GEN-SETS

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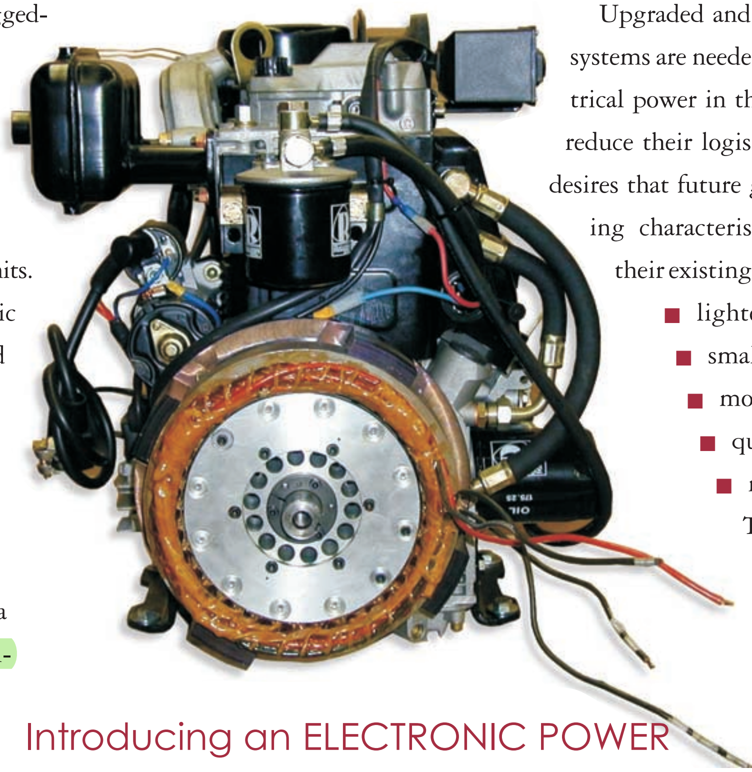
Introducing an ELECTRONIC POWER CONVERSION SYSTEM for an ADVANCED MOBILE GENERATOR SET.



EXISTING MILITARY GENERATOR sets (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 3,000 m.

These 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. Fixed-speed engines are forced to run outside their optimum fuel consumption envelope when they 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]-[5].

Upgraded and enhanced tactical power systems are needed to provide reliable electrical power in the battlefield. In order to reduce their logistics burden, the military desires that future gen-sets have the following characteristics when compared to their existing gen-sets; they should be:

- lighter
- smaller in volume
- more fuel-efficient
- quieter
- more reliable.

The desire for future gen-sets is that they be portable, lightweight systems that are electronically controlled, signature- suppressed, and capable of operating on DF-2/JP-8 fuels in extreme environmental conditions [6], [7]. With advanced diesel engines and variable-speed technology, goals for the program were to reduce weight by 50% and increase efficiency by up to 30%. The speed of the engine is determined from a user-selectable interface that allows the engine to run at its most efficient operating point for a given load and ambient thermal

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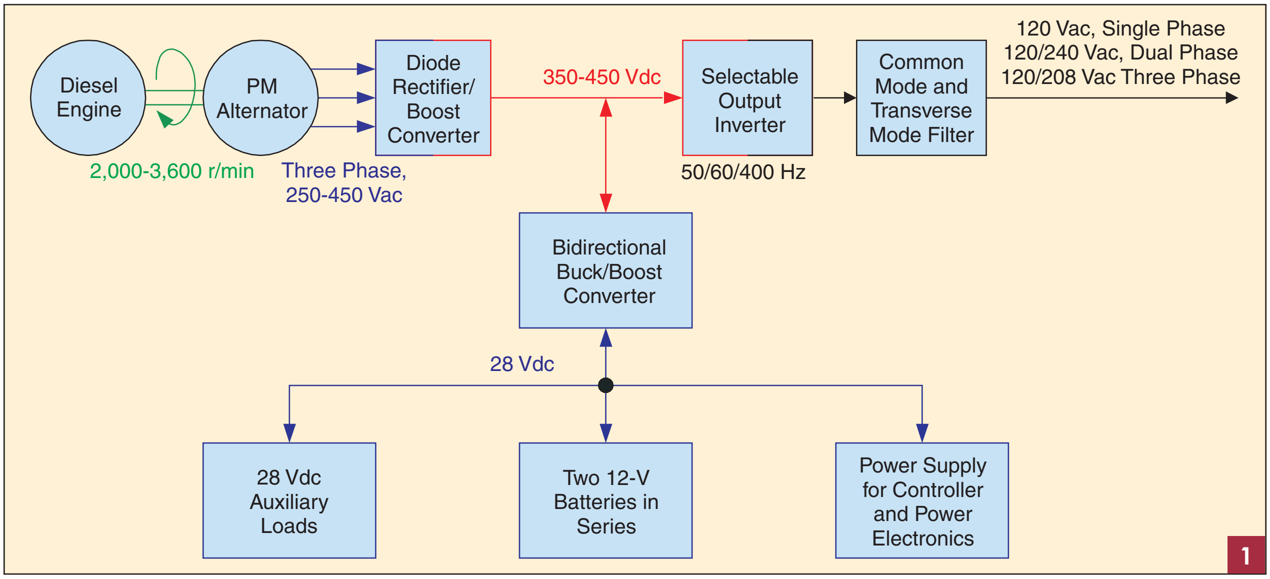


