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Designing An Open-Source Power Inverter (Part 1): Goals And Specifications

by Dennis Feucht, Innovatia Laboratories, Cayo, Belize

This is the first in a series of articles that will disclose the engineering of a kilowatt-level, scalable open-source battery inverter that I have dubbed the "Volksinverter". Just as the old Volkswagen Beetle was intended to be a car for the people, this inverter is meant to be a product suitable for widespread use, and which can be built and/or serviced by technically savvy individuals.

Its key characteristic is the open-source nature of this design. Open-source disclosure is important for an infrastructure subsystem such as an inverter, because when failure unexpectedly leaves the distribution loads without electricity, repairing the inverter becomes a high-priority task requiring the availability of adequate technical information.[1]

In this article series, the design of the Volksinverter will be described in enough detail that a technical owner will be able to maintain, repair, or even modify the design, including the magnetic components. Like Linux, the Volksinverter design will lend itself to discussion by user groups on the Internet who will be able to share ideas, observations, procedures, modifications, corrections and enhancements of it. Anyone will be free to manufacture and sell it, as-is or in modified form.

The Need For Open-Source Power Electronics

In the past, the electronics industry disclosed what was being sold, not expecting the buyer to put out money for an item only partially revealed. The more recent trend to nondisclosure is the most severe for consumer items. Lacking complete specifications, no less technical information, manufacturers are able to sell undocumented products to undiscriminating buyers.

The nondisclosure trend has even spread to manufacturers of technical products such as measurement instruments. In the past, companies such as H-P and Tektronix informed customers in great detail about their products. Tek user-service manuals were called "Instruction Manuals". This policy has changed.

Here's an example from Keithley, "As is now standard in the test and measurement industry, we do not release schematics to our instruments. For some of the older instruments, they will be available in their service or user manuals."[2] This example is not intended to single out Keithley (or Tektronix) but to give only one example of a general trend that Keithley regards as "standard in the … industry".

This denial of information prompted an onlooker to comment, "The Keithley 2000 [DMM] is a direct competitor with Agilent's 34401A. Agilent has the schematics for their meter in the service manual. For many folks like me who repair their own equipment, that makes Agilent the better choice. Although I have the Keithley 2000 on my bench since I need the scan card option, perhaps you'd sell more 2000 DMMs if you were to make the schematics available? Just sayin'"[3]

This dialog illustrates that users want to have technical knowledge of their products. Even service manuals—if you can get them—often have block diagrams instead of component-level circuit diagrams. This trend is in part driven by the increasing complexity of electronics and of the use of custom parts such as magnetic components, ASICs, and microcomputers (microcontrollers, DSPs, and the like) with internal programming.

Perhaps in today's global market, suppliers are less confident of their ability to maintain steady progress technically, and to remain ahead of competition. While secrecy might offer marginal protection from competitive advantage, anyone who can reverse-engineer a product and publish the results on the Web can support a reversal of this trend.

Without informing the buyer what the product *is* (and not merely what it *is for*), the buyer can only use but not maintain, repair, or even modify the product. In a global market where after-market repair by authorized distributors is not available (or desirable) and where do-it-yourself field repair, whether by an individual or a local business is the only viable option, open-source products are attractive, as illustrated by the above comments.

Magnetic components are typically high in reliability in that transformers are usually one of the least likely components of a circuit to fail. Even so, the design margins of magnetic parts nowadays are often reduced, failures occur, and some knowledge of the parts is desired. While magnetics suppliers have catalogs of inductors and transformers for common applications such as gate drivers and switching supplies of standard voltages, most magnetic components are designed for the particular application as custom parts.

Without some critical design information, replacement of such a part depends wholly on being able to acquire the part from the supplier, and this is increasingly infeasible in a global market. Custom microcomputer replacement poses the same problem.

The Volksinverter which will be described in this article series is a design exercise to overcome these limitations. All aspects of the Volksinverter will be revealed in detail here (and elsewhere[4])—not only the circuit and magnetics designs, but also the design perspective and rationale, design formulas, and various subtleties. The documentation begins with this article and a description of the specifications.

Volksinverter Description

Although the entire system is called an "inverter", an inverter stage is just one section or subsystem within the converter and it is preceded by a battery converter, as shown in the Volksinverter block diagram in Fig. 1.

