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Designing An Open-Source Power Inverter (Part 2): Waveshape Selection

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An *inverter* is a kind of power converter that outputs bipolar waveforms and inputs power at a relatively constant voltage. Major applications for inverters are in motor drives, fluorescent lighting, and as alternative sources to the power grid for *off-grid electric* power of 120 V or 240 V, 60 Hz or 50 Hz bipolar waveforms. Off-grid power-source design is considered here.

Part 1 of this series[1] discussed the need for an open-source kilowatt-level inverter design and outlined a power architecture for such a design. Besides enabling a more serviceable, maintainable product, the proposed Volksinverter enables many improvements in the performance and functionality of what's typically provided by low-cost power inverters marketed to consumers.[2] These improvements will be described in the course of this article series.

The first part in this series also described the three major functional blocks that comprise the inverter's power architecture—the battery converter, the inverter, and the control and control power supply—and the power architectures used within these blocks and their operation. Key electrical specifications for the inverter design example were also given along with some details on the prototypes and choice of magnetic components.

Here in part 2, we delve further into system design issues, explaining how battery choices influence the selection of electrical specifications for the inverter, including its power protection features. Then we step back and review some mathematics relating to inverter-produced waveshapes, which will help us later in optimizing inverter design to meet various design goals. But first, we'll note the similarity between inverters and another power supply function, which will help us to understand the origins of certain inverter design equations.

The Inverter-PFC Analogy

Battery-sourced inverters perform the inverse function of a PFC (power-factor correction or control) rectifier input of battery chargers, as shown in Fig. 1. Many of their circuit equations are identical, with input and output variables exchanged.

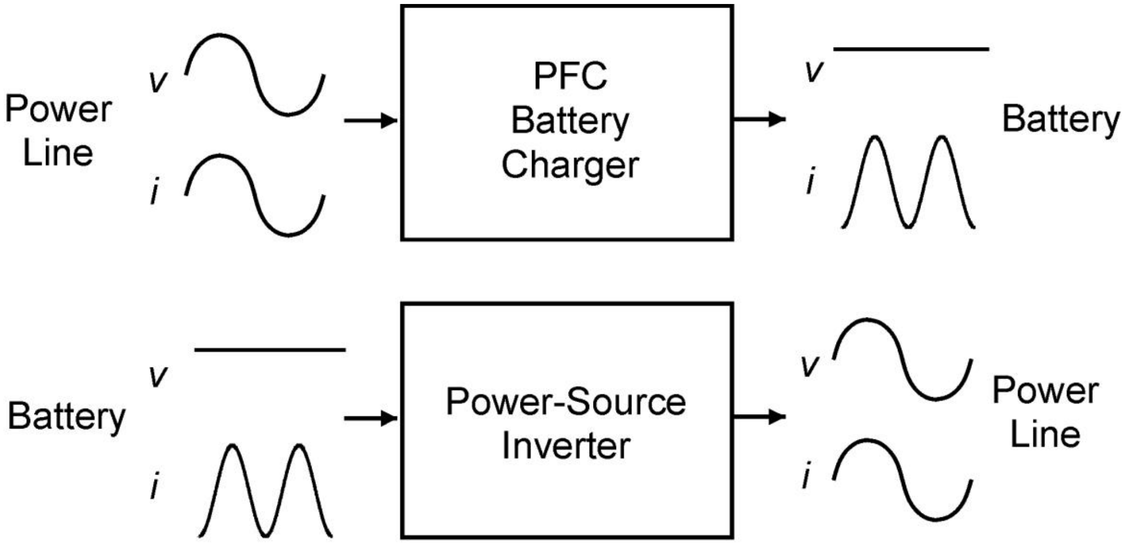

Fig. 1. A battery charger with a PFC input performs the inverse function of a battery-driven inverter. The waveforms and design equations are comparable.