Functional block diagram of power conversion components in generator set.

conditions. It is also possible to control the engine to run where it is most audibly quiet, at its least-polluting operating point (from an emissions point of view), or at its most reliable, stiffest point such that it is less sensitive to load transients. This article describes a proof-of-concept development for a 7.5-kW gen-set in a family of military gen-sets in the 5- to 60-kW range.

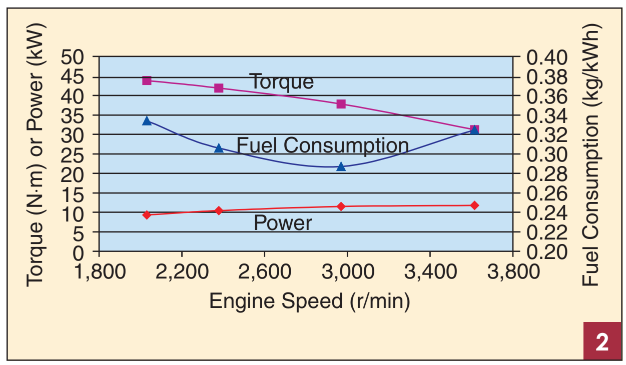
Gen-Set Operation

A block diagram of the electronic power conversion system for the proof-of-concept gen-set developed at the Oak Ridge National Laboratory (ORNL) is shown in Figure 1 [6], [7]. The military gen-set uses an internal combustion (IC) diesel engine to drive a radial-gap permanent magnet (PM) alternator at variable speed. The speed of the engine is determined from a user-selectable interface that allows the engine to run at its most efficient operating point for a given load and ambient thermal conditions. The variable frequency, variable voltage produced by the PM alternator is diode-rectified to dc voltage, and an inverter is used to produce selectable-frequency, controllable ac voltage.

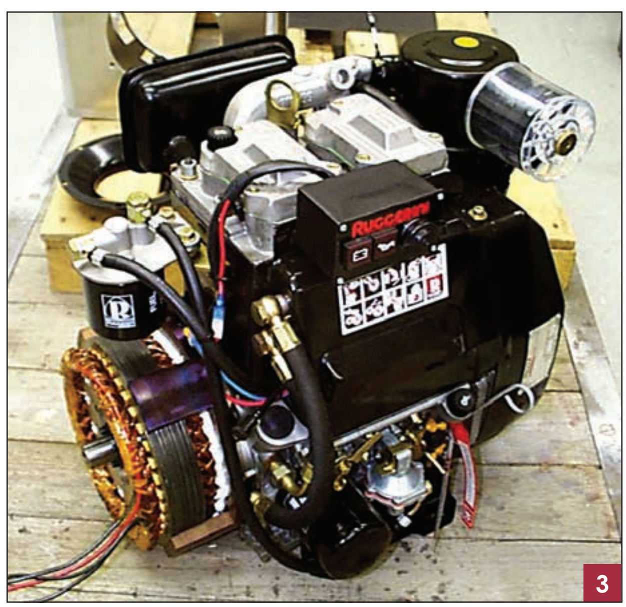
The user is allowed to select single-phase 120-V, dual-phase 120/240-V, or three-phase 120/208-V. Each of these voltage configurations can be generated at 50, 60, and 400 Hz such that the unit can be compatible with equipment produced from around the world or for aerospace applications. The power-conversion system also incorporates a bidirectional dc-dc converter that can charge 24-V batteries that are used to start the IC engine and to power auxiliary loads [8]. The converter can also draw power from the batteries to help maintain the dc link during severe load transients.

