mode of rectification is less than 350 Vdc (corresponding to a gen-set speed of 2000 to 2800 rpm), an asynchronous boost circuit becomes active to maintain the dc link voltage. The circuit that boosts the alternator voltage when the speed is low operates asynchronously with rotor position. However, for a large transient load (such as starting an induction motor), another means is needed to boost the dc link voltage. During these transient times, the bi-directional dc-dc converter could supply power from a battery set to keep the dc link voltage above 350 V. The bi-directional circuit operation is described in section IV.

### III. ASYNCHRONOUS BOOST OPERATION

The gen-set was designed such that the inverter can produce 120 Vrms line-neutral voltage for dc link voltages between 350 Vdc and 450 Vdc. During normal, unboosted operation, the alternator line-line voltage is rectified by the three-phase, full bridge rectifier  $D_1$  in conventional six-pulse rectification as shown in Fig. 2. During this mode, the boost rectifier is inactive and transistor  $Q_1$  is off. The minimum desired dc link voltage of 350 Vdc corresponded to an alternator speed of 2800 rpm.

When the DC link voltage produced by this normal mode of rectification is less than 350 Vdc (corresponding to a gen-set speed of 2000 to 2800 rpm), the asynchronous boost circuit becomes active to maintain the dc link voltage. The circuit that boosts the alternator voltage when the speed is low operates asynchronously with rotor position. When the boost is active, transistor  $Q_1$  turns on and effectively shorts out the alternator through the full-bridge rectifier  $D_2$  shown in Fig. 2. During this time, the three-phase full-bridge rectifier diodes in  $D_1$

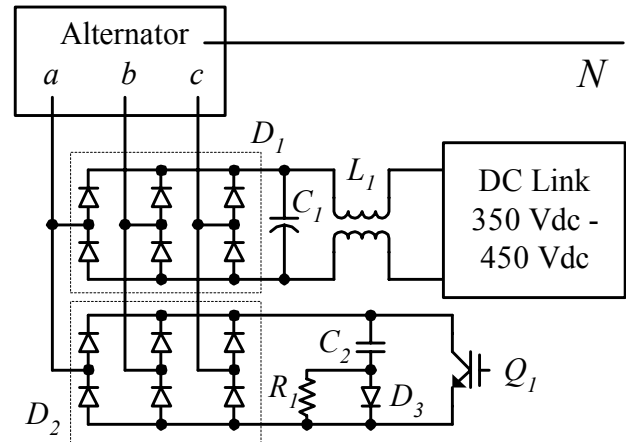


Fig. 2. Schematic of alternator boost rectifier.

block, and capacitor  $C_1$  supplies the inverter load. The current being supplied by the alternator ramps up due to this short, and the current is limited only by the alternator leakage inductance.

When  $Q_1$  turns off, the current then flows through the three-phase full-bridge rectifier  $D_1$  to charge  $C_1$ . Transistor  $Q_1$  is operated as a DC current mode boost and the diodes in  $D_1$  must be the fast recovery type because they are operated at the boost switching frequency. The diodes in  $D_2$  are commutated at the alternator frequency and therefore do not have reverse recovery requirements. The parasitic inductance of the path through  $D_1$  and  $C_1$  where the boost current flows when  $Q_1$  is turned off can cause a large voltage spike at  $Q_1$ . However, the snubber composed of  $C_2$  and  $D_3$  offers a low inductance diversion path for this current and thus limits the di/dt to a value that will not produce damaging voltage spikes.

### IV. BI-DIRECTIONAL CONVERTER DESCRIPTION

The bidirectional power supply takes power from the 350 V dc link and converts it to 28 V to power 28 V auxiliary loads and to recharge the engine starting battery. The converter is able to provide 7 kW for less than 10 seconds or 1.4 kW continuously. This section contains a description of the bi-directional converter operation. A schematic of converter circuit is shown in Fig. 3, and the control circuit with the main converter components is shown in Fig. 5.

The converter was required to operate between voltages of 350 and 28 volts, or a 12.5:1 voltage ratio. In order to reduce the transformer turns ratio, circuits that produced a large inherent voltage ratio were implemented. When transferring power from the high voltage bus to the low voltage bus, the half-bridge converter has an inherent voltage reduction of  $\frac{1}{2}$ . It is followed by the transformer and a current doubler rectifier [8], which produces another voltage gain of  $\frac{1}{2}$ . With this inherent voltage scaling of four, the turns ratio of the transformer was reduced to 2.8:1 allowing for an efficient magnetic design with low leakage inductance and losses.