Impact Of Battery Selection On System Design

Battery-source, off-grid inverters convert to bipolar power from a battery bank. Battery voltage is usually 12 V for under 1.5-kW systems and 24 V or 48 V for higher power. A 1.5-kW design is presented in the Volksinverter article series as a concrete design example and *template* for similar designs or parts thereof.

Lead-acid battery banks, charged by solar panels or wind generators, are still prevalent though suboptimal in most off-grid installations as the inverter supply. They are usually unsealed and "deep-cycle," meaning that the lead plates are thicker. The life of $Pb\text{-}H_2SO_4$ batteries is a strong function of how deeply they are discharged. At 50% discharge, they last for about 1000 charge-discharge cycles. Thick-plate Plante or deep-cycle batteries last longer, and like lithium-ion batteries are sensitive to undercharge and overcharge. Too much of either will ruin the battery.

The optimal battery chemistry for off-grid residential or small-scale commercial use is nickel-iron. NiFe batteries outlast human lifetimes and are insensitive to overcharge or undercharge. Their charging efficiency is somewhat lower than lead-acid or Li-ion batteries, but with low-cost solar panels, additional panels pay for themselves very quickly relative to replacement of worn-out batteries. Lithium-ion batteries are becoming common from automotive use. They also have a shorter charge-discharge cycle lifetime than NiFe.

Another consideration that gives us pause when selecting Li-ion batteries for this application is their potential scarcity in the future. It is projected that the world's known reserves of lithium minerals will be depleted in about seven years. While such predictions don't usually come true, there could be shortages.

Inverter functions include protection of both the inverter electronics and the battery bank. One of the functions is to shut down the inverter when the batteries become excessively discharged. Low-voltage shutdown for 24-V NiFe battery systems is often set at around 20 V. The inverter should not restart until the input voltage from the batteries is around a 24-V threshold. This allows the battery state-of-charge to be at least partially restored, if not to a fully charged state.

Additionally, overvoltage shutdown over 30 V might be required to keep the inverter input stage from dissipating excessive power, or to avoid transistor breakdown. Thermal sensing of one or more of the power switches allows the inverter to shut down from overtemperature.

Finally, shutdown caused by a load fault (overcurrent output) should also be in the design. The inverter design given here is specified for the Volksinverter. It has a nominal 24-V NiFe battery bank of 18 series cells. The inverter input voltage range is from undervoltage protection through shutdown at 20 V to overvoltage protection at 30 V.

Waveshape

The notation used in the Volksinverter article series for various waveshape-related values of waveform parameters is as follows:

- $\hat{x}$ is the peak value or amplitude of x, an electrical waveform
- $\tilde{x}$ is the rms value of x
- $\bar{x}$ is the average value of x.
- X is the average amplitude of $x(t)$ when non-zero, and is a constant

An important consideration for inverter design is the *shape* of the output waveform. Typical low-cost inverters output a three-level *bipolar square wave*, as shown in Fig. 2.

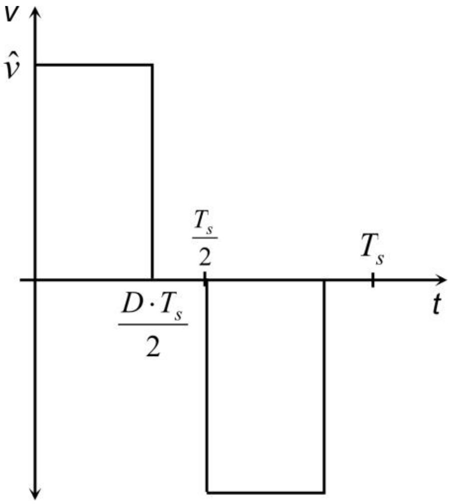

Fig. 2. One cycle of a symmetric bipolar square wave, misnamed a "modified sine wave" in commercial literature. It is not a modification of a sine wave but is more easily and cheaply generated as a square wave.

