STATPOWER

TECHNICAL WHITE PAPER

The PROsine™ technology advantage

Summary

Inverter/chargers are increasingly popular elements of electrical systems in recreational vehicles, boats, long-haul trucks, industrial vehicles and remote homes. Statpower's PROsine inverter/chargers represent a new technology which has significant advantages over the older, low frequency technology more commonly used.

The older inverter technology produces what is commonly termed a *quasi-sine wave* or *modified sine wave* output. This output waveform exhibits high distortion and has little resemblance to the true sine wave produced by the electric utility system. PROsine inverter technology produces a low distortion sinewave output that closely matches the characteristics of the utility voltage. The superior waveform and better voltage regulation offered by PROsine inverter technology provide the following benefits:

- numerous appliances that are incompatible with the older technology inverters may now be operated successfully
- no audio buzz on TVs, stereos, answering machines, and cordless phones
- clean video images on TVs and computer monitors
- more reliable operation of computer equipment
- motor operated loads such as pumps and fans deliver the same performance as when operating from utility power
- microwave ovens deliver the same performance as when running from utility power

Low frequency inverter/charger technology can cause significant voltage fluctuations in the DC electrical system connected to the inverter/charger. Fluctuations as high as 4- to 5-volts peak-to-peak, occurring at a 120-hertz rate, can occur on a 12-volt system, both in inverter mode and in charger mode. These voltage fluctuations (*voltage ripple*) affect the operation of other equipment powered by the DC electrical system. In contrast, PROsine technology creates little or no voltage ripple, resulting in more consistent and reliable operation of other equipment connected to the DC electrical system.

PROsine battery charger technology delivers consistent charging performance when AC line voltage is low—a frequent occurrence in many RV parks and marinas. PROsine charging technology also delivers excellent performance when operating from small or fully loaded generators. Chargers in common, low frequency inverter/chargers are very sensitive to the line voltage and deliver less than the rated current when the line voltage falls below 110 VAC. They may also perform below specification when operated from small or fully loaded generators.

Initially, the older, low frequency technology has a cost advantage over the more advanced PROsine technology. However, the PROsine technology becomes considerably more competitive when the total life cycle cost of the AC and DC electrical system is considered including the design, debugging and customer service costs incurred to deal with the compromises inherent in the older technology. When electrical systems include state-of-the-art entertainment electronics, top-of-the line electronically controlled appliances, complex engine control systems and advanced system metering and monitoring functions, it makes little sense to compromise on the quality of the power source.

Introduction

Inverter/chargers are increasingly popular elements of electrical systems in recreational vehicles, boats, long-haul trucks, industrial vehicles and remote homes. In their inverter mode of operation, they convert battery power (low voltage DC) to household AC power to run a wide variety of electrical and electronic equipment. In their charger mode of operation, they use AC power from a “shorepower” connection to the utility system or from a generator, to recharge the batteries in the system. They are a quiet, clean, compact and convenient alternative to gasoline or diesel powered generators in situations where AC power is needed and utility power isn’t available.

Statpower’s PROsine inverter/chargers represent a new technology which has significant advantages over the older, low frequency technology more commonly used. This technical bulletin compares the performance of the new PROsine sine wave technology with that of the older, low frequency quasi-square wave technology and outlines the benefits you can obtain by adopting PROsine technology.

PROsine inverter technology

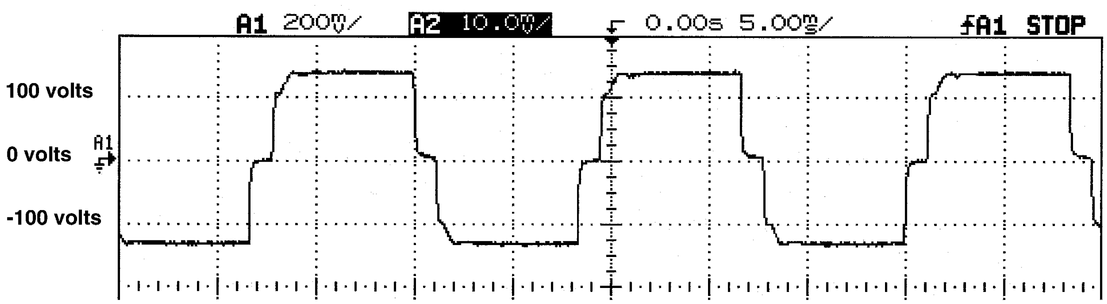
Inverter output voltage

Ideally, the inverter output voltage should match the requirements of the electrical and electronic equipment it is intended to operate. Household electrical equipment intended for use in North America is designed to operate from a 120-volt (or 240-volt) sine wave AC voltage with a frequency of 60 hertz. Most equipment will accept some deviation from this standard, but performance may degrade as the deviation increases. The higher quality inverter/chargers currently on the market do a good job of maintaining the frequency of the output voltage at precisely 60 hertz, but there are often significant deviations from the standard waveform and voltage requirements.

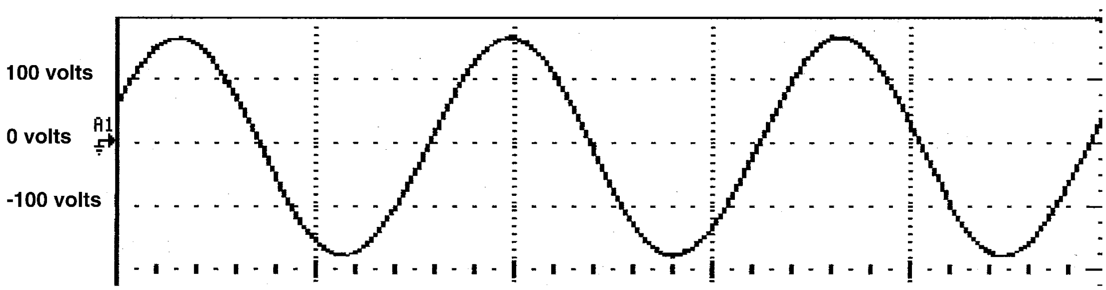
Waveform

Most inverter/chargers based on low frequency technology produce an output waveform that is described by marketers as a *modified sine wave* or a *quasi-sine wave*. A more accurate technical description is that it is a *pulse width modulated quasi-square wave*—referred to in the remainder of this Bulletin as *quasi-square wave*. It has been used largely because the circuits required to produce this waveform are inexpensive and efficient (see the Appendix for more technical details).