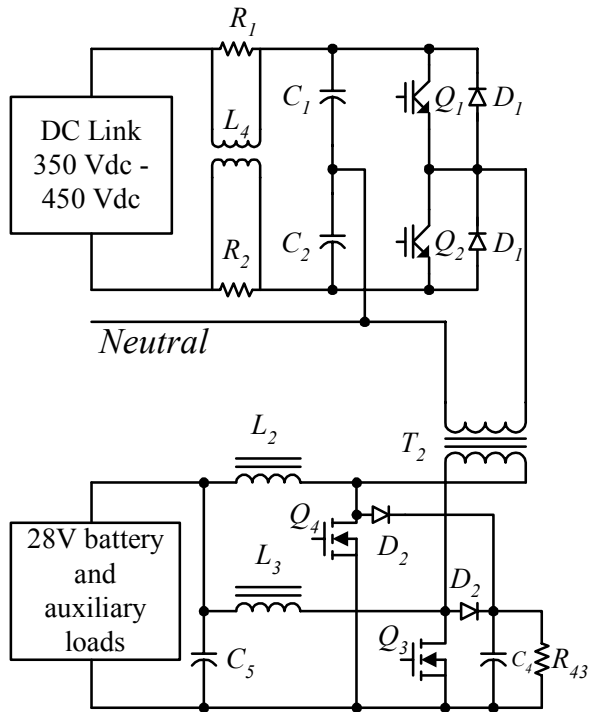


Fig. 3. Schematic of gen-set bi-directional converter.

For high voltage to low voltage operation, the dc link voltage is passed through an R-L link damper consisting of the two resistors  $R_1$  and  $R_2$  and  $L_4$  as shown in Fig. 3. This link damper prevents oscillation between the  $C_1$  and  $C_2$  capacitors of the bi-directional converter and the DC link capacitors on the main gen-set inverter. The  $C_1$  and  $C_2$  capacitors serve as high frequency energy storage for power transfer in either direction and make up the reactive half of the half bridge converter with the IGBTs  $Q_1$  and  $Q_2$ . Fig. 6 shows the waveforms for the IGBTs and MOSFETs when the bi-directional converter operates in buck mode.

To minimize the size of the high frequency transformer  $T_2$ , the IGBTs are driven at a 20 kHz frequency. Transformer  $T_2$  had a turns ratio of 2.8:1; this combined with the voltage halving of the half-bridge and a second voltage halving by the current doubler rectifier (diodes  $D_2$  and filtered by  $L_2$  and  $L_3$ ) allowed the IGBTs to be operated at a maximum duty ratio of 0.85 when converting 350 Vdc to 30 Vdc.

When operating in the boost mode (transferring power from the low voltage bus to the high voltage bus), the half bridge circuit (that acted as a current doubler rectifier in buck mode) now operates as a boost converter, with the switches operated in overlap [9]. The other converter that acted as a half-bridge converter in buck mode is now operating in the reverse direction and is a voltage doubler rectifier with a gain of 2. Fig. 7 shows the waveforms for the inductors' current and MOSFETs when the converter operates in boost mode.

The selection of these two topologies for the composition of the converter was to minimize the energy storage requirements

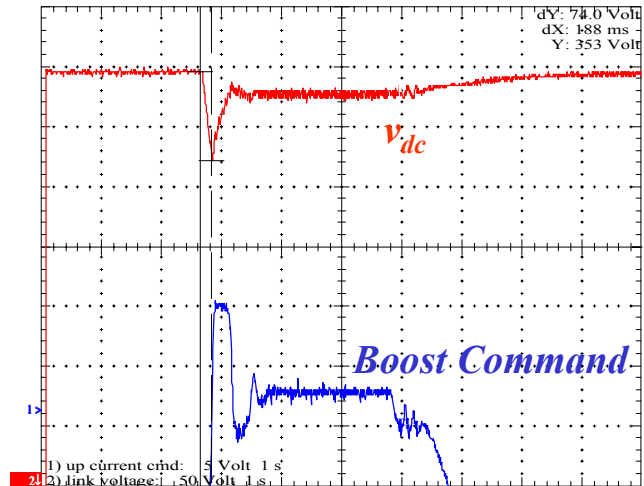


Fig. 4. DC link voltage maintained by boost from bi-directional converter upon loss of voltage from prime mover.

and transformer turns ratio such that it is of minimum size and weight yet able to provide enough ride-through until the engine can pick up the load. Fig. 4 shows how the bi-directional converter is able to maintain the dc link under the extreme case of complete loss of power from the rectified alternator voltage. The voltage dips to 280 V from 350 V in Fig. 4, but the converter operates under the less stringent requirements of maintaining the dc link during a short-term transient load increase and not for a complete loss of prime mover power.