This symmetrical bipolar square wave is usually referred to in commercial literature as a "quasi sine wave" or "modified sine wave" though it is hardly anything like a sinusoid in waveshape. The duty-ratio, *D*, is set to produce an RMS value equal to a sine wave. The RMS value, $\tilde{x}$ of a square wave normalized to its amplitude, or peak value, $\hat{x}$ is

$$\frac{\tilde{x}}{\hat{x}} = \sqrt{D}$$

For sine waves, $\hat{x} = \sqrt{2} \cdot \tilde{x}$. To set the RMS value equal to that of a sine wave, the duty-ratio must be set to

$$D = \left(\frac{\tilde{x}}{\hat{x}}\right)^2 = \left(\frac{1}{\sqrt{2}}\right)^2 = \frac{1}{2}$$

An important waveform performance parameter for inverters is the *crest factor*,

$$\chi = \frac{\hat{x}}{\tilde{x}} \Rightarrow \text{sine wave } \chi = \sqrt{2}\text{; square wave } \chi = \frac{1}{\sqrt{D}}$$

A design goal is to minimize χ because component ratings are related to the peak whereas the desired inverter output of x is related to the RMS. Expressed in χ, *D* is

$$D = \frac{1}{\chi^2}$$

For a sine wave, $\chi = \sqrt{2}$ and $\chi^2 = 2$.

The crest factor impacts inverter power as the peak-to-average ratio. Average power is typically the rated power. This is highly dependent on the waveshape. For a sinusoid,

$$\frac{\hat{P}}{\overline{P}} = \frac{\hat{v} \cdot \hat{i}}{\tilde{v} \cdot \tilde{i}} = \chi^2 = 2 \text{ , sine waves}$$

For unipolar and bipolar square waves,

$$\frac{\hat{P}}{\overline{P}} = \frac{1}{D}\text{, square waves}$$

For D = ½, the peak/avg power value is the same as for a sine wave of equal RMS value. Over a half-cycle of the output sine wave, the output power will range from zero to twice the average power.

Often, the peak power-line voltage, which is close to 175 V, is not that of a 125-V rms sine wave, but is less. (The international power-line standard voltage has been increased to 125 V rms.) To maintain a comparable RMS value to a sine wave, D must be increased, and this brings down the peak/avg value. One commercial inverter (the Vector Mfg. Co. VEC050D) outputs 145 V peak and 120 V rms. Then D must be set to

$$D = \left(\frac{\tilde{v}}{\hat{v}}\right)^2 = \left(\frac{120\text{ V}}{145\text{ V}}\right)^2 \approx 0.685 \Rightarrow \frac{\hat{P}}{\overline{P}} = \frac{1}{D} = 1.46$$

The reduction in peak power is a substantial 27%. This scheme, however, is not without an undesirable consequence, for some equipment depends on a 170-V peak to produce the required internal voltages. Power supplies that have a transformer input, rectifier, and a peak-charging storage capacitor depend on the peak voltage to be around 170 V. A 15% reduction to 145 V places such a supply at its lower input-voltage margin, and operation can be marginal.

Universal-input switching supplies are rated for this reduced peak voltage, though they sacrifice efficiency or cost for a wide input-voltage range. The square waveshape has the benefit of delivering more power longer to peak-charging supplies because the peak is held for the on-time fraction, D of the half-cycle time. This reduces the peak current through the rectifier diodes and filter capacitor, heating them less and extending their life. Square-wave power is advantageous for such loads.

A disadvantage of square waves for power distribution is their large harmonic content. The higher frequencies in the square wave cause electromagnetic interference (EMI) with communications equipment and are dissipated as additional power loss in the input filters of line-operated loads. Sine-wave motors dissipate the harmonics as heat. Generally, square waves are not preferred to sine waves as a power-distribution waveform.