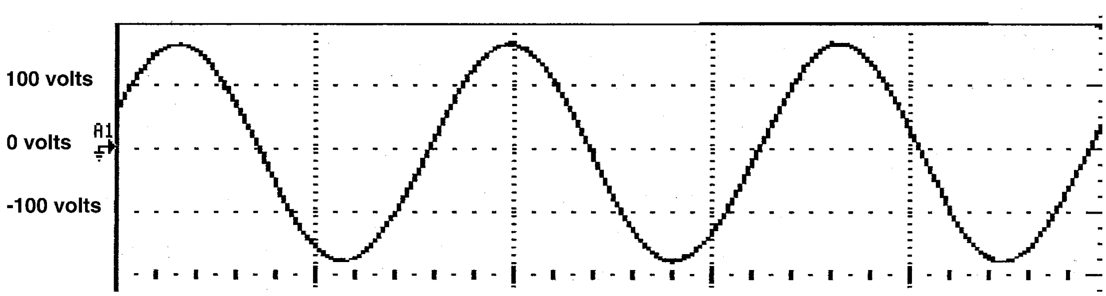
In contrast, PROsine inverter technology produces a low distortion, true sine wave that closely matches the ideal. As can be seen from the oscilloscope traces in Figure 1, the quasi-square waveform has little resemblance to the true sine wave produced by the utility system or by the PROsine inverter. The quasi-square wave has *total harmonic distortion* (a measure of waveform purity) as high as 47% whereas the PROsine inverter waveform typically has less than 3% total harmonic distortion. The PROsine inverter exhibits more than 3% total harmonic distortion when operating large nonlinear loads, but is still superior in waveform quality to the quasi-square wave inverter.



Output voltage from quasi-square wave inverter



Output voltage from PROsine 2.5 sine wave inverter



Electric utility voltage

Figure 1: The waveforms produced by common inverters, a PROsine inverter and utility-supplied power as measured by an oscilloscope.

Voltage stability

Quasi-square wave inverter/chargers typically have two problems with voltage stability or regulation. The first problem is that these inverter/chargers regulate the RMS (root mean square) value of the output AC voltage, holding the value constant as the input voltage from the battery varies, but they do not regulate the peak value of the output AC voltage. Statpower has measured peak voltages ranging from 112 volts to 196 volts on quasi-square inverter/chargers as the input voltage varies from 10 volts to 15 volts.

The correct peak voltage for a 120 VAC sine wave is 170 volts. The PROsine inverter technology maintains the same regulation on the peak voltage as it does on the RMS voltage, holding the peak output voltage close to 170 volts as the input battery voltage varies.

While simple resistive loads such as light bulbs are sensitive only to the RMS value of the voltage, other loads are sensitive to the peak voltage as well. Examples include battery chargers, microwave ovens and inexpensive electronic devices with limited power supply regulation. Noticeable effects of varying peak voltage include:

- unpredictable battery charging performance on rechargeable items such as cellular phones and cordless tools and appliances
- unpredictable cooking times for microwave ovens
- reduced picture size on some TV sets

To determine the effects of varying peak voltage on microwave oven cooking performance, Statpower performed tests in which a measured amount of water was heated in a microwave oven for a fixed time and the temperature rise of the water was recorded. The temperature rise is a measure of the cooking power of the microwave oven. The microwave oven was powered by two popular 2000-watt quasi-square wave inverter/chargers and by the PROsine 2.5 inverter/charger. The inverter/chargers were operated at three different input voltages. Table 1 below summarizes the results.

Table 1: Comparative Microwave Oven Cooking Performance

	TEMPERATURE RISE		
INPUT VDC	**BRAND A**	**BRAND B**	**PROSINE 2.5**
10.5	31°C	32°C	45°C
12	40°C	41°C	45°C
14	47°C	47°C	47°C

The results show that the PROsine technology delivers consistent microwave oven cooking performance. A microwave oven, operating from a quasi-square wave inverter/charger, may deliver as much as 30% less cooking power as when it is operating from a PROsine inverter/charger.

The second voltage regulation problem with quasi-square inverter/chargers is that they are often unable to maintain the proper RMS voltage as the battery discharges and its output voltage drops. Figure 2 below shows the output voltage regulation of two popular quasi-square wave inverter/chargers and of the PROsine 2.5 inverter/charger. The PROsine 2.5 maintains a consistent output voltage across the range of input voltages while quasi-square inverters show a droop in output voltage as the input voltage drops. The output voltage for Brand A falls outside the normally accepted tolerance limits for steady state voltage (+6% and -13%) when the input voltage drops below 11.5 volts.

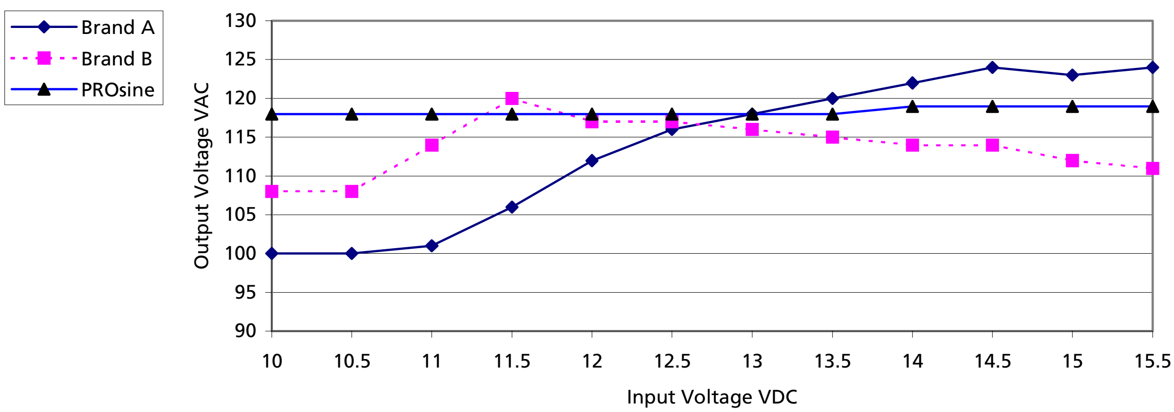


Figure 2: Output voltage regulation of inverter/charger technologies

The PROsine advantage

With PROsine technology, pure sine wave power is now available at reasonable cost for consumer applications. But does true sine wave solve real end-user problems? *Home Power* magazine has extensively evaluated both quasi-square wave inverters and pure sine wave inverters in a residential environment. They have concluded that sine wave inverters do provide real advantages. The advantages they cite for sine wave inverters over quasi-square inverters include:

- operation of appliances that are incompatible with the quasi-square waveform
- no audio buzz on TVs, stereos, answering machines and cordless phones
- cleaner video images on TVs and computer monitors
- more reliable operation of computer equipment
- quieter, faster, cooler operation of motor operated loads such as pumps and fans
- quieter, faster operation of microwave ovens

Common appliances that may be incompatible with a quasi-square waveform (i.e. may not work properly or may be damaged), but which will operate properly from a true sine wave, include:

- rechargers for cordless tools
- lamp dimmers
- digital clocks
- motor speed controls in power tools and appliances
- appliances equipped with electronic clocks, timers or control units such as microwave ovens, washing machines, bread makers, home entertainment equipment
- laser printers and photocopiers

To an original equipment manufacturer (OEM) making a choice of inverter/charger technologies, the PROsine sine wave advantages include:

- no need to select special appliances that will work with a quasi-square waveform
- no need to design in special AC line filters to reduce interference in audio or video
- no need to educate customers about incompatible loads and the other quirks of quasi-square wave inverters
- fewer customer complaints or queries about inconsistent operation of the electrical system

DC interface

The effect of inverter operation on the DC electrical system is often not considered when choosing an inverter technology. However, the inverter is likely the largest single load on the DC electrical system and can have a profound effect on its performance.