IGBTs were used for the high voltage switches and MOSFETs for the low voltage switches. Since the IGBTs could not be operated as a synchronous rectifier, the benefit of using the MOSFETs as synchronous rectifiers was deemed unworthy, and the PWM control signal for each converter direction operates independently. In low voltage to high voltage mode, the circuit operates as a transformer coupled boost circuit with the same limitations where the output cannot be controlled below the level of the input voltage, or in this case 11.2 times the input voltage. Thus the minimum controllable voltage, with a low voltage bus of 30 volts is 336 volts. In order to eliminate uncontrolled charging current, the boost mode is not enabled until the high voltage link has been brought up by the alternator boost circuit described in section III.

For the downconverter (high voltage to low voltage conversion), the control method is voltage mode control. The switching stage is a half bridge, which is not suitable for peak current mode control, which would destabilize the midpoint voltage. For boost operation, the current in the switches are not monotonic and do not lend themselves to peak current mode control, thus a hall effect current sensor is used to sense the actual inductor currents for control.

In Fig. 5, the boost error amplifier  $U1$  and opto-isolator  $U2$  control the flow of power. The boost regulation point is set to

340 volts so the boost will not try to operate when the DC link voltage is under alternator control. When the DC link voltage is greater than 340 volts, the error amplifier saturates and the error voltage becomes negative. The zero crossing detector *U4C* enables the downconverter PWM when this occurs. The downconverter PWM regulates the 28 volt voltage by controlling the conduction of the half bridge IGBTs  $Q_1$  and  $Q_2$  in Fig. 4. In this mode the anti-parallel diodes  $D_1$  provide a path for the magnetizing current of the transformer. The rectifiers are the body diodes of MOSFETs  $Q_3$  and  $Q_4$ , which are devices with faster body diodes than standard parts. The inductor currents are sensed as positive currents during boost and are therefore inverted by *U5A* for the downconverter current limit function.

Input to output isolation, as well as high side drive, is maintained during downconverter operation by gate drive transformer *T1*. When the DC link voltage falls, because of a load transient on the inverter that the engine cannot provide at its present speed, the error amplifier comes out of saturation.

When the error voltage reaches zero volts, the downconverter PWM is inhibited; as it further increases, the boost converter starts switching, and the current commanded from the 28 volt source is directly proportional to the magnitude of the error voltage signal. The minimum

conduction of  $Q_3$  and  $Q_4$  is 51% with a 1% guaranteed overlap where they both are conducting. The maximum conduction of  $Q_3$  and  $Q_4$  is 80%, with a 30% overlap time. The effective boost duty cycle is the overlap time of the switches as a ratio of the half cycle time, thus the boost duty cycle is 2% to 60%.

The limitations on the transient response of the boost is the slew rate of the error voltage and the rate of reversing the current in inductors  $L_2$  and  $L_3$ . Once the engine has been accelerated to a speed that is capable of supplying the load, it will hold the DC link voltage at 350 volts or greater. When that happens, the error amplifier will again saturate, inhibiting boost switching and allowing the downconverter to operate. With both MOSFETs off and positive current still flowing in inductors  $L_3$  and  $L_4$ , a path for this current to flow is necessary. Diodes  $D_2$  allow this current to continue into  $C_4$  where the energy is subsequently dissipated by  $R_{43}$ .  $C_4$  is sized to accept the maximum currents in  $L_2$  and  $L_3$  and not produce an excessive voltage on the drains of  $Q_3$  and  $Q_4$ . The magnetics are designed thermally for the 1.5KW continuous delivered power in downconvert mode. In boost mode, the inductors are allowed to swing 50% with the peak current of 350A.