Input Current And Power

For a resistive inverter load, $R_o = v_o/i_o$, where

$$v_o = \hat{v}_o \cdot \sin(\omega_o \cdot t) \;\; ; \;\; i_o = \hat{i}_o \cdot \sin(\omega_o \cdot t)$$

the output power is

$$P_o = v_o \cdot i_o = \hat{P}_o \cdot \sin^2(\omega_o \cdot t)\,,\, \hat{P}_o = \hat{v}_o \cdot \hat{i}_o$$

For a constant input voltage, such as from a battery, $v_g = V_g$ where v_g represents inverter input voltage and V_g represents a constant value corresponding to the nominal battery value. Then for the ideal case of 100% efficiency, $P_g = P_o$, where P_g is input power, and

$$V_g \cdot i_g = \hat{P}_o \cdot \sin^2(\omega_o \cdot t) \;\Rightarrow$$

$$i_g = \frac{\hat{P}_o}{V_g} \cdot \sin^2(\omega_o \cdot t) = \hat{i}_g \cdot \sin^2(\omega_o \cdot t)$$

For a sine-wave inverter, the input current will have a sine-squared waveshape. This results in essentially the inverse of the equations for a PFC circuit, where input and output variables are exchanged.

The average input current is

$$\bar{i}_g = \frac{1}{T_o/2}\cdot\int_0^{T_o/2} i_g(t)\cdot dt = \frac{\hat{i}_g}{2}$$

where $T_o = 2\cdot\pi/\omega_o = 1/f_o$, and f_o is either 50 or 60 Hz. For $\sin^2$ current, the peak is twice the average. The RMS value of sine-square input current is

$$\tilde{i}_g = \sqrt{\frac{2}{T_o}\cdot\int_0^{T_o/2} i_g^2(t)\cdot dt} = \sqrt{\frac{2}{T_o}\cdot\int_0^{T_o/2}[\hat{i}_g\cdot\sin^2(\omega_o\cdot t)]^2\cdot dt} = \frac{1}{2}\cdot\sqrt{\frac{3}{2}}\cdot\hat{i}_g = \sqrt{\frac{3}{2}}\cdot\bar{i}_g$$

Approximating, $\tilde{i}_g \approx 0.612\cdot\hat{i}_g \approx 1.225\cdot\bar{i}_g$.

The *form factor* is another circuit performance parameter, and for the input sine-squared current is

$$\kappa_g = \frac{\tilde{i}_g}{\bar{i}_g} = \sqrt{\frac{3}{2}} \approx 1.225$$

The form factor of the output sine-wave current for each half-cycle is

$$\kappa_o = \frac{\tilde{i}_o}{\bar{i}_o} = \frac{\left(\dfrac{\hat{i}_o}{\sqrt{2}}\right)}{\dfrac{\hat{i}_o}{\pi/2}} = \frac{\pi}{2\cdot\sqrt{2}} \approx 1.111$$

The larger input-current form factor implies that greater resistive losses will occur in the input circuit. This compounds an already difficult constraint of low input resistance (low voltage, high current) for battery-source inverters.

Yet for a sine-wave output, the sine-squared demand in current over each half-cycle cannot be avoided. However, it need not be demanded from the input. By using adequate interstage storage between an input converter and output inverter stage, the sine-squared current is drawn from converter output storage capacitors instead. This is the conventional two-stage inverter design scheme.

The waveshape choice for the INV401 (the inverter stage in Fig. 1 of part 1[1]) is a *third-harmonic sine-wave* (3HSW), a shape between that of a square wave and sine wave that has a reduced peak at the same RMS value, but with no higher harmonics than the third harmonic. In the next part of this series, inverter circuit design alternatives are examined.

References

1. "Designing An Open-Source Power Inverter (Part 1): Goals And Specifications" by Dennis Feucht, How2Power Today, May 2021.
2. "Improving Reliability Of Low-Cost Power-Source Inverters" by Dennis Feucht, How2Power Today, October 2020.

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."