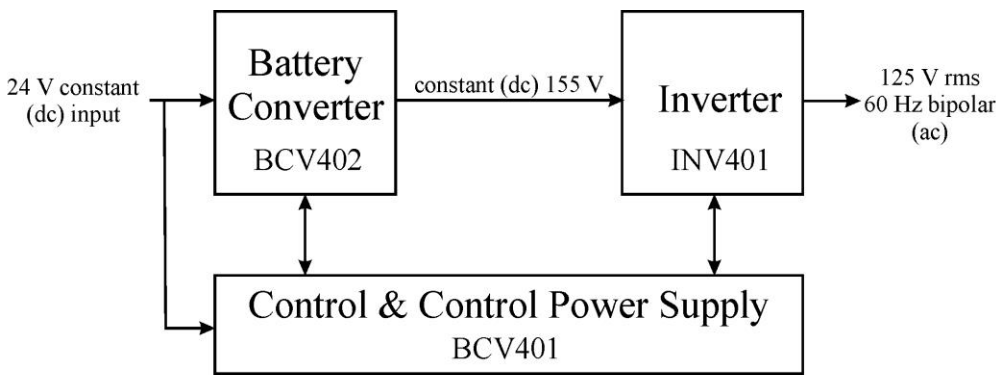

Fig. 1. An "inverter" includes the input-stage battery converter (BCV402) with control support (BCV401). The converter outputs a constant 155 V, the peak of the bipolar waveform generated by the inverter (INV401). The BCV and INV designators refer to the board-level modules used to construct the Volksinverter prototype.

A system-level diagram of the various Volksinverter functions is shown in Fig. 2. Magnetics components appear on all three subsystem modules: the INV401 has passive overcurrent protection (OCP) in the PWM output filter inductor (line impedance compensation); the BCV401 has a control supply inductor; and the BCV402 has an inductor and transformer, part of the boost push-pull power-transfer circuit.