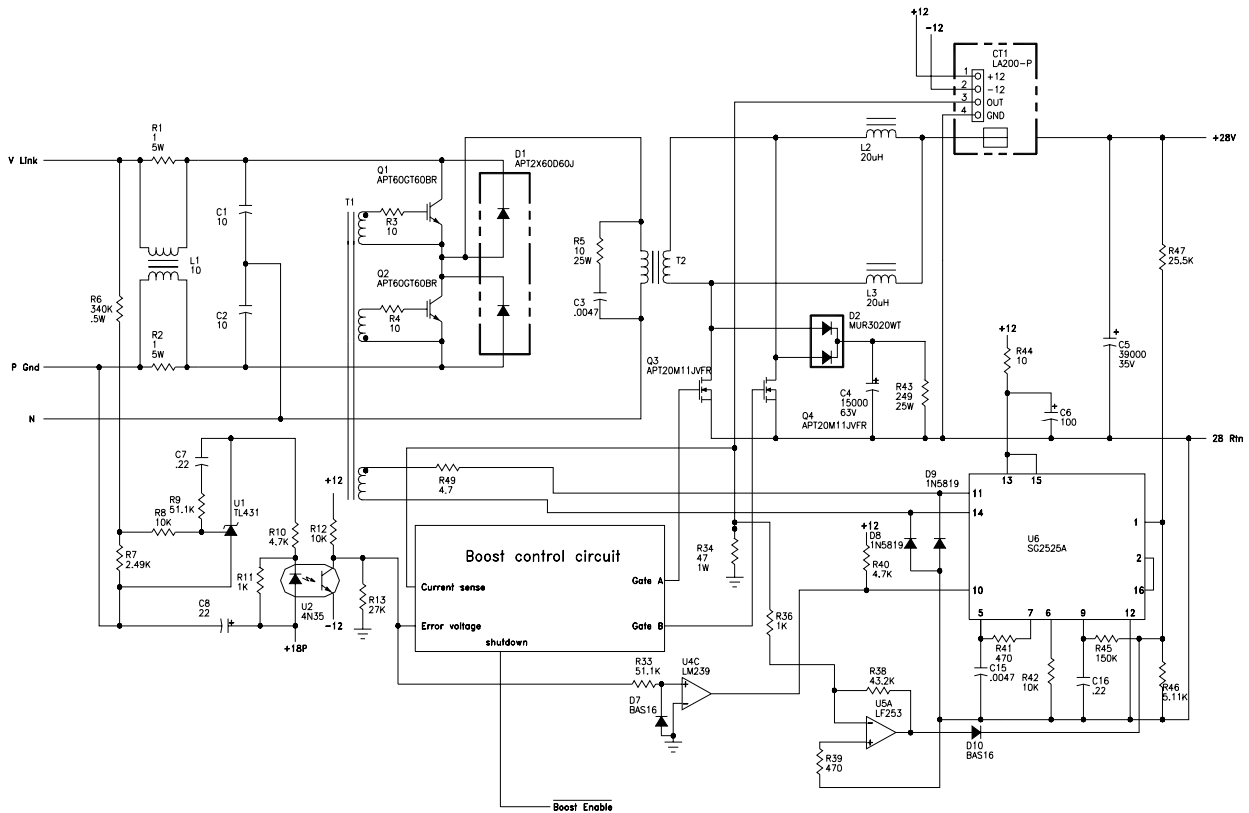


Fig. 5. Control circuit for bi-directional converter.