Engine and Alternator Description

Each gen-set size was determined by selecting an advanced diesel engine that had a high power-to-weight ratio. For the smallest gen-set, an air-cooled Ruggerini MD 191 rated at 13 kW was used as the prime mover. The engine



Peak torque, power, and fuel consumption for the diesel engine in the proof-of-concept gen-set.

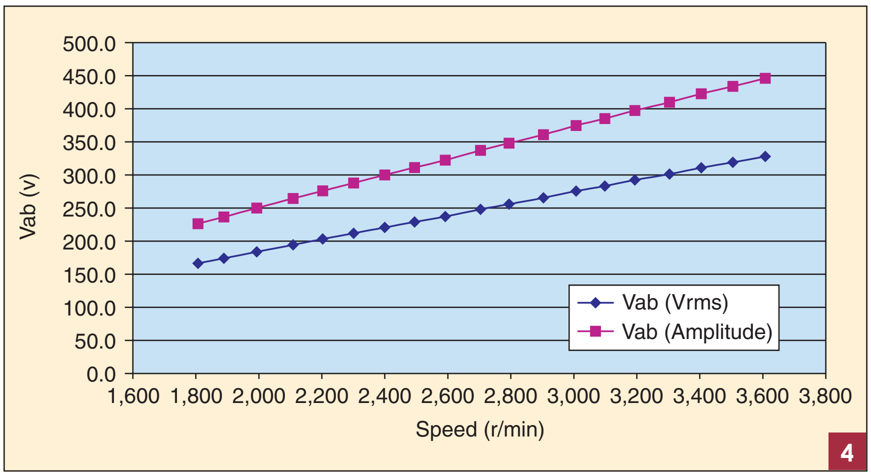


PM alternator mounted to gen-set engine.

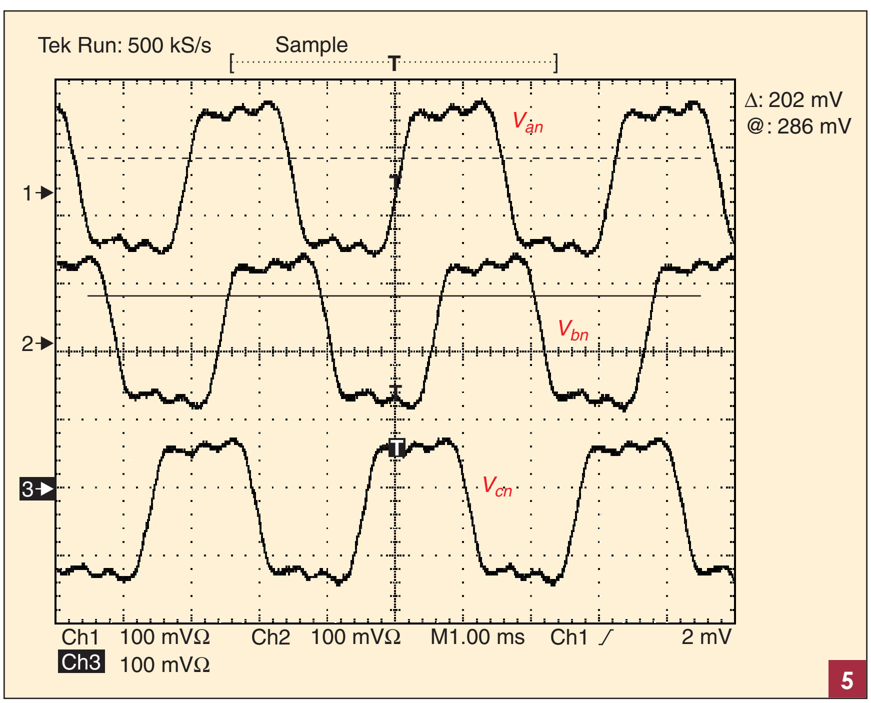
was completely characterized for power, torque, fuel consumption (Figure 2), and emissions of CO_2, NOx, CO, and THC over its operating speed range.

For each engine size, a radial-gap PM alternator with high flux magnets (NeFeB) was designed such that the alternator produced trapezoidal back electromotive force (EMF) with a peak line-line voltage of 450 V at the top engine speed. This allowed enough design margin such that 600-V devices were used for the main power components. For the smallest gen-set size, a bearingless cantilever design for the alternator allowed the stator to bolt directly to the engine block. The rotor mounted directly to the engine shaft and had a diameter of 17 cm and a depth of 4 cm. Figure 3 shows the Ruggerini engine coupled to the PM alternator. Line-line peak output voltage of the PM alternator (Figure 4) varies linearly with speed, as expected, such that at 3,600 r/min the alternator produced a waveform with a line-line amplitude of 450 V, and at 2,000 r/min a voltage waveform with an amplitude of 250 V. Figure 5 shows line-neutral voltage waveforms for the alternator operating at 3,200 r/min.