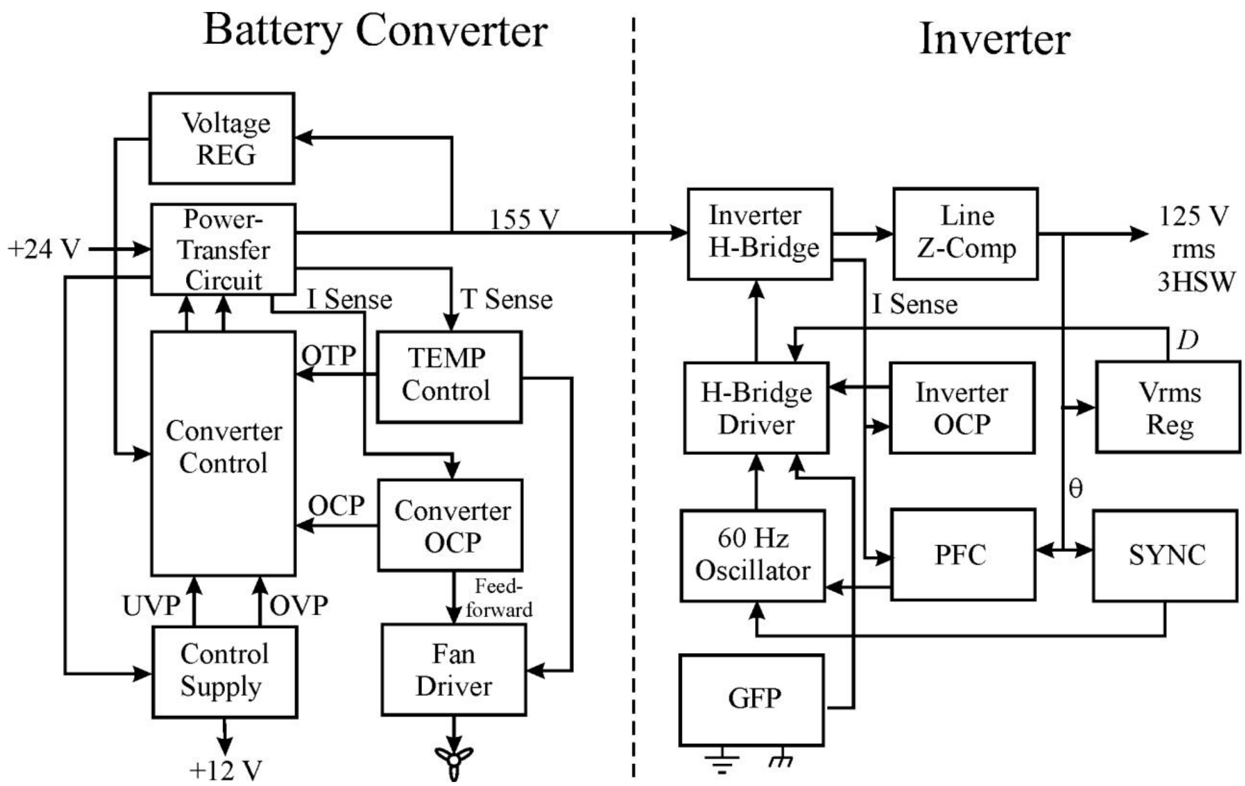

Fig. 2. Block diagram of the Volksinverter. Protection functions include overcurrent (OCP), overtemperature (OTP), undervoltage (UVP), overvoltage (OVP) and ground fault (GFP).

Protection circuits are a significant part of the design. Undervoltage protection (UVP) prevents MOSFETs from partial-conduction high-r_{on} during power-on and power-off of the controller. Overvoltage protection (OVP) shuts down the BCV402 drive when the battery voltage exceeds a safe value for the switches.

Overtemperature protection (OTP) senses one of the converter power MOSFETs with a diode in a measurement circuit based on the temperature-dependent voltage of silicon junctions. The circuit, using a low-cost commodity op-amp, generates an accurate voltage for ΔT which is compared with an upper temperature threshold. If exceeded, the converter is shut down.

This temperature measurement circuit also drives another hysteretic (or "window") comparator of the fan driver for hysteresis control of the fan, turning it on at T_J = 50°C and off at T_J = 20°C above ambient, as measured by a reference-temperature diode on the circuit-board, paired with the temperature-sensing diode on the MOSFET.

Overcurrent protection (OCP) senses a power-circuit current with a sense resistor, amplifies its voltage, compares it to a power-switch safety threshold, then shuts down power transfer if exceeded. OCP is taken to an additional level of refinement in recognizing three time periods in which different criteria apply to OCP.

The first period is the brief time it takes the OCP circuits to respond to an overcurrent fault. During this time, only the power-circuit itself can provide passive protection, and the output inductor limits *di*/*dt* of the H-bridge during the microseconds of passive protection. When the OCP circuits respond after some delay through the amplifier and comparator, thresholds are set for maximum transient current. It is set higher than the continuous current, which has a thermal limitation and becomes relevant after a few seconds of heat transfer time.

The inverter also has a ground-fault protection (GFP) circuit for third-wire safety. While the power output is not statically isolated from the battery (though the main power flow is, through a transformer), the battery negative terminal is input as system ground. Any current from the output-receptacle safety ground to the inverter ground is monitored and the inverter is shut off if the voltage difference between the two grounds exceeds a safe limit.

The inverter output waveshape is that of a sine-wave with a third-harmonic component, or a *third-harmonic sine wave* (3HSW). Its shape is between that of a sine wave and square wave. As we will see, it reduces the *crest factor*, χ—the peak to RMS ratio—of the waveform, allowing lower-cost parts with lower voltage and current ratings to supply the same RMS values.

A lower χ^2 is why low-cost inverters output bipolar square waves instead of sine waves; the key parameter is χ. For sine waves, $\chi^2 = 2$; for square-waves with >50% duty-ratio, $\chi^2 < 2$. The lower-amplitude square-wave peak extended for a longer time results in the same RMS output.

Functions

The BCV401 controller module performs the following functions:

1. A 5-V reference starts the +12-V supply and is an accurate voltage for threshold detectors.
2. The +12-V control power supply powers the control and gate-drive circuits.
3. The OTP uses a diode to sense heatsink temperature and has a red LED indicator.
4. The fan controller is hysteretic, is driven by the OTP circuit, and operates between high and low temperatures.
5. The OVP shuts down the converter above 31-V input and lights the blue LED indicator.
6. The UVP shuts down the gate drive below 20-V input and lights the orange LED indicator.
7. A VBAT UVP shuts down the +12-V supply for VBAT < 20 V.
8. A green LED indicates that +12-V power is available.
9. A 200-kHz clock generator drives PWM flip-flops and gates to generate correct gate-drive waveforms.
10. A peak-current comparator changes state at ISN current peaks and sets duty ratio by resetting the drive logic to the *D*′ state.
11. An error amplifier drives the peak current comparator to regulate output voltage, sensed as VSN.
12. The OCP protects against transient and steady-state overcurrent and drives the red LED indicator.