Ripple current

Since an inverter delivers single phase AC power, the power delivered fluctuates from zero to a maximum value 120 times a second. If there is no filtering or energy storage in the inverter, this translates into a similar fluctuation in the current drawn from the DC electrical system. This fluctuating current is called *ripple current*.

Inverters rated above 1000 watts draw high currents (several hundred amps) from the DC electrical system when operating at rated power. The ripple current in these cases can be very high and will cause a corresponding voltage fluctuation on the DC electrical system. These voltage fluctuations (*voltage ripple*) can affect the operation of other equipment connected to the DC electrical system. Effects may include buzzing in audio systems, interference with radio reception, erratic operation of metering and monitoring equipment in RVs and boats, and interference with electronic equipment, ranging from depth sounders to engine control computers.

The magnitude of the voltage fluctuation will depend on a number of factors, including:

- the amount of energy storage or filtering in the inverter
- the size and quality of the battery bank (a small bank of old, worn out batteries will make things much worse)
- the configuration of the DC wiring

Statpower performed some tests to determine the magnitude of voltage fluctuations that can occur. Tests were performed with two popular 2000-watt quasi-square inverter/chargers and with the 2500-watt PROsine 2.5 inverter/charger, each running at rated power. The battery bank consisted of two deep-cycle 8D batteries (540 amp hour total capacity). Connections between the batteries and the inverter/chargers were short (approximately 1 meter) and made with heavy 2/0 cable.

The oscilloscope traces in Figure 3, 4 and 5 below clearly show that the quasi-square inverter/chargers produce much higher voltage ripple. Voltage fluctuations in the nominal 12-volt circuit are as high as 4- to 5-volts peak-to-peak because the quasi-square inverters incorporate little or no internal energy storage to filter the ripple current. PROsine technology incorporates internal energy storage capacitors that reduce the DC current ripple. As a result, the voltage fluctuations caused by the PROsine 2.5 are only about 0.5 volts peak-to-peak, even though the PROsine 2.5 is operating at 25% higher power.

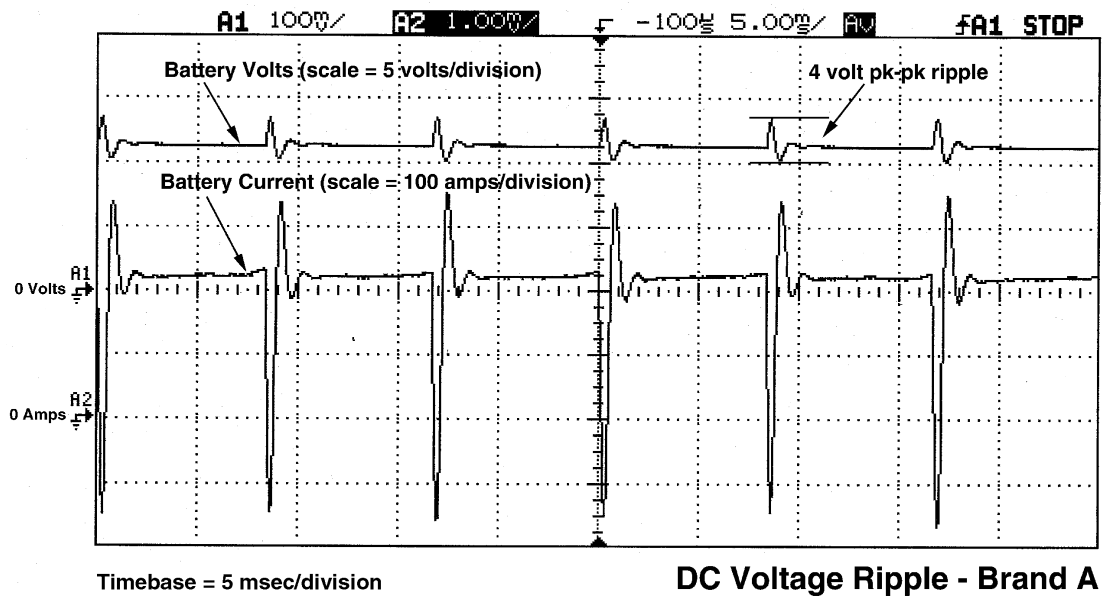


Figure 3: DC ripple current caused by Brand A, a 2000-watt quasi-square wave inverter/charger

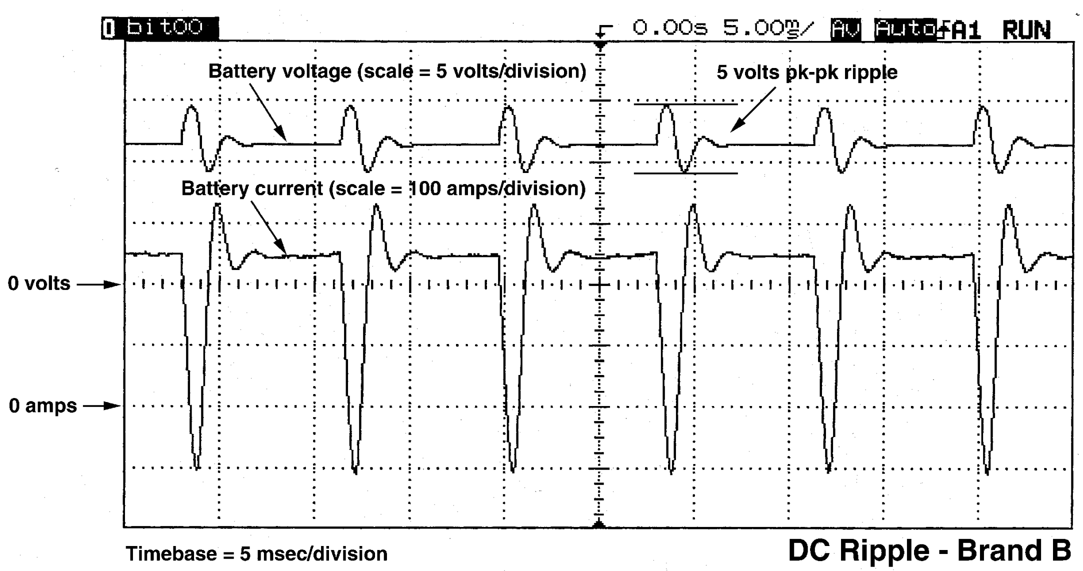


Figure 4: DC ripple current caused by Brand B, a 2000-watt quasi-square wave inverter/charger