THE GEN-SET IS ABLE TO RUN AT ITS MOST EFFICIENT CONDITION TO MINIMIZE FUEL CONSUMPTION.



PM alternator voltage versus speed.



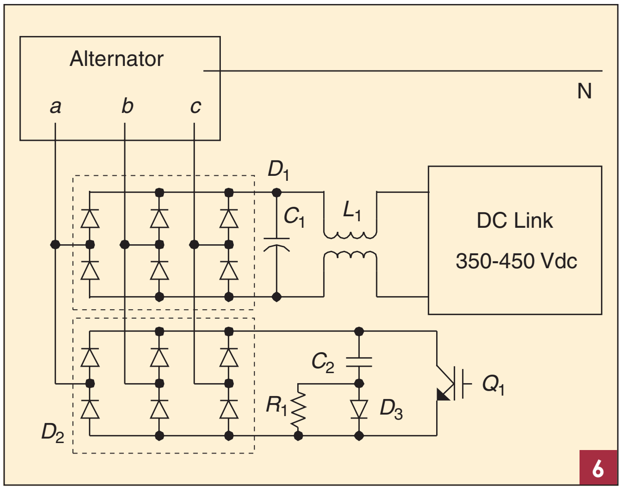
PM alternator voltage waveforms at 3,200 r/min (100 V/div).

Asynchronous Boost Operation

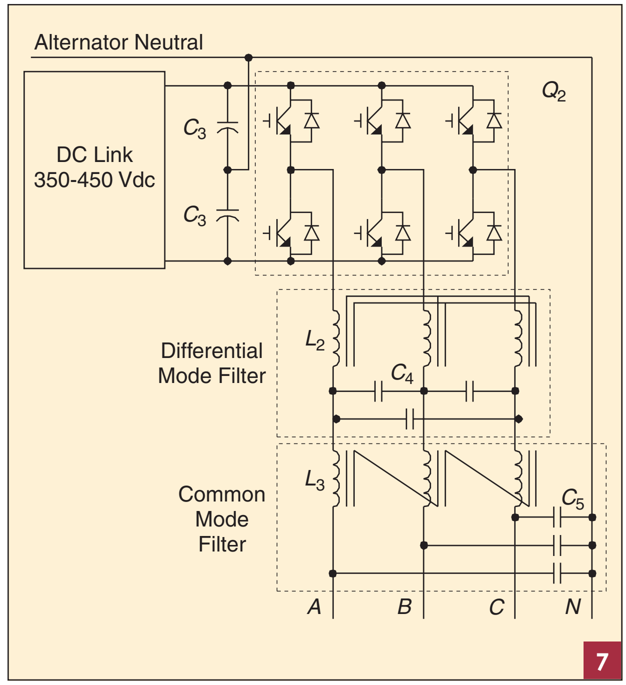
The gen-set was designed such that the inverter can produce 120-V root-mean-square (rms) line-neutral voltage for dc link voltages between 350-450 Vdc. During normal, unboosted operation, the alternator line-line voltage is rectified by the three-phase, full-bridge rectifier D_1 with conventional six-pulse rectification (Figure 6). During this mode, the boost rectifier is inactive, and transistor Q_1 is off. The minimum desired dc link voltage of 350 Vdc corresponds to an alternator speed of 2,800 r/min.

When the dc link voltage produced by this normal mode of rectification is less than 350 Vdc (corresponding to a gen-set speed of 2,000-2,800 r/min), 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 (Figure 6). During this time, the three-phase, full-bridge rectifier diodes in D_1 block and capacitor C_1 supplies the inverter load. The current being supplied by the alternator ramps up due to this short and 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



Schematic of gen-set boost rectifier.



Schematic of gen-set inverter and filters.

frequency. The diodes in D_2 are commutated at the alternator frequency; therefore, they 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, thus limiting the di/dt to a value that will not produce damaging voltage spikes.