The BCV402 power-transfer subsystem performs the following functions:

1. A fuse provides thermal overcurrent protection.
2. The boost push-pull (BPP) power-transfer circuit drives the transformer to produce secondary output voltage.
3. A low-TC resistor senses switch currents and differentially amplifies for a 40-A fs (8-A/V) ISN output on a control bus (CTRLBUS) with a 5-µs delay.
4. A 155-V output 1/31 voltage divider outputs 5 V full scale to VSN on the CTRLBUS.
5. The secondary circuit is a diode-capacitor rectifier.
6. A primary circuit input inductor has a MOSFET clamp at 42 V to circulate inductor current when both BPP MOSFETs are off, during a fault state.

7. The PWRBUS from the BCV401 supplies +5 V and +12 V to the BCV402 module.

The INV401 inverter subsystem module performs the following functions:

1. The H-bridge circuit inputs 155 V and converts it to a bipolar (±) 3HSW waveform.
2. The H-bridge drives an output LC filter that reduces waveform harmonics and protects the H-bridge against overcurrent during the passive-current protection phase.
3. The H-bridge driver circuits translate the switching waveform to near 155 V for the high-side switches.
4. The low-side H-bridge switches are in series with a resistance that senses current.
5. The sensed current as a voltage is amplified by a differential amplifier and input to OCP comparators that respond during both the transient and steady-state time intervals of overcurrent, driving a red LED indicator.
6. The safety ground of the outlets is input to a GFP circuit which asserts the /FAULT bus and latches, resetting only by recycling the BCV401 power.
7. A 1200-Hz clock generator drives logic that sequences through 10 states of each output waveform half-cycle.
8. A sequencer logic overflow toggles the half-cycle polarity flip-flop, alternating between + and – half-cycles.
9. The sequential outputs are each weighted by a resistor that charges an on-time capacitor for an amount of time corresponding to the on-time of the PWM waveform for the corresponding third-harmonic sine value.
10. A PWM comparator outputs a transition marking the end of the on-time, and flips a flop that drives the PWM logic and resets the on-time capacitor.
11. A power-on reset circuit sets the flip-flops in the logic to their initial state.
12. The output of a voltage divider across the H-bridge outputs (VAC) is fed to a zero-crossing detector that, upon sensing a zero-crossing, resets the sine-wave sequencer to the zero-crossing state.
13. Logic gates output a segmented (20-step) PWM sine wave. The sine value as a fraction of peak value is the duty ratio of the PWM waveform that drives the bridge circuit.
14. The faults, /OCP and /GF, assert the /FAULT bus to the BCV and also reset the inverter PWM flip-flops.

Volksinverter Specifications

The following specifications in the table should be regarded as a *template*—the typical example of possibilities achieved by scaling the given plan, designed for 1 kW of output. Scaling is also included in the magnetics design. The given specifications are the combined specifications for a configuration consisting of one INV401 inverter board, one BCV401 converter control board, and two BCV402 converter power-transfer boards.

This configuration can supply at least 1 to 2 kW of average (continuous) output power, depending on the choice of magnetics component alternatives designed later in this series. The power range can be extended with larger MOSFETs, lower sense-resistor values, larger fuses, and re-scaled heat-sinking. The nominal design is scaled for 500 W to 750 W per BCV402 and over 1000 W per INV401.

Table. Inverter specifications used in the design example in this article series.

BCV401 and BCV402 input voltage range	20 to 30 V
BCV402 output voltage and INV401 input voltage	155 V, ± 5 V (±3.2%)
INV401 output voltage	125 V rms third-harmonic sine wave
INV401 output frequency	60 Hz, ± 1%, adjusted
System ambient operating temperature range	0°C to 50°C
Moisture RH range	0% to 90 %, non-condensing

Several prototype boards with their assigned magnetic parts are shown in Figs. 3 and 4. The INV401 is designed to handle a 1.2-kW input (though rated at 1-kW output) and the converter controller, BCV401 is largely scale-independent.