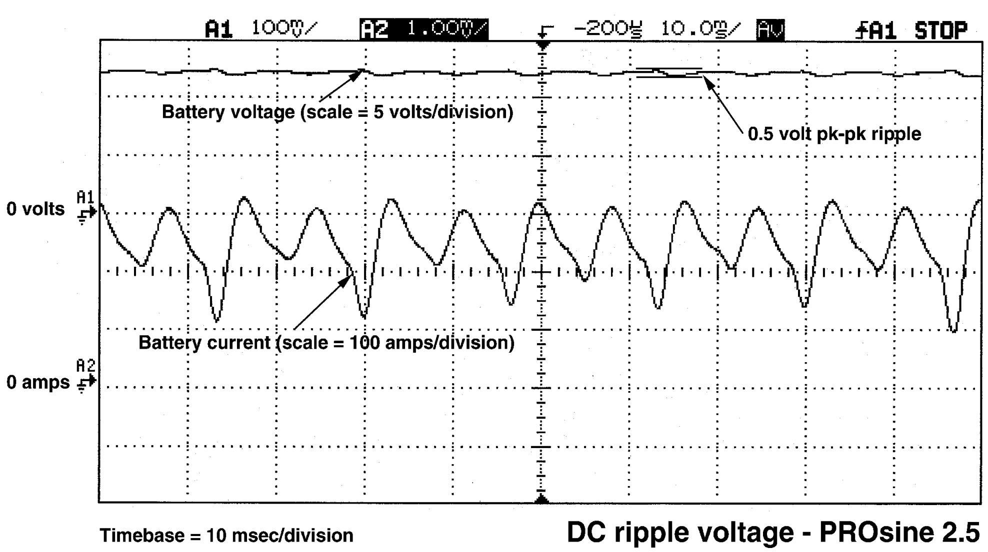


Figure 5: DC voltage ripple—PROsine 2.5 inverter/charger

The PROsine advantage

PROsine inverter technology dramatically reduces inverter-induced voltage ripple on the DC electrical system. As a result, the possibility of interference with other electrical and electronic equipment is greatly diminished, and the need for extra filters and other "fixes" is eliminated.

PROsine smart battery charger technology

PROsine inverter/chargers incorporate the smart battery charger technology that Statpower introduced in its popular TRUE*CHARGE* battery chargers.

Charger features

Multistage charging plus equalization. The charging technology delivers a 3-stage charge cycle and also provides for a user-triggered equalization mode to restore maximum capacity to flooded batteries. The microprocessor controller in the PROsine precisely regulates the voltage and current delivered to the battery, accurately charging without risk of overcharging and battery damage. Proprietary software algorithms compensate for a variety of conditions which “fool” less sophisticated charging technologies into delivering an improper charge.

Multiple battery types. PROsine inverter/chargers can be configured to properly charge either conventional flooded (wet or liquid electrolyte) lead-acid batteries or sealed lead-acid gel batteries.

Temperature compensation. Charging can be adjusted to account for battery temperature, either through user selection of a temperature range or automatically through a temperature sensor mounted to the battery.

Power sharing. The PROsine charger can be programmed to share power so that it will automatically adjust its AC current draw as other appliances connected to the circuit increase or decrease their current consumption. This allows the charger to deliver the highest possible charge current at all times without the risk of overloading the AC supply circuit and tripping circuit breakers.

High power factor charging

The PROsine charger circuit is designed to draw a sinusoidal current from the AC utility line that is exactly in phase with the utility voltage. As a result, it exhibits a power factor that is very close to unity. In contrast, the charger circuits in low frequency, quasi-square wave inverter/chargers draw current from the AC utility line in pulses as shown in Figure 6 below. As a result, the chargers exhibit a lower power factor—approximately 0.7. This lower power factor means that the charger draws about 30% more AC current to deliver the same DC charging current. For example, the PROsine 2.5 charger circuit requires only about 15 amps of AC current to deliver 100 amps of charging current while the charger circuits in low frequency, quasi-square wave inverter/chargers typically require over 20 amps of AC current to deliver 100 amps of charging current.

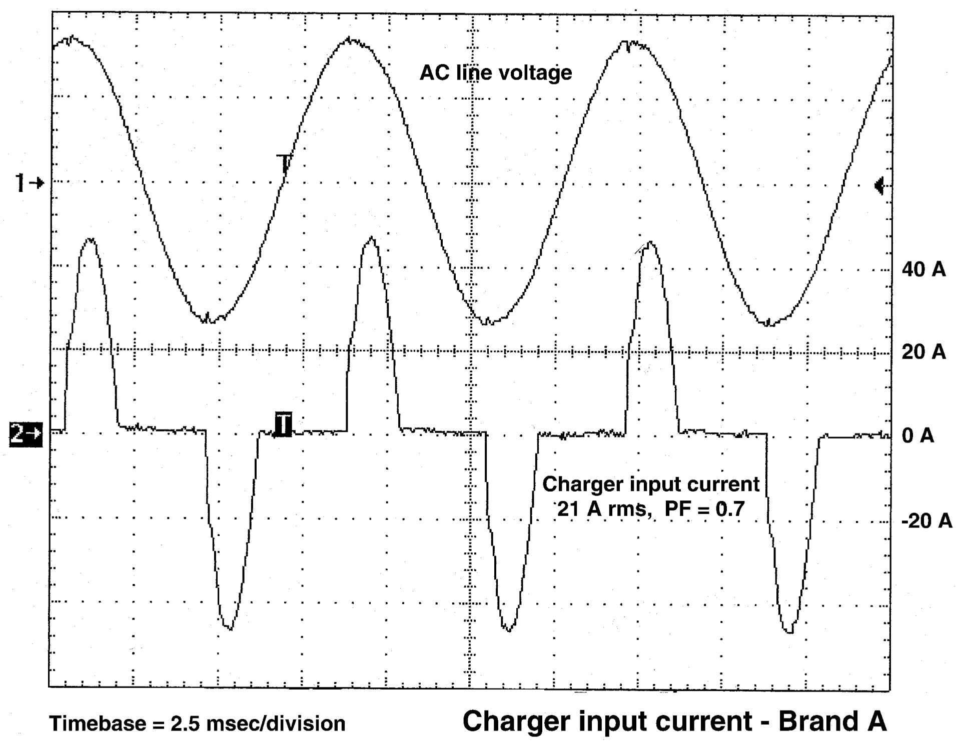


Figure 6: Quasi-square wave inverter/charger—current draw in charger mode

The PROsine advantage

High power factor charging and the resulting lower AC current requirements result in faster battery charging when a limited capacity AC source is available, since the charger will not have to reduce its input current as much to accommodate the demands of other AC loads on the circuit. On a 15-amp shorepower circuit, a PROsine charger can deliver as much as 100 amps while the charger in a competitive quasi-square inverter/charger can deliver only 70 amps.

Users also see better performance when charging from generators since generators are better able to deliver the sinusoidal current draw of the PROsine charger rather than the high peak current pulse draw of the quasi-square wave inverter/charger.

Ripple-free charging

Voltage ripple on the DC electrical system is as important an issue when the inverter/charger is in charge mode as it is in inverter mode. The charger circuits in low frequency, quasi-square wave inverters deliver charging current in pulses, which results in large ripple voltages. Their ripple performance is similar to that of the old unfiltered ferroresonant converter/ charger technology that is being phased out by most RV and boat OEMs. As can be seen in Figure 7 below, ripple voltages of 4 volts peak-to-peak can occur when charging reasonably sized battery banks (two 8D batteries in parallel). In contrast, PROsine technology delivers a smooth ripple-free current to the battery, resulting in almost no voltage ripple.