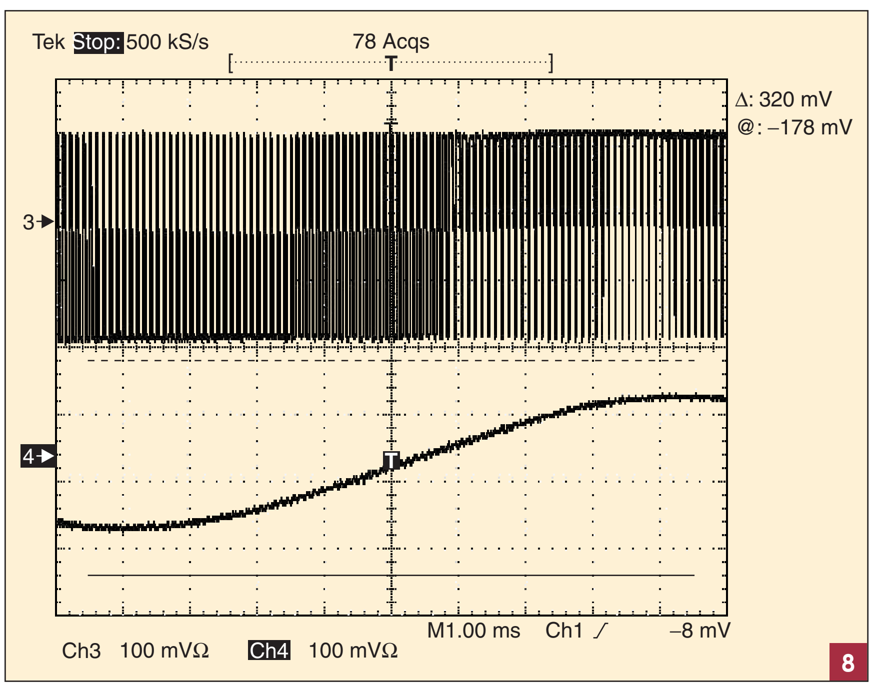
The alternator and load neutrals are connected to the center of two capacitors C_3 (Figure 7). The connection allows unbalanced load currents to flow through the alternator in parallel with the capacitors and eliminates the requirement that they have a low impedance at the fundamental frequency. The inductor L_1 (Figure 6) prevents what would be an undesired consequence of this connection. Without L_1, each of the C_3 capacitors would charge to the half-wave rectified, line-neutral voltage of the alternator, resulting in poor power factor and high crest factor in the alternating current.

Inverter and Output Filter Description

A traditional full-bridge, three-phase inverter composed of a 600-V, 200-A, six-pack insulated-gate bipolar transistor (IGBT) module Q_2 (Eupec BSM200GD60LD) was controlled with a digital-signal processor (DSP) to produce a pulsewidth modulated (PWM) output (Figure 7). The PWM waveform is passed through a three-phase, common-mode, inductance-capacitance (*LC*) filter composed of L_3 and C_5 and a three-phase, differential mode *LC* filter composed of L_2 and C_4 to achieve near sine-wave (< 3% total harmonic distortion) waveforms (Figures 8 and 9). The differential mode filter was designed for a corner frequency of 3.3 kHz, and the common mode filter has a corner frequency of 1.3 kHz.

Bidirectional 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

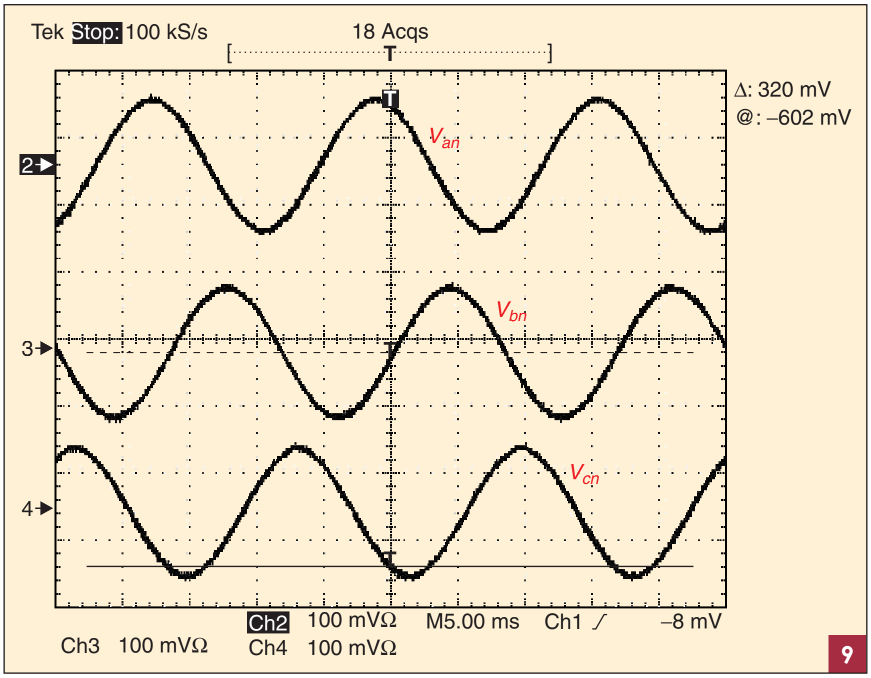


Pre- and post-filtered line-neutral output voltage waveforms from the proof-of-concept gen-set. (100 V/div, 1 ms/div).