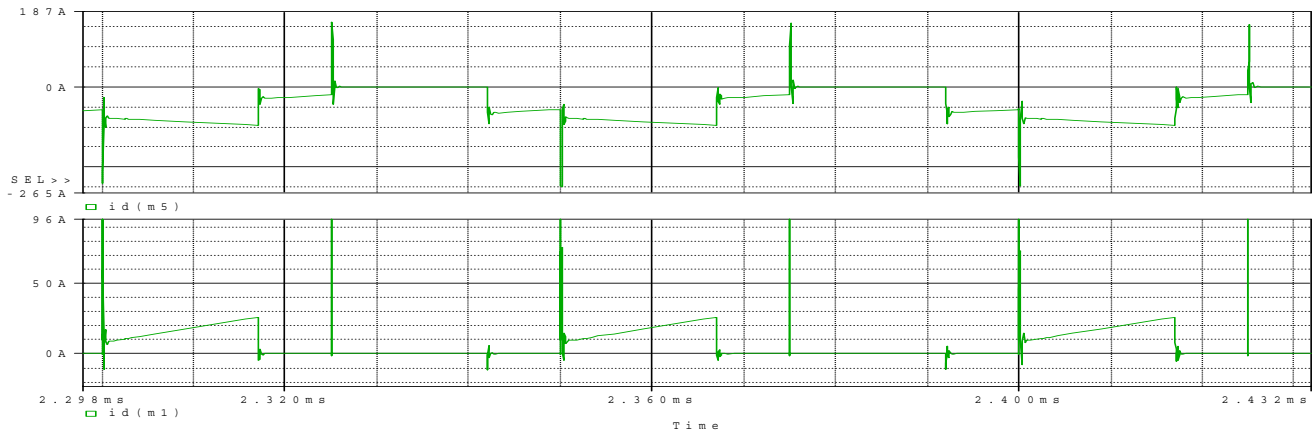


Fig. 6. Waveforms for MOSFET current (top) and IGBT current (bottom) with bi-directional converter in buck mode.

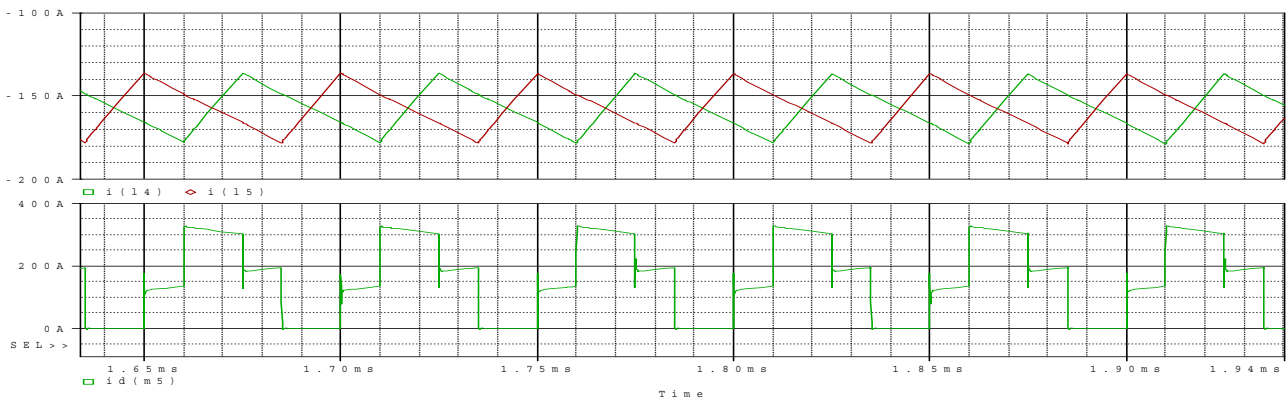


Fig. 7. Waveforms for inductors' current (top) and MOSFET current (bottom) with bi-directional converter in boost mode.

## V. CONCLUSIONS

To minimize the volume and weight of a portable generator set shown in Fig. 8, variable speed operation of the internal combustion engine is desired. The description of a bi-directional dc-dc converter that has minimum energy storage components is shown to be able to produce low voltage dc for recharging a battery set and powering auxiliary loads. This converter is also used to maintain the high voltage dc link during transient load conditions such that the generator set can provide regulated ac voltage to the load.

## ACKNOWLEDGMENTS

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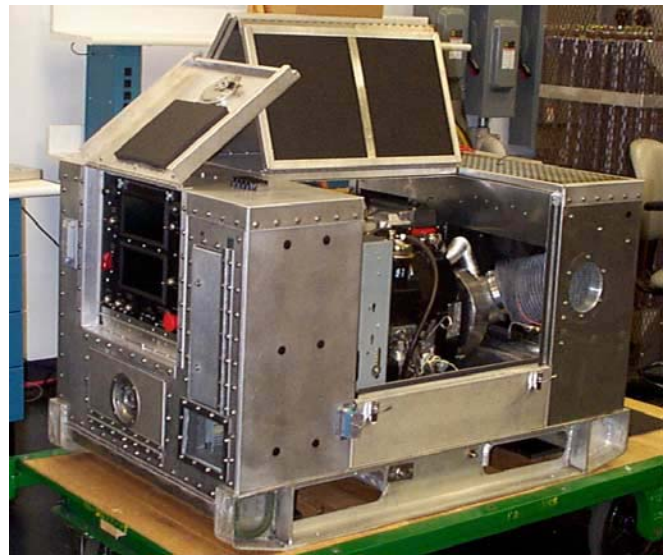


Fig. 8. Proof of concept 7.5kW-rated gen-set.

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