The BCV402 power-transfer board, however, became a test-bed for various magnetic core types and sizes. Both input inductor and transformer were designed a half-dozen times for different cores and power ratings, and these designs are presented in later parts of this series.

By refining the magnetics design procedure using concepts from previous *How2Power Today* magnetics articles by the author, the inductor and transformer design templates can be applied to various cores for scaling rated converter power over the range of 460 W to 760 W. By applying the same procedure to multiple core sizes, additional insight is gained in how sizing affects design optimization.

As each subsystem design is considered, special attention is given to the magnetics design, though the Volksinverter as a design template shows how the magnetics and circuit designs are coordinated for an optimal overall system. The strategy is to begin with the INV401 inverter output component, then progress to the BCV401 converter control, having the simplest magnetic component to design. Last are the BCV402 inductor and transformer, the most difficult and important to optimize.

Circuit explanations are included so that the context for magnetics design is understood. Most of the circuitry is familiar to power-electronics engineers and technicians. However, the battery converter power-transfer circuit is a *boost push-pull*, and the INV401 inverter synthesizes a *third-harmonic sine-wave* waveform, both somewhat unusual yet optimum.

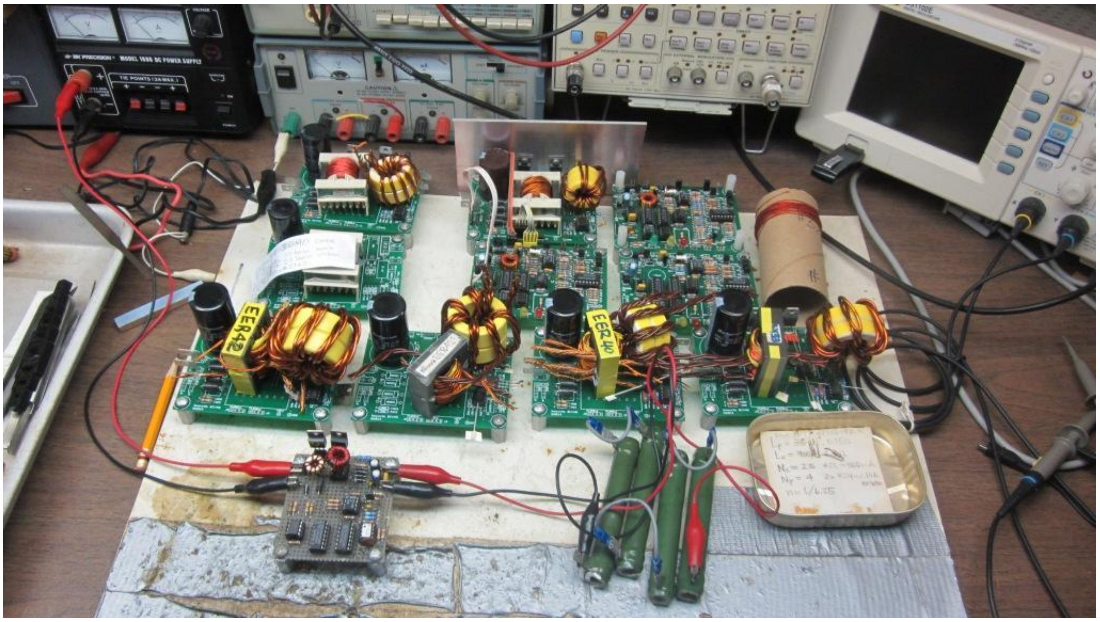

Fig. 3. Circuit boards with the allotted magnetic components. The upper-right boards are BCV401 converter control boards; upper-center (with heat sink) and lower row are BCV402 converter power-transfer boards. The hand-wired board at lower-left is a prototype of a scaled-down, low-power BCV401 and BCV402, combined for examining design problems in the boost-push-pull circuit. The paper tube (upper-right) is a convenient way to store winding bundles for constructing magnetic components. Recycled flat cans keep small parts from becoming lost on a bench.