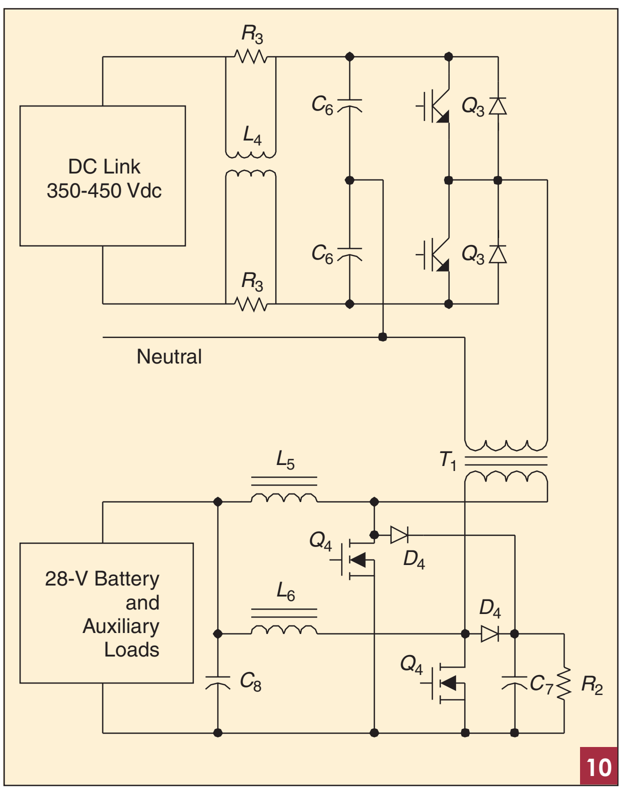
and to recharge the engine-starting battery. The converter is able to provide 7 kW for up to 10 s or 1.4 kW continuously. When operating in this buck mode, the converter operates as a voltage-mode, half-bridge, transformer-coupled buck regulator with a current-doubler rectifier. In boost mode, the converter can use the 28-V power from the battery to supply the dc link during load transients when the engine has not responded with sufficient speed to maintain the dc link above 350 Vdc. The selection of these two topologies was to minimize the energy storage requirements and transformer turns ratio such that it is of minimum size and weight yet able to provide enough ridethrough until the engine can pick up the load [8].

For high- to low-voltage operation, the dc link voltage is passed through a resistance-inductance (*RL*) link damper consisting of the two R_3 resistors and L_4 (Figure 10). This link damper prevents oscillation between the C_6 capacitors of the bidirectional converter and the dc link capacitors C_3 on the inverter (Figure 7). The C_6 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 Q_3 IGBTs.

To minimize the size of the high-frequency transformer T_1, the Q_3 IGBTs are driven at a 20-kHz frequency. Transformer T_1 has 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_4 and filtered by L_5 and L_6), allows the Q_3 IGBTs to be operated at a maximum duty ratio of 0.85 when converting 350 V to 30 V.



Filtered line-neutral inverter output voltage waveforms (100 V/div, 5 ms/div).



Schematic of the gen-set bidirectional converter.