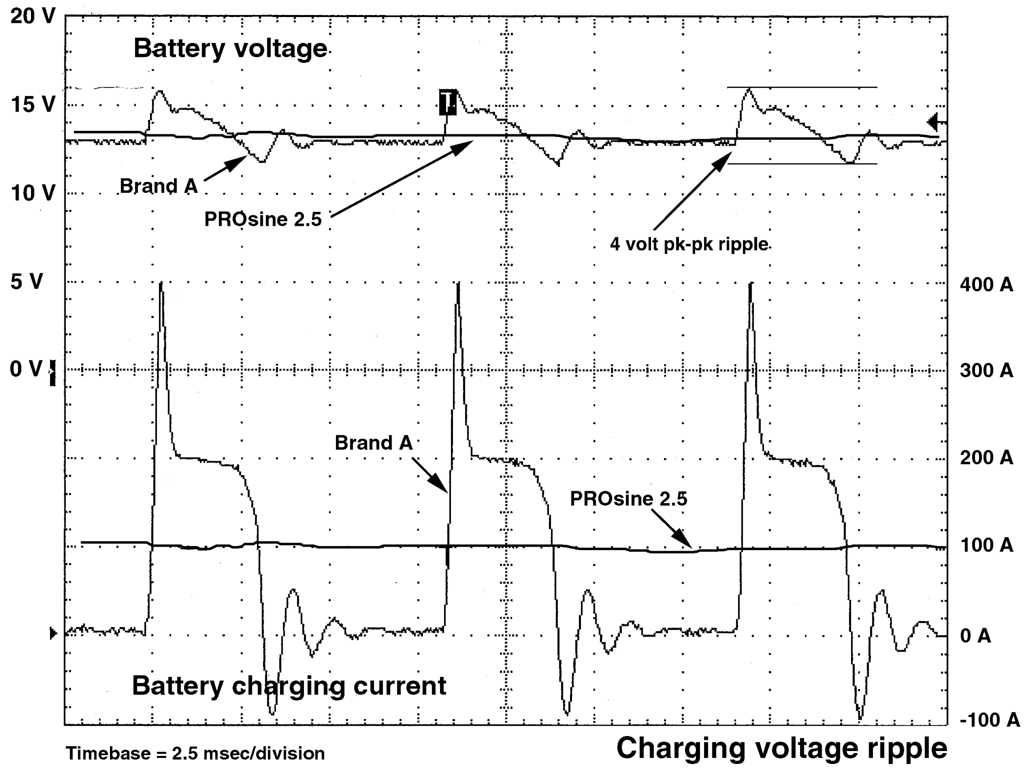


Figure 7: Charging current and voltage for quasi-square wave inverter/charger (Brand A) and PROsine 2.5 inverter/charger—both delivering 100ADC average

The PROsine advantage

PROsine ripple-free charger technology dramatically reduces charger induced voltage ripple on the DC electrical system. As a result, the possibility of interference with other electrical and electronic equipment is greatly diminished and the need for extra filters and other "fixes" is eliminated.

Wide voltage range operation

PROsine charger technology operates properly over a wide range of input voltages. The PROsine charger will deliver its rated charging current even if the AC line voltage drops as low as 95 VAC. In contrast, the charger circuits in low frequency, quasi-square wave inverter/chargers are sensitive to the peak AC voltage. They are unable to deliver rated current when the AC line voltage drops below 110 VAC. Table 2 shows the current delivered to a battery at 13.3 VDC by two popular quasi-square wave inverter/chargers and by the PROsine 2.5 inverter/charger, as a function of AC line voltage. At lower AC line voltages, the older technology chargers may not be able to deliver enough current to supply DC house loads, much less recharge a large battery bank.

TABLE 2: The charge current of inverter/chargers over a range of input voltages

	CHARGE CURRENT (AMPS)		
Input VAC	Brand A	Brand B	PROsine 2.5
120 VAC	100 A	100 A	104 A
110 VAC	101 A	78 A	104 A
105 VAC	84 A	53 A	104 A
100 VAC	59 A	12 A	104 A
95 VAC	13 A	6 A	104 A

The PROsine advantage

Low AC line voltage is a common problem in RV parks and marinas, particularly during peak periods when the electrical systems are fully loaded. Generators also tend to suffer from AC voltage droop or clipping of the peak voltage when they are heavily loaded. When the AC line voltage droops or the peak voltage is clipped, older technology chargers may not be able to keep up with the current demands of DC house loads. The house batteries may actually be discharged further, rather than recharged. PROsine charger technology provides assurance that house load demands will be met, and onboard batteries will be fully and rapidly charged, even when the shorepower service is less than perfect or the generator is fully loaded.

PROsine charger technology delivers good charging performance with relatively small generators—a generator rated at 2.5 kilowatts will operate the charger at its maximum rate. Generators used with quasi-square wave charger technology must usually be oversized—recommended minimums are in the range of 3.5 kilowatts to 5 kilowatts for 100-amp/120-amp charger ratings. PROsine technology allows the choice of a smaller, lower cost generator or allows more AC loads to be operated during charging if a larger generator is employed.

PROsine smart transfer switch

PROsine inverter/chargers are equipped with an automatic, microcomputer-controlled, transfer switch which allows incoming AC power from an external source (shorepower or generator) to be transferred through to loads connected to the inverter/charger. When the external AC power is disconnected or interrupted, the transfer switch automatically connects the loads to the inverter output.

Fast transfer time

While PROsine inverter/chargers are not designed specifically for uninterruptible power supply (UPS) applications, the transfer time from incoming AC power to inverter power is under 20 milliseconds—fast enough to hold up most computers, digital clocks and appliance controllers.

The PROsine advantage

Slow transfer switches are irritating. Computers must be restarted, and clocks and appliances must be reset every time a transfer is made from generator or shorepower to inverter power. With the fast PROsine transfer switch, the transfer is seamless.

Smart transfer from inverter to external AC power

When switching from inverter power to external power from the shorepower connection or the generator, the PROsine inverter/charger monitors the incoming AC voltage for a minimum of 10 seconds to ensure that it is stable and within normal limits. This ensures that the generator has come up to speed and its voltage has stabilized.

In addition, the PROsine synchronizes the phasing of the inverter voltage to the phasing of the external power so that when the transfer is made, there is no sudden voltage transient which can upset the operation of AC loads.

The PROsine advantage

Simple transfer switches that use a fixed time delay without monitoring the incoming voltage may reconnect while voltage is still not stable or within proper limits, resulting in a voltage transient that can reset computers, digital clocks and other electronic devices.

Similarly, simple transfer switches that do not synchronize the inverter voltage to the incoming voltage cause voltage transients that may upset some loads, and even cause tripping of circuit breakers and other protective devices.

The PROsine smart transfer switch technology provides a fast, glitch-free transfer that is transparent to the downstream AC loads.

PROsine high frequency power conversion technology

PROsine technology is based on high frequency power conversion. In this technology, which was first applied in the aerospace and computer industries, power is regulated and converted by switching it at high frequencies—typically in the range of 20 kilohertz to several hundred kilohertz. Voltages are stepped up or stepped down with small ferrite core transformers, which also provide electrical isolation.

Lightweight

Because large low frequency transformers and inductors are not required by this technology, the resulting products can be much lighter than equivalent products based on low frequency technologies. As can be seen from the table below, the weight differences are significant.