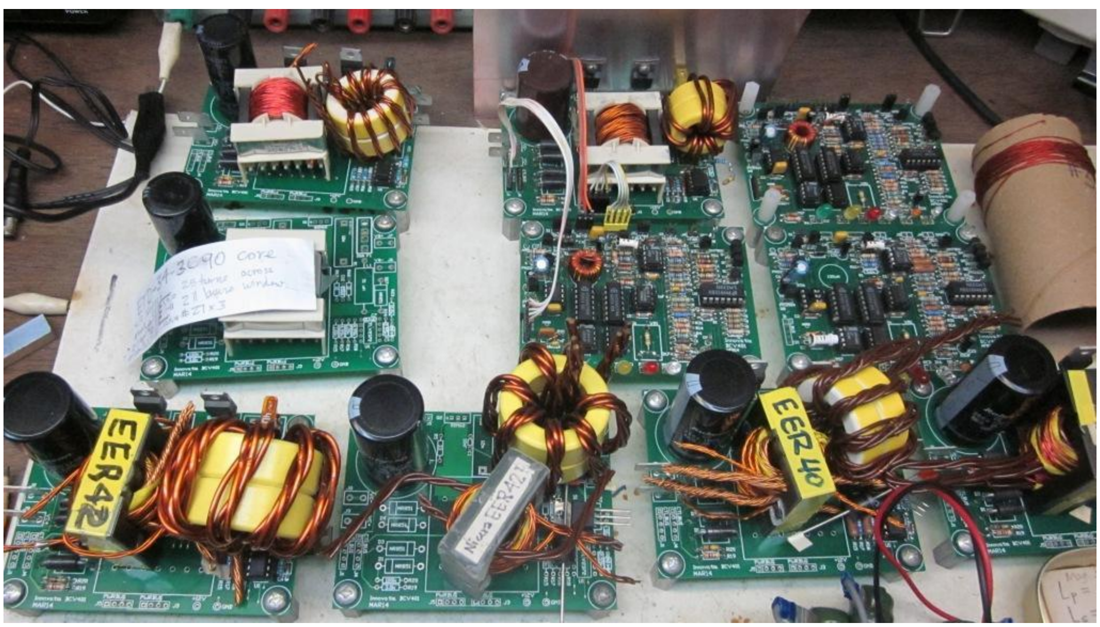

Fig. 4. A closer view of the prototype power-transfer boards. Several sizes of transformer and inductor designs are shown, including EER40 and EER42 transformers. All these prototype magnetics parts are wound by hand and could be rebuilt in the field without winding equipment. The inductors could be shrunk in size using higher-price cores.

Some of the goals in designing open-source, field-reparable, user-maintainable power products are achieving

1. Detailed open-source technical documentation, including essential design information such as circuit diagrams.
2. Minimum use of custom components; the Volksinverter has no microcomputer (microcontroller, DSP or the like), though it would reduce parts count.
3. Fewest possible adjustments, to simplify calibration procedures.
4. Component replacement without the requirement for special tools. This is accomplished by using through-hole components, resulting in single-technology construction (because the power components are unavoidably through-hole.)
5. Minimum use of mechanical components: heat-sinks are flush with the side of the circuit-boards on which the power switches are mounted.

These goals are kept in mind in this extended design "walk-through". The only custom components in the Volksinverter are the magnetics components and circuit boards. The boards could be stacked with spacers but are often better mounted on a planar surface and interconnected with cables and square-pin connectors or else soldered. Cabling with connectors allows quicker diagnosis, testing, and substitution of modules. Power connections are made with 0.25-inch quick-disconnect (QDC) connectors.

Although PQ and RM cores have emerged as the best core shapes for low-R_g (low-voltage, high-current input) converters such as battery converters (as are found, for instance, in the Statpower Prowatt 1500), the author has a large inventory of ETD and toroid iron-powder (Micrometals 26 material) cores which are used instead. The design concepts are unaltered by them, and while transfer-power density is not as high as for the best shape of cores, the design optimization procedure is no different. These converter transformer cores are ETD34, ETD39, EER40 and EER42, all of which have bobbins conveniently fitting the same board hole pin patterns.

The inductor designs are based on stacked 2 × T130, 2 × T131 (which have the same OD but different ID, for comparison of circuit ⇔ field matching), E162, 2 × T150, and 2 × T157 where the "2 ×" indicates two stacked cores—all Micrometals 26, a popular, low-cost commodity iron-powder material.

The magnetics designs to follow provide multiple examples of how the design template is applied. While a few aspects of it pertain to this particular inverter design, the template is readily applied to a wide variety of magnetics design problems, and has applicability well beyond the design of battery inverters.

References

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About The Author

Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

For further reading on inverter design, see the How2Power Design Guide, locate the Power Supply Function category and select "DC-AC power inverters."