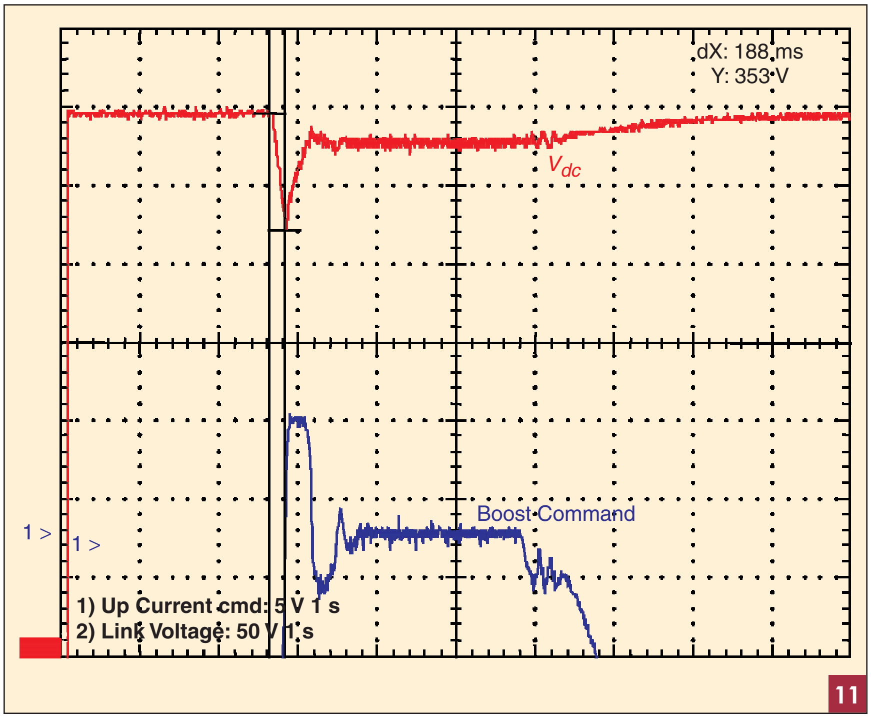
For low- to high-voltage operation, the boost mode is activated when the dc link voltage falls to 340 Vdc, or 10 V below the nominal dc link voltage. When both of the Q_4 transistors are on, transformer T_1 is shorted, and the battery voltage is applied to inductors L_5 and L_6. When one of the two switches is turned off, the input voltage plus the energy stored in the inductor is applied to T_1. Transformer T_1 steps up the voltage that is then rectified by the antiparallel diodes of the Q_3 IGBTs. When both of the Q_4 switches are off, any stored energy in inductors L_5 and L_6 is transferred through D_4 to C_7, which is then discharged by R_2.

Figure 11 shows how the bidirectional converter is able to maintain the dc link voltage under the extreme case of complete loss of power from the rectified alternator voltage. The dc link voltage dips from 350 to 280 V for the case shown in Figure 11; however, the converter only needs to operate under the less stringent requirements of maintaining the dc link during a short-term overload and not for a complete loss of power from the prime mover.

Controls

The 7.5-kW-rated proof-of-concept gen-set is shown in Figure 12. A user control and status display panel on the gen-set unit (Figure 13) provides an interface to a digital control system. The controls were implemented on two TI TMS320F6701 floating-point DSP processors of the Daytona dual DSP PCI card. In addition to this, a peripheral component interconnect (PCI) interface card was designed and implemented to interface the DSP card via a 32-b parallel port. This interface board (OrnlDas) contains eight independent, 14-b, analog-to-digital (A/D) converters that operate at 1.2 μs and 12 more analog channel inputs that operate at 5 μs. An OrnlDas card also contains a universal asynchronous receiver/ transmitter (UART) to communicate to the front panel displays, four 16-b D/As for analog control, and four 16-b input/output (I/O) digital channels.

The control is split between the two DSPs on the Daytona card. The primary DSP, which can communicate with the OrnlDas card, performs all of the I/O with the gen-set. It also regulates the output voltage on a point-by-point basis. The second DSP takes the analog and digital data and computes rms voltages and currents, power levels, and power factors of the ac waveforms; the dc link, battery, and 28-V auxiliary-load voltages and currents; and the average temperatures, oil pressure, engine speed, etc. These are displayed on the screens on one or more of the display selections. Other functions of the DSPs include control of the output current to generate PWM duty cycles and the determination of the optimum engine speed for a given output power.



DC link voltage maintained by boost from bidirctional converter upon loss of voltage from prime mover (50 V/div, 1 s/div).

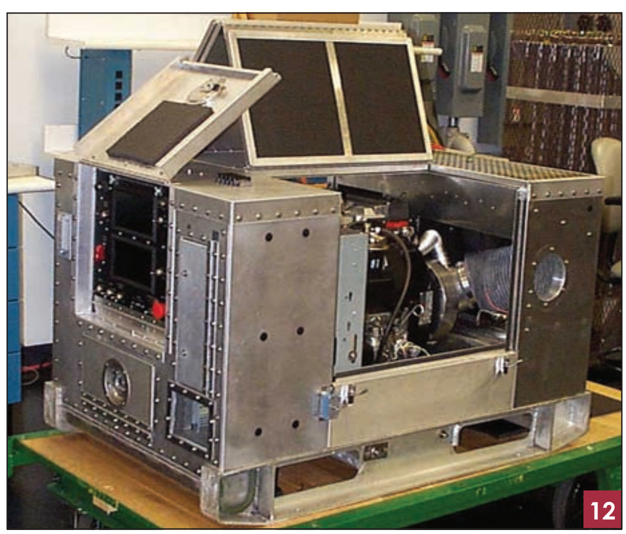
All operator inputs on the display panel (Figure 13) are routed directly to the DSP. It is the DSP that then interprets the information and decides on the "safe" conditions before controlling the rest of the system. Since it is the software that interprets the functions of all the switches and other inputs, it is easy to change or update the control logic to match different conditions, engines, or even power electronics. The system was also designed to enable the addition of diagnostics and prognostics to facilitate field maintenance and repair.