PRODUCT	WEIGHT
PROsine sine wave inverter/charger (3 kW)	32 lb
Low frequency, quasi-square wave inverter/charger (3 kW)	60 lb
Low frequency, sine wave inverter/charger (2.5 kW)	95 lb

The PROsine advantage

The weight saved by choosing a PROsine inverter/charger can be used to provide other user features or more cargo capacity in weight-restricted vehicle designs. A lighter product is easier to install and allows more choice of installation location and orientation.

Appendix: Overview of inverter/charger technologies

Line frequency transformer, quasi-square wave inverter/chargers

This technology is currently the most common in the market. Inverter/chargers based on this technology are produced by companies such as Heart Interface, Trace Engineering, Vanner, Dimensions Unlimited and Tripp-Lite.

Although circuits differ among manufacturers, Figure 8 illustrates a representative power conversion circuit. In inverter mode, switch S2 is closed and switch S1 is open, connecting the high voltage winding of the line frequency transformer to the load. The MOSFET H bridge is switched at four times the line frequency with a switching sequence of:

Q1,Q4 on Q2,Q3 off
Q2,Q4 on Q1,Q3 off
Q2,Q3 on Q1,Q4 off
Q2,Q4 on Q1,Q3 off

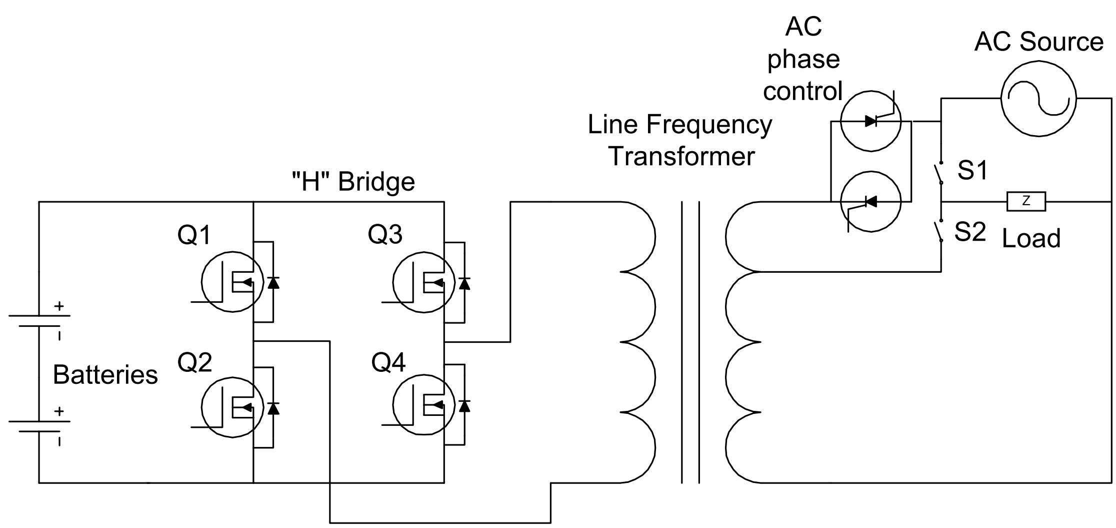


Figure 8: Line frequency transformer, quasi-square wave inverter/charger

The resulting voltage applied to the low voltage winding of the line frequency transformer is a quasi-square AC waveform that is stepped up by the transformer. The output voltage from the secondary of the transformer is shown in Figure 9—it is commonly called a *quasi-sine wave* or a *modified sine wave* in the industry. Regulation of the RMS value of the output voltage can be achieved by varying the duty cycle of the waveform. This is illustrated in Figure 10 which shows the wavefoRMS for three different input voltages. As the input voltage changes, the peak voltage of the AC output also changes, but the RMS value can be kept constant by changing the duty cycle.

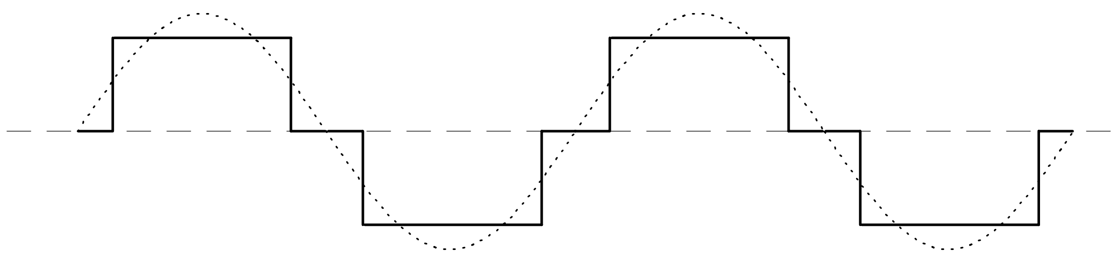


Figure 9: Quasi-sinusoidal output voltage

When the converter is in charger mode, switch S1 is closed and switch S2 is open. Voltage from the AC source is applied to the high voltage winding of the line frequency transformer through a phase controlled switch. The voltage may be applied to a different winding tap than that used in inverter mode, allowing a different turns ratio. The resulting AC voltage on the low voltage winding is rectified by the H bridge and applied to the battery. The rectification may be accomplished by the inherent anti-parallel diodes in the power MOSFETS, or synchronous rectification may be used in which the MOSFETs are switched in phase with the AC voltage.

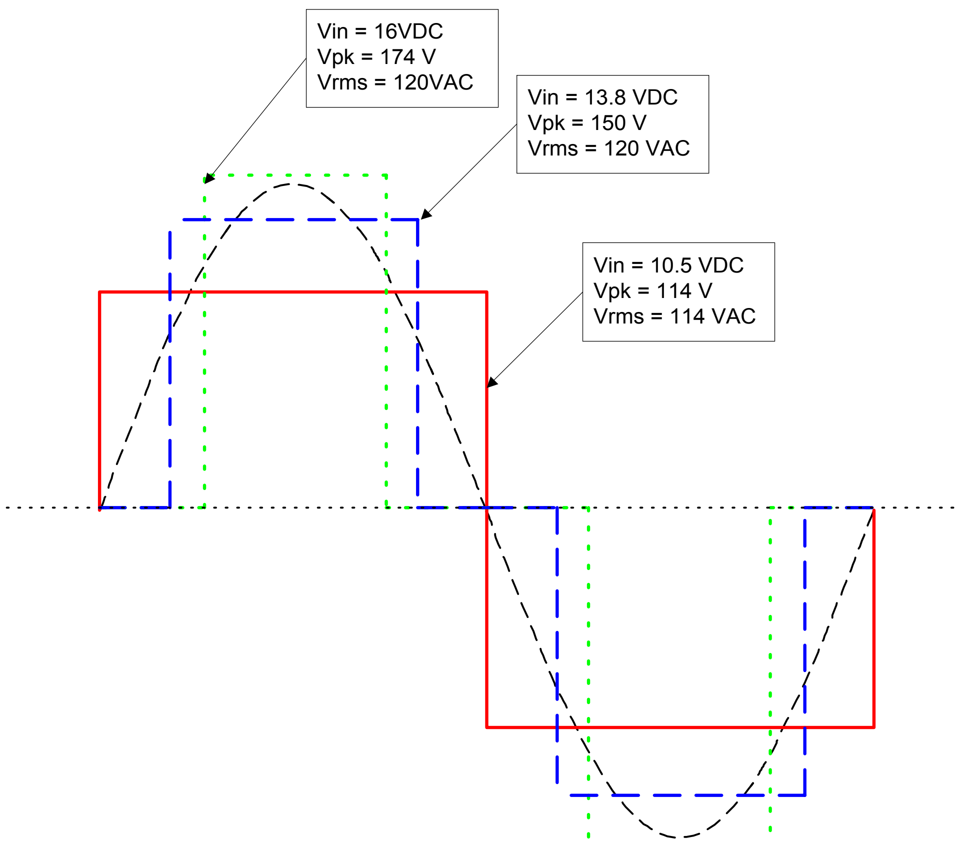


Figure 10: Regulation of RMS output voltage

The phase-controlled switch (typically composed of anti-parallel SCRs or a triac) is employed to regulate the charging current. By advancing or retarding the phase angle (relative to the zero crossing of the AC voltage) at which the switch is turned on, the current can be increased or decreased.

When properly implemented, this technology is efficient and cost effective. However, it has several disadvantages which the PROsine technology seeks to rectify:

- output voltage in inverter mode is non-sinusoidal and is only regulated for its RMS value. Some loads are sensitive to non-sinusoidal waveforms and only operate well when the applied voltage is sinusoidal. Others are sensitive to the peak voltage of the AC waveform and require regulation of the peak voltage close to the peak voltage of the sine wave voltage.
- a pulsating current is drawn from the battery in inverter mode since there is no (or little) internal energy storage
- power factor in charger mode is low and current distortion is high
- charger current is pulsating
- line current transformer is large and heavy

Low frequency transformer, sinusoidal inverter/charger technology

Trace Engineering, in its SW series of sine wave inverter/chargers, uses a multi-transformer configuration that has the secondary windings wired in series and each primary winding connected to an H bridge of switches (e.g. power MOSFETs). By controlling the switching sequence of the switches, a stepped approximation of a sinusoidal voltage is produced on the secondary windings. The switching H bridges may also be controlled to convert an AC voltage, applied to the transformer secondary windings, to a DC voltage for battery charging purposes. US Patent No. 5,373,433 (Thomas) discloses this approach in more detail.

This approach improves on the non-sinusoidal inverter/chargers in providing a sinusoidal output voltage and in having higher power factor, lower AC current distortion in charge mode. However, since there is little internal energy storage, this technology still has large pulsating currents at the DC port in both inverter and charger modes. Also, these inverter/chargers are very large and heavy because they require multiple low frequency transformers.

PROsine technology—High frequency link, sinusoidal inverter/charger

The PROsine inverter/charger is based on two independent power conversion stages connected by an internal DC bus (DC link converter topology) (Figure 11). One power conversion stage—a bidirectional DC/DC converter, employing small high-frequency transformers—transfers power between the DC bus and the inverter/charger's DC terminals. The other converter stage—a bidirectional sinusoidal DC/AC converter—transfers power between the DC bus and the inverter/charger's AC terminals.

When the PROsine inverter/charger is operating as an inverter, the DC/DC converter steps the battery voltage up to a regulated DC bus voltage. The DC/AC converter then inverts the DC bus voltage to a 120 VAC, 60-hertz sine wave voltage at the AC terminals.

When the PROsine inverter/charger is operating as a battery charger, DC/AC converter acts as a unity power factor rectifier, converting the AC voltage at the AC terminals to a regulated DC bus voltage. The DC/DC converter draws current from the DC bus and delivers a controlled charge current to the battery in accordance with the 3-stage charge profile.The DC bus voltage is regulated to be somewhat higher than the peak of the AC voltage expected at the AC terminals. For a 120 VAC system, the DC bus voltage will be approximately 215 volts.

The DC bus has load balancing energy storage elements (typically capacitors) that allow the DC/DC stage to transfer continuous, ripple-free power to and from the DC terminals, despite the presence of a ripple at twice the AC frequency (e.g. 120 hertz for 60-hertz AC frequency) in the power transferred between the DC bus and the AC terminals.

The DC/AC converter stage power section, shown on the right of Figure 11, has the following basic power section elements:

- the DC bus, shared with the DC/DC converter section, which has a fixed DC voltage and can source or accept current
- the AC port, which, depending on the operating mode, may be connected to a load or to an AC voltage source
- a full-bridge converter consisting of four power switches (e.g. power MOSFETs or IGBTs)
- a low pass filter network between the full bridge converter and the AC port

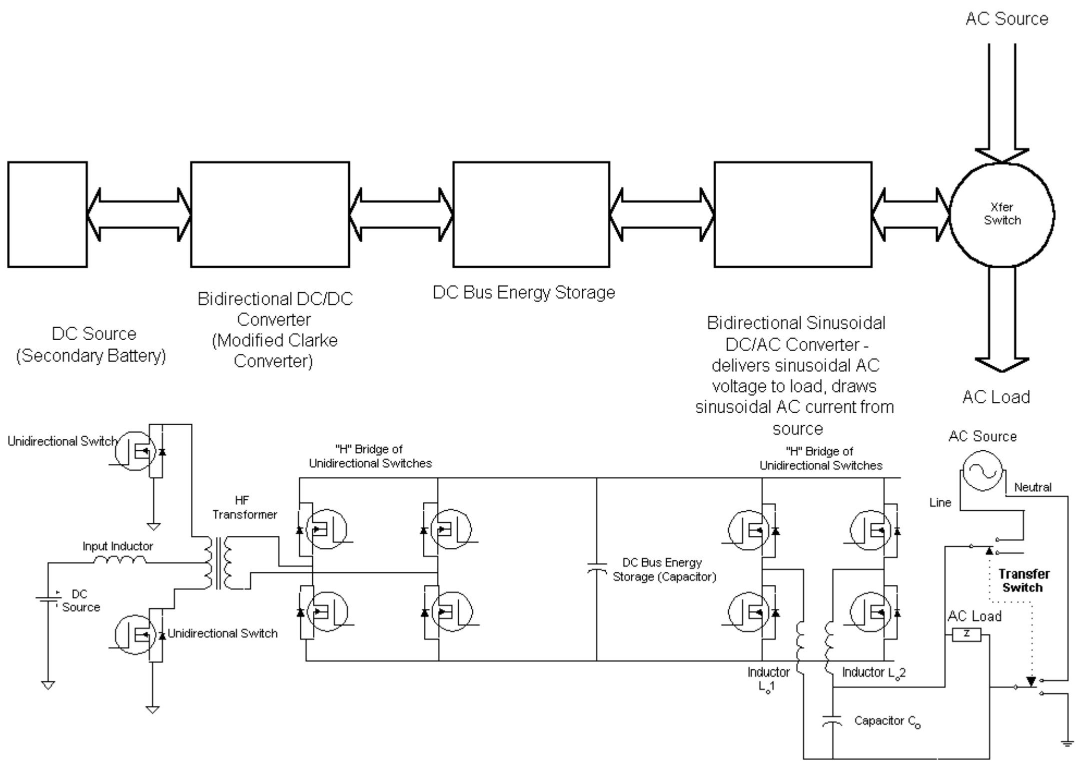


Figure 11: Bidirectional Inverter/Charger

Pulse width modulated switching is employed to control the switching of the four switches in the full-bridge converter so that the converter can operate in all four quadrants of the $i_o - v_o$ plane, and the power flow through the converter can be in either direction. The switching is controlled so that the desired sinusoidal waveform is produced at the AC terminals. Diagonally opposite switches in the bridge converter are treated as two switch pairs; switches in each pair are turned on and off simultaneously. One of the two switch pairs is always on when the circuit is active.