The display panel allows the user to monitor phase voltages, currents, power, and power factor from a user digital display. The display also shows the engine speed and the status of certain parameters, such as oil pressure and temperature and intake or exhaust temperature. Output selection of 120-V/single phase, 240-V/dual phase, and 208-V/three phase are switch selectable as shown at the bottom of the picture (Figure 13). The output frequencies of 50, 60, and 400 Hz are also switch selectable. Once the electrical output is energized, however, these switches are ignored to prevent false changes during operation and damage of the connected load.

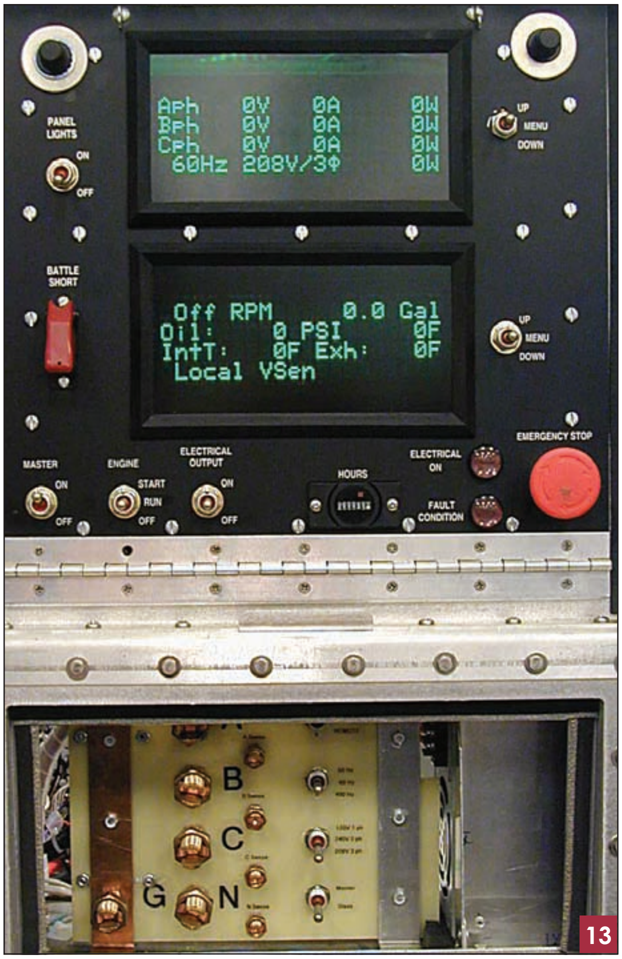
Conclusion

Several power electronic converters have been implemented in the design of a proof-of-concept gen-set that is lighter, smaller, and more fuel efficient than conventional fixed-speed gen-sets. The unit also has the flexibility of several selectable voltage and frequency options that greatly reduces the inventory logistics burden for a family of different unit types and sizes. With integrated controls and power electronics, the gen-set is able to run at its most efficient condition to minimize fuel consumption. It would also be possible to control the gen-set such that it ran at other different optimized conditions such as:

- maximum headroom for supplying load transients
- most audibly quiet
- least polluting for certain emissions.



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



13 Gen-set user interface and display panel (top half of picture) and field output connections, voltage configuration, and frequency selection switches (bottom half of picture).

Acknowledgments

We would like to acknowledge the efforts of John Andriulli, Curt Ayers, George Farquharson, George Ott, Larry Seiber, and Cliff White in development and test of the proof-of-concept gen-set. This project is part of the Advanced Medium-Sized Mobile Power System (AMMPS) program conducted by the U.S. Army Communications and Electronics Command (CECOM) Research, Development, and Engineering Center, Power Generation Branch, under the sponsorship of the U.S. Department of Defense Program Manager for Mobile Electric Power (PM-MEP).

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