The switching signals for the full-bridge converter are generated by comparing a triangular carrier waveform (Vcarr) at the desired switching frequency with the reference voltage Vref. The resulting control signal, Vpwm, is shown in Figure 12.

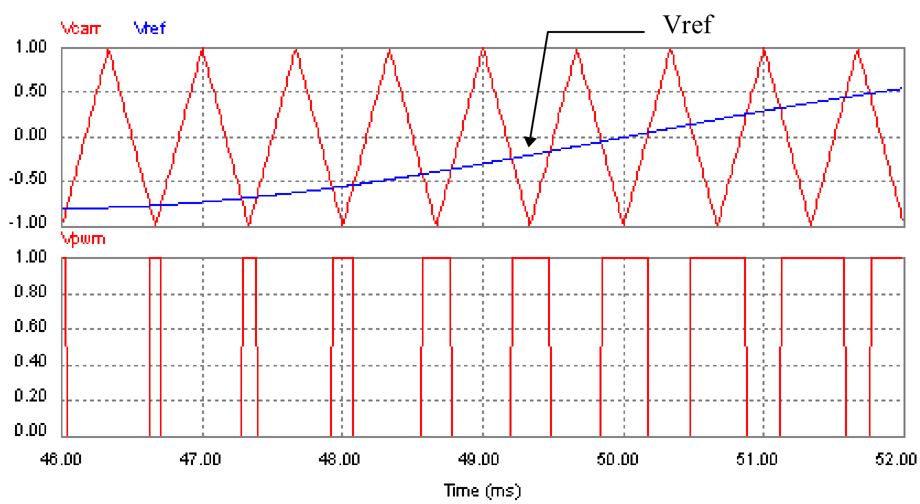


Figure 12: Bipolar PWM using triangle intercept method

When Vpwm is high, one pair of switches is on, and when Vpwm is low, the other pair of switches is on. The resulting output voltage (Vinv) measured at the output of the full bridge converter jumps between +Vbus and -Vbus depending on whether Vpwm is high or low. However, the effective (integrated) value over many switching cycles is:

$$V_{inv,eff} = {V_{bus}}/{V_{tri}} \times V_{ref}$$

where V_{tri} is the amplitude of the triangular carrier

Figure 13 illustrates that if the reference voltage is a sinusoid, the bridge output voltage will be a series of width modulated pulses with an effective integrated value that varies sinusoidally with the reference.

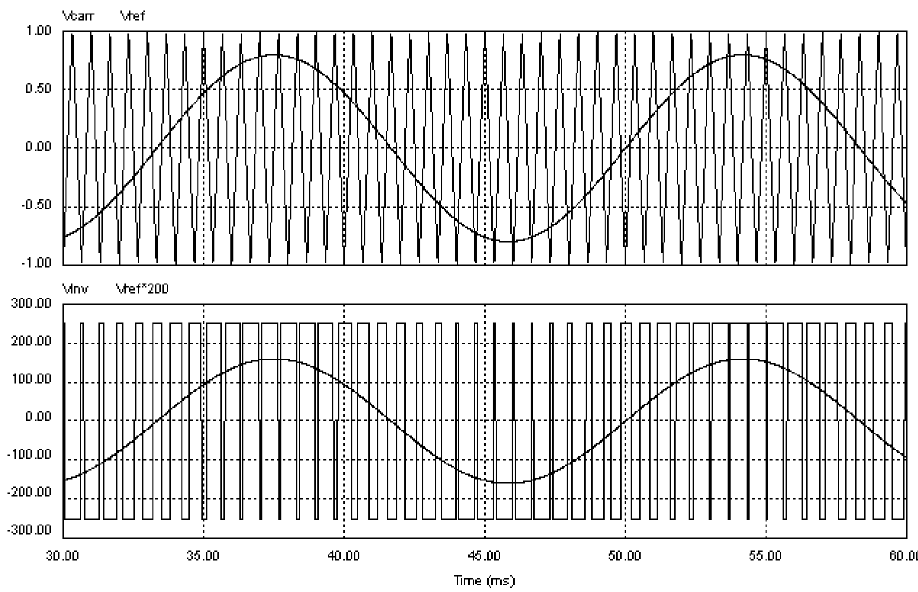


Figure 13: Sinusoidal pulse width modulation
Top trace—triangular carrier and sinusoidal reference voltage
Bottom trace—bridge output voltage and its effective value

For purposes of clarity, in Figure 13 and 14, the carrier frequency is shown as much lower than it actually is. In the actual PROsine circuit, the carrier frequency, and thus the switching frequency, is on the order of 40 kilohertz. When modulated by a sinusoidal reference, the bridge output voltage (Vinv) has a frequency spectrum consisting of a large component at the frequency of the reference signal (e.g. 60 hertz), and additional harmonic components around the frequency of the carrier (e.g. 40 kilohertz) and around odd integer multiples of the carrier frequency.

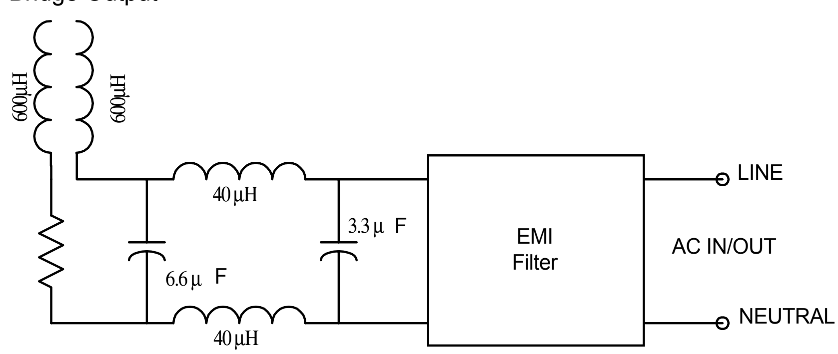


Figure 14: Low pass filter network

Since the reference frequency and the carrier frequency are widely separated, the harmonic components of Vinv can be removed with a relatively simple and compact low pass filter consisting of inductors and capacitors, leaving only the 60-hertz component at the AC port terminals. The filter network is shown in Figure 14.

PROsine technology represents an advance over the older low frequency quasi-square wave technology in many respects. AC waveform quality is superior in both invert and charge modes, and the DC electrical system is not subjected to high current ripple. Performance is less affected by fluctuations in input voltage (AC or DC). Weight is substantially reduced.

Peak inverter efficiency at the best operating point is slightly less than 90%. This is a few percentage points lower than the peak efficiency for the best quasi-square wave inverters at their best operating point. However, the efficiency of PROsine technology is on par with quasi-square wave technology at 75% to 100% of rated power, where power losses are the highest